Panorama of the models of behavior of grounds and rocks, joints

Summary:

The objective of this document is to provide an overall vision of the possibilities of modeling which are offered to the user in modeling of the behavior of the grounds and the rocks, to which one also added the behavior of the joints to describe the interfaces between géomatériaux mediums. Various choices are always possible and the goal of this document is not to substitute themselves for the analysis of the engineer but well to enable him to more easily choose the options of modeling, according to the needs and of the tools available, and to direct it towards more specific documents.

Contents

1 Introduction

1.1 General information on the behavior of the grounds and the rocks, the joints

The modeling of the behavior of the grounds and the rocks which constitute many works geotechnics seeks to represent complex phenomenologies, in particular nonlinear according to the aims of the conducted study. One can for example be interested to evaluate the capacity of bearing pressure of a foundation, the rise of the water pressures, compressings sismo-armatures, the evolution of a zone of slip, the margin available before appearance of liquefaction, the long-term behaviour of an underground work, the amplification of the waves in a sedimentary basin…

The mechanical behavior of géomatériaux is characterized by:

- an asymmetry between states of traction and compactnesses;
- irreversible evolutions, to describe by internal variables of history;
- one *consolidation*, for a way of spherical constraints, which has a strong non-linearity;
- a curve "of *state critical* ", which is a data of material, in the plan $\log_{10} p'-e$ (*confining pressure* , known as too *average effective constraint* $p'=\frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma}')$ – *index of the vacuums* e , which is connected directly to *index of density* D_r) where the ground when it undergoes a pure shearing does not present any more evolution of the voluminal deformations (one has $\dot{\varepsilon}_p^v=0$); and one reaches a plate of resistance in the confining pressure plan – constraints déviatoires $p'-q$. For a non-cohesive soil, the curve "of critical condition" is rather rectilinear in the plan $\log_{10} p'-e$ while it is curved for a clay soil. At the initial state of the ground, in the plan $\log_{10} p'-e$ the field on the left of the curve "of *state critical* " characterizes the dilating situations, while on right-hand side there is contractance;
- one *dilatancy* , i.e. a coupling between voluminal behavior and behavior deviatoric, variable during the evolution of and also the evolution impoverishment of the soil of the pore water pressures which play on p' . One associates the name of Roscoe with this phenomenology. The phase of dilatancy succeeds a preliminary phase in general of *contractance* ; these two phases are separated by a curve "from *characteristic state* " in the plan $p'-q$ (where one has $\dot{\varepsilon}_p^v=0$), dependent on the cf, consolidation statement for example [feeding-bottle 27]. *angle of dilatancy* ψ characterize the slope of this curve, which is always below the curve "of critical condition" or superimposed;
- one *resistance* depending on the history of loading, increasing or decreasing (positive or negative work hardening), associated with residual deformations. A dilating ground can see its resistance decreasing (*softening*) after a stage of positive work hardening, while a ground contracting can know a positive work hardening until the rupture, described by the curve "of*critical condition* " traced in the plan confining pressure – constraints déviatoires $p'-q$. The natural angle of repose ϕ_{pp} characterize the slope of this curve "of*critical condition* " in the plan $p'-q$. In the case of a clay, these situations are associated with the value of the degree of *consolidation* ground (called *OCR*), while for a sand, the initial state in the plan $\log_{10} p'-e$ defines the lenitive characteristic and dilating or contracting nonlenitive behavior ;
- one *cohesion* initial (i.e. a resistance for a loading deviatoric) for clays, almost worthless for dry sands, even if those once saturated have a certain cohesion; the cohesion of the rocks is generally much higher;
- this phenomenology thus reflects a common characteristic: dependence of the behavior to the state of the material Dyears the plan $\log_{10} p'-e$. S *elastic characteristics* also depend on the

initial index of the vacuums e_0 and of the confining pressure: this characterizes a nonlinear law of elasticity;

- loops of*hysteresis* under cyclic loading, on which the form is also dependent on confining pressure, and of*index of plasticity* I_p who is measured in laboratory ;
- in particular a pulverulent material (sand…) under cyclic loading deviatoric controlled in deformation is made denser gradually (contractance), especially if it is *coward* at the initial state (low value of D_r); on the other hand if the material is *dense* (*on-consolidated*) he knows a phase of damage (dilatancy) after attack of the peak, followed by the rupture (critical condition). If the amplitude of these cycles is strong, one can observe the absence of a stabilization of the cyclic answer: there is not any more accommodation but appearance of the ratchet;
- rigidities tangent and secant depending on the history of loading;
- an influence rate loading: one *viscosity* equivalent can allow to represent this effect, even if it is difficult to quantify for sands; this characteristic is important for clays and the rocks; all the properties of behavior referred to above can be dependent the rate loading;
- and finally strong *space variability of the properties* mechanics, characteristic of a natural material.

For these common characteristics, it is advisable to define the principal differences between a ground and a rock:

- one *ground* is characterized by a generally porous medium having a behavior *furniture*, i.e. sufficiently deformable so that it can be “worked”; the law of behavior of a ground will mainly stick to characterize sound *plastic flow*, its resistance under loading *cyclic* ; a ground can be described by a porous continuous medium of granular type: the plastic flow and the long-term behavior are closely related to the problems of the variations of pore water pressures of the fluid present in porosity;
- one *rock* is characterized by a cohesion much higher than a ground, and a stiff behavior having a certain hardness; the law of behavior of a rock will mainly stick to characterize *cracking* instantaneous and differed, as well as the rupture in *tiredness*. The state of*damage* rock, at the level of a solid mass, is quantified by factor RQD (Rock'n'roll Quality Designation). It is important to take account of the discontinuous character of a rock solid mass at the level of the structure, i.e. to incorporate in modeling the taking into account of possible fractures which exceed the limits of representation of the law of behavior. A model of *joint* can prove to be relevant. The porosity of a rock is generally much lower than that of a ground, therefore the hydraulic coupling in the rocks exploits the long run especially.

interfaces mediums made up of géomatériaux are in general characterized also by complex behaviors: one cannot be always satisfied with a perfect modeling by simple continuity of displacements, equivalent to the continuity of the vector-constraint to the interface. One thus defines a model of *joint*. One finds the phenomena of cohesion, dilatancy as in the grounds, and moreover, the unilateral character of the rupture. The hydraulic coupling plays a crucial role in certain types of application.

The various models of behavior try to represent whole or part of these characteristics.

The parameters of the models of behavior are identified starting from laboratory tests:

- simple, triaxial shearing (consolidation with various values of containment, in situation drained or not), torsion, isotropic, œdometric compression (drained cylindrical test-tube subjected to a monotonous axial compression plain, and to blocked side displacements: obtaining a curve of consolidation) ;
- these tests can be monotonous or cyclic, drained or not drained, with strain imposed or imposed stress;
- resonant column: obtaining the elastic modules;
- creep, rupture, and relieving for the rocks;

whose results must be sometimes corrected to reflect the way of real constraints in place, and in situ tests, with variable depths in the ground. These tests are supplemented by geological analyses and recognitions:

- SPT (*standard penetration test*), test carried out by depression of a tube, which does not provide direct measurement of physical parameter;
- CPT (penetrometers), monotonous static cone penetration test inserted at constant speed, which does not provide direct measurement of physical parameter;
- pressure gauge: obtaining the elastic modules, the resistance and the modules of creep; one thus considers for example the test with the pressure gauge “Ménard” carried out by putting increasing pressure controlled in a vertical cylindrical drilling.
- CPTU (with measurement of the pore water pressure);
- celerity of the waves of shearing V_s on low level of deformation (*cross-country race-hole*, SASW);
- test with the flat jack in order to evaluate the state of initial stresses in a rock solid mass.

These tests produce relations between many cycles and CSR (cyclic stress ratio equal to τ/σ'_v), the state of surconsolidation (OCR, connected to the index of plasticity I_p), CRR (cyclic resistance ratio), curves of cyclic degradation $G-\gamma$. The elastic field of behavior of the grounds is limited to very weak deformations: $\varepsilon<10^{-5}$.

In *Code_Aster*, one adopted the convention of the mechanics of the structures: the constraints and deformations are positive in traction, the stresses compressive have negative values.

1.2 Objectives

The modelisator will have to find the best compromise between complexity (of the phenomena, of the calibration of the parameters…), the cost of the study, the robustness of integration, and precision or the representativeness of the results searched, according to the available data (laboratory parameters and tests) and the cases of physical validation available in the field of loading aimed by the study, by correctly choosing the type of models of behavior, knowing that a great choice of models of behavior is available in *Code_Aster*, but also in the literature…

This document is designed to help it in this task. It gathers elements already available elsewhere in the documentation of *Code_Aster*, and also the experience feedback of the authors having contributed to these models of behavior brings. One thus exposes in a generic way various angles of comparative analysis of these models: materials concerned, phenomenology, characteristics and type of formulation of law, modelings usable with *Code_Aster*, number and type of parameters, procedure of identification starting from the tests available, number and type of internal variables (in a strict sense: corresponding to the mathematical formulation of the law, but also variable local useful for the analyst: sizes of interest for the engineer), Chave-tests of checking and validation, references, publications, general opinion (robustness, developpability…), prospects.

1.3 Works geotechnics made up of géomatériaux like porous environments

The geotechnical work consists of a ground, or a rock, generally porous (the solid phase is known as skeleton of ground), and this porosity is occupied by fluids: water, air, gas, air entrained, according to a variable saturation. These fluids run out within the porous environment and take part in the mechanical answer; various laws of diffusion govern these flows, to see [R7.01.11]. These laws correspond to dissipative phenomena, for example the law of Darcy which describes the flow of the phase (S) fluid (S) within the matrix porous, and parameterized by (them) the permeability (S). According to the boundary conditions of the medium imposed on (X) fluid (S), one is in situation *drained* or in situation *not drained*. One will consult documentation for the use of the models of porous environment [U2.04.05].

Concept of " *effective constraints* " allows to describe the contribution of the skeleton of ground the total mechanical answer of the porous environment, associated with its kinematics, described by the tensor of deformation $\boldsymbol{\varepsilon}$. It is the principle of Terzaghi which breaks up the tensor of the total constraints into effective constraints and in contribution due to (X) fluid (S) : $\boldsymbol{\sigma}=\boldsymbol{\sigma}'-b.p_{lq}\mathbf{Id}$, where p_{lq} indicate the pressure of pore (presumedly positive in compression in *Code_Aster*) in the monophasic case (case *saturated*), $\boldsymbol{\sigma}'$ the tensor of the "effective constraints" and b the coefficient of the isotropic tensor of BIOT; on the assumption of Terzaghi, one a: $b\rightarrow 1$.

If a gas phase is also present, one utilizes saturation in liquid S_{lq} in the following total differential expression: $d\,\boldsymbol{\sigma}=d\,\boldsymbol{\sigma}'-b.\left(d\,p_{gz}\mathbf{Id}-S_{lq}.d\,p_c\mathbf{Id}\right)$, where p_{gz} indicate the pressure of gas (presumedly positive in compression in *Code_Aster*) and $p_c=p_{gz}-p_{lq}$ indicate *capillary pressure* said too *suction* (positive with of not-saturated). L then is definedconcept has of " *clear constraints* ": $d\,\tilde{\boldsymbol{\sigma}}=d\,\boldsymbol{\sigma}+b.\left(d\,p_{gz}\mathbf{Id}\right)$.

In the absence of phase water in the ground, in particular above level of the water table, one can deal with the problem of balance of the work in pure "mechanical" situation. If not, one will deal with the problem of balance in modeling (thermo) hydro-mechanical coupled, with the corresponding finite elements.

While the presence of a phase water in the ground exploits little the speed of the waves of shearing; on the contrary, that exploits the speed of the waves of pressure. For a clay soil above level of the water table, partial saturation also exploits the value of the speed of the waves of pressure.

Certain models are designed to provide a mechanical answer in "total constraints" which summon the contribution of the skeleton and that of the phase "water" and control the expression of the criteria.

A model of mechanical behavior defined in effective constraints is designed to describe them situations drained and not drained; its identification is preferentially carried out according to the type of application considered, because the models of behavior do not completely model the interaction between skeleton and liquid phase.

The transition from the case saturated to the case unsaturated is delicate, because of the management of the appearance or disappearance of a phase; Code_Aster treats this transition in a transparent way using a modeling of the type `*HH2*` [U2.04.05]. In addition, a solution suggested in the literature to treat the situations not drained in the presence of entrained air, in the vicinity of total saturation consists in adopting an equivalent compressibility of the fluid to take account of entrained air and a corrected cohesion. This equivalent compressibility can be evaluated for example with the model of Button manufacturer, [25], and selected like parameter of entry of the models of *Code_Aster*.

The joints are characterized by a very different hydraulic behavior according to the normal direction with the joint or the tangential directions, for which the opening and the tortuosity of the joint play of essential and nonlinear manner. In opposite direction, the hydraulic flow also exploits the characteristics of rupture of the joint.

2 The modeling of the behavior according to the type of analysis with to carry out

The grounds are initially porous environments: their mechanical answer results from the behavior of the solid skeleton combined with that of the liquid phase, even the gas phase present in porosities of the ground, whose flow is characterized by the permeability.

The mechanical models for the géomatériaux ones (grounds, rocks) can for the majority being used in mechanical modelings only or modelings THM, via the keyword KIT_HM, KIT_HHM, KIT_THM, KIT_THHM, within the framework of the assumption of *effective constraints*, i.e. an assumption which governs the contribution of the pore water pressures du/des fluid (S) present in porosities) with the balance of the porous environment, if one is in a quasi-saturated situation. In the partially saturated case, certain models are formulated in *total constraints*, or forced clear.

A field of study of checking of a geotechnical work consists in checking its *bearing capacity*, in particular under the action of monotonous loadings, with respect to various modes of ruin, in particular by shearing and slip according to *rough surfaces*, or many *modes of diffuse ruin* in the volume of ground…

Another field of study of checking of a geotechnical work consists of the analysis of *compressings* under the action of monotonous or cyclic loadings.

For more raised cyclic loadings, for example induced by an earthquake, one must analyze the risk of *liquefaction*, by:

- *loss of resistance*, relating to the non-cohesive soils more that argillaceous fine grained soils. The rupture by liquefaction results in one *interstitial overpressure* increasing which then causes a deconsolidation of the ground (the effective pressure of consolidation of the ground approaches zero), which brutally loses its resistance in shearing and thus its bearing capacity, by the cancellation of the effective constraints. That can occur in conditions of cyclic or monotonous loading, in not drained conditions, in particular for loose sands. One distinguishes from
- *cyclic mobility*, for the fine grained soils argillaceous or dilating, coming from softening and the evolution from the pore water pressures, following the crossing of the curve of critical condition. *rupture by cyclic mobility* corresponds to a way where the effective average constraint decreases quickly, dilatancy appears and the cyclic deviatoric deformation grows and accumulates until the ruin.

A local criterion suggested is the ratio of excess of pore water pressure r_u. This criterion has several alternatives: an alternative “engineering” where the resistance of the ground is expressed with the level of vertical constraint estimated in the work, another where this one is expressed directly using the brought up to date resistance calculated by the law of behavior. The two expressions are available according to differential” compared to an initial state or instantaneous instantaneous version a “absolute. When the value of r_u tends towards the unit, then one has “fluidization” of the ground.

One will be able to use the operator `POST_LIQUEFACTION` [U4.84.41], in postprocessing of a nonlinear calculation of balance.

It is possible to use to discretize the kinematics of the medium: voluminal finite elements 3D [R3.01.00] or surface 2D, when that is possible, by resorting to simplifying assumptions such as plane deformations, plane constraints or axisymetry, with or without the taking into account of the hydraulic coupling.

In addition, to reduce the difficulties associated with the laws with behavior in dilating phase which produce a loss of unicity of solutions, *Code_Aster* propose methods of regularization, in particular by first gradient of dilation voluminal, cf [R5.04.03] and the finite elements associated.

Notice 1 :

> *One will make the distinction enters* checking *and* validation *: the checking gets along within the meaning of the equations modelled and expressed in the software while the validation indicates the confrontation of the results of the model in the software compared to experimental measurements referring, in situations representative of the applications concerned.*

Notice 2 :

> *The laws of behavior hereafter are formulated into small transformations (HP), but it is possible with Code_Aster to use them within a framework of great transformations (model GDEF_LOG for the large ones plastic deformations and GROT_GDEP while remaining in small deformations) for studies in pure mechanics.*

2.1 The phenomenology and modelings of the behavior of the grounds

Here first of all a material list met in géomechanics and their phenomenology.

Materials	Phenomenology
inflating clay, bentonite	Hydromechanics coupled. isotropic nonlinear elasticity, depend on the capillary pressure.
non-cohesive soil, low registers	Hydromechanics coupled. Elasticity (not) linear. Flow figure deviatoric and voluminal, dilatancy, internal friction and cohesion, critical condition. Cace of traction treated by a perfect elastoplastic flow. Constraints depending on the capillary pressure. Often in drained situation, because often very permeable.
granular ground, sands, silts	Hydromechanics coupled. Elasticity (not) linear. Flow figure deviatoric and voluminal, contractance, dilatancy, internal friction and cohesion. Écrouissage mixed; critical condition. Liquefaction. Cace of traction treated by a perfect elastoplastic flow. Constraints depending on the capillary pressure. Damping grows with the level of cyclic amplitude of distortion, but it is observed that when containment increases, for the same distortion, damping decreases.
clay soils	Hydromechanics coupled. Elasticity (not) linear. Flow figure deviatoric and voluminal, contractance, dilatancy and cohesion. Écrouissage mixed; critical condition. Cace of traction treated by a perfect elastoplastic flow. Constraints depending on the capillary pressure. Damping grows with the level of cyclic amplitude of distortion, but it is observed that when the index of plasticity I_p (in %), for the same distortion, damping increases decreases. The effect of the surconsolidation OCR on damping seems negligible.

The following tables describe the models of behavior:

- 'GONF_ELAS' ;
- 'MOHR_COULOMB' ;
- 'CJS' ;
- 'CAM_CLAY' ;
- 'HUJEUX' ;
- 'IWAN' ;
- 'BARCELONA'.

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
standard "inflating clay" (bentonite...)	Constraint clear ($\boldsymbol{d}\tilde{\sigma}=\boldsymbol{d}\sigma+dP_{gz}\mathbf{Id}$) depending on the pressure of swelling which it even depends on suction (or capillary pressure). Effect of thermal dilation.	'GONF_ELAS' isotropic nonlinear rubber band	modelings supported	HHM, THHM
			Parameters	keywords ELAS (3) and GONF_ELAS (2)
			Variable parameters with the temperature	not
			Number of internal variables and significance	0
			CAS-tests reproducing the behavior	swelling of a clay cell which one saturates gradually: plan (wtnp119a, B, C, D), axi (wtna110a, B, C, D) and 3D (wtnv136a, B, C, D)
			CAS-tests of physical validation	
			References	Doc. [R7.01.41]. LAEGO.
General opinion	Experience feedback limited.			
Robustness, developpability	Simple law.			
Publications	Gerald Radioactive P. and al., "Numerical Modelling of Coupled Mechanics and Gas Transfer around Waste in Storage Length-Term" Newspaper of Theoritical and Applied Mechanics, Sofia, 2008, vol. 38, No 1-2, pp. 25-44 (definition of the law and benchmark)			
EDF publications				
Outlines	Not at this stage.			

Representative materials	Phenomenologies	Name Code_Aster and type of law	Implementation Code_Aster	
standard “non-cohesive soil”	Behavior with the rupture of a ground under monotonous loading. Multicriterion model characterized by the intersection of 6 plans within the space of principal constraints. It is not limited in the direction of the spherical constraints of compression. Perfect plastic flow. Cohesion, dilatancy and internal friction. Pas de progressive “mobilization” of plasticity in shearing.	‘MOHR_COULOMB’ in effective constraints, HP isotropic linear elasticity, elastoplastic nonassociated	modelings supported	3D, 2D (D_PLAN, C_PLAN, AXIS), THM
			Parameters	keywords ELAS (2) and MOHR_COULOMB (3)
			Variable parameters with the temperature	not
			Number of internal variables and significance	3 voluminal plastic deformation $V1$; normalizes deviatoric deformations $V2$; indicator of activation of plasticity (1) or not (0). $V3$
		Implicit integration of the relations of behavior. Consistent tangent operator. Two plastic multipliers to the maximum at the same time.	CAS-tests reproducing the behavior	SSNV232 (drained triaxial compression test monotonous), SSNV233 (test of torsion drained monotonous), WTNV142 (triaxial compression test not drained monotonous), COMP012 (triaxial compression test drained monotonous).
			CAS-tests of physical validation	SSNP104 (into monotonous: rigid sole posed on a ground) ,
			References	Doc. [R7.01.28].
General opinion	Model simple, robust, of first analysis into monotonous; very used. The criteria of rupture are written according to the principal constraints major and minor, therefore they are independent of the intermediate constraint. Model little used in the field of the fill and concrete dams [according to CIH]. Considered: development of versions modified of the models of MOHR_COULOMB.			
Robustness, developpability	The calculated tangent matrix is better than that obtained by disturbance. However, it and preferable to formulate the law in terms of invariants. It is planned to develop this formulation with the MFront tool.			
Publications				
Outlines	Update of the case of validation because currently the results are not in coherence with the similar modelings made with Z-soil.			

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
standard "non-cohesive soil, granular "	Modèle multicriterion and multi-mechanisms: • a nonlinear elastic mechanism, • an isotropic plastic mechanism, with normal flow; • a plastic mechanism déviatoire nonassociated (with critical condition). Model arranged hierarchically including several levels of complexity: two surfaces of load: isotropic requests (with isotropic work hardening) and deviatoric requests (with mixed work hardening). Surface of breaking load by limiting values associated with the variables of écrouissagE. Model unsuited to the actual position under investigation of liquefaction.	'CJS' linear elasticity (CJS1) or not linear (CJS2 and CJS3) elastoplastic with work hardening déviatoire isotropic (CJS2) or kinematics nonlinear (CJS3). in effective constraints, HP.	modelings supported	3D, 2D, THM CONT_PLAN, CONT_1D (by BORST)
			Parameters	keywords ELAS (2) and CJS (6 to 16, according to the level of the selected model)
			Variable parameters with the temperature	not
			Number of internal variables and significance	16 in 3D and 14 in 2D. isotropic threshold $V1$; angle of the threshold déviatoire $V2$; components of the tensor of work hardening kinematic, distance standardized with the threshold déviatoire, relationship between the threshold déviatoire and the threshold deviatoric criticism, sign of the contracted product of the deviatoric constraint by the deviatoric plastic deformation, indicator of activation of mechanisms (0 to 3).
		Implicit integration of the relations of behavior. Tangent operator of speed. Two plastic multipliers: for the isotropic one for the déviatoire. Method of the secant for elasticity nonlinear. Procedure of relieving inside iterations of Newton to avoid	CAS-tests reproducing the behavior	SSNV135 (Essai triaxial drained CJS1), SSNV136 (Essai triaxial drained CJS2), SSNV154 (Essai triaxial drained CJS3), WTNV100 (Essai triaxial not drained CJS1).
			CAS-tests of physical validation	
			References	Doc. [R7.01.13]. B. CAMBOU, K.

		certain problems of oscillation. Procedure of treatment of states tensile stresses.		JAFARI, "Models behavior of the non-cohesive soils", Re-examined Frankly. Géotech. n°44, pp. 43-55, 1988.
General opinion	In the model CJS, the ray of rupture is correlated with the slope of maximum dilatancy. Force of CJS : the calculated sizes are easily interpretable. Weaknesses of CJS : how to define the elastic range (module limited to a secant module)? And discharges it with this model is all the time elastic. The semi-alternate cycles are badly reproduced. Curves $G-\gamma$ obtained with CJS are inadequate. On a drained triaxial compression test then not drained, it misses an anisotropic elasticity. And one liquifies too quickly into cyclic. Mixed work hardening déviatoire could be improved. To also make evolve isotropic work hardening (because the semi-alternate cycles are badly reproduced). Level CJS4 (cyclic) could not be implemented: a robust formulation at the time of the establishment in *Code_Aster* not having been available. The model CJS is used little: because phenomenology is reduced. Ever used in earthquake. Few publications. Behavior CJS1 is equivalent to the criterion of Mohr-Coulomb and does not take account of rise in temperature.			
Robustness, developpability				
Publications				
Outlines	It is considered the suppression of CJS in Code_Aster. Up to date put formulation of the model in J. Lasted, E. Vincens, Constitutive modelling of cohesionless soils and interfaces with various internal states: year elasto-plastic approach, Computer and Geotechnics, flight 63, pp. 33-45, 2014. It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.			

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
type "clay soils", "compressible", normally consolidated, poroplastic.	Multicriterion model and multi-mechanisms: • a nonlinear isotropic elastic relation (left deviatoric linear and a nonlinear voluminal part), • a mechanism plastiquE isotropic associated • a mechanism plastiquE deviatoric nonassociated, A hammer-hardenable surface of load (negative and positive work hardening, governed by only one scalar variable) in the shape of ellipses in the diagram of the first two invariants of the constraints ($tr(\boldsymbol{\sigma})$, $\|(\boldsymbol{\sigma})\|_{VM}$). Critical condition characterized by a worthless variation of volume: right-hand side separating the zones from dilatancy (softening) and of contractance (hardening) of material. Unrecoverable deformations under hydrostatic loading corresponding to an important reduction of porosity. Tally of "not generalized standard materials"	'CAM_CLAY' called modified Camwood-Clay in effective constraints, HP isotropic nonlinear elasticity on the directions of hydrostatic and linear load on the deviatoric directions hardening or lenitive elastoplasticity rule of normal isotropic flow possible thermoelastic dilations	modelings supported	3D, 2D, THM
			Parameters	keywords ELAS (2, in fact not used) and CAM_CLAY (8)
			Variable parameters with the temperature	not
			Number of internal variables and significance	7. Critical pressure $V1$; indicator of activation of plasticity (1) or not (0) $V2$; constraint of containment $V3$; equivalent constraint $V4$; voluminal plastic deformation $V5$; equivalent plastic deformation $V6$; indices of vacuums $V7$.
		Implicit integration of the relations of behavior. Tangent operator of speed equal to the coherent tangent operator. UN alone plastic multiplier.	CAS-tests reproducing the behavior	SSNV160 (Test of monotonous compression hydrostatic), SSNV202 (Drained monotonous test oedometric), WTNV122 (Triaxial compression test not drained).
			CAS-tests of physical validation	SSNP136 (Test of foundation slipping by into monotonous drained).
			References	Doc. [R7.01.14] BURLAND J.B., ROSCOE K.H. "One the generalized stress-strain behaviour of wet clay", Engineering Plasticity, Heyman-Leckie, Cambridge, 1968.

General opinion	Model simple, robust, of first analysis into monotonous; very used. Not applicable for sands. Number of parameters relatively low, which makes the model very easy to use. Limitation of the model: the alignment of the critical points on a line of slope M fixed: this assumption is called in question for very cohesive materials. It is necessary to readjust this slope M for several beaches of average constraint. It is recognized that this model underestimates the deviatoric deformations for on-consolidated clays. The positive work hardening of material is cancelled as soon as one arrives on the critical condition. Other models allow that work hardening can still be positive a little beyond: model of Hujeux for example. A study of validation independent carried out with the university of Liege and the Lagamine code was carried out in 2012: on the case of a foundation slipping by in mechanical modeling simple then HM and also on the case of the consolidation of a column of ground. She concluded on the identity from the results got by the two computational tools, the differences being charged to the various possible choices of hydraulic finite elements and smoothness of grid, to see Doc. [U2.04.05].
Robustness, developpability	Current defect of Code_Aster: the elastic modulus of rigidity remains constant, therefore on strong levels of hydrostatic loading, the Poisson's ratio makes tighten the behavior towards the incompressibility, which blocks the coupling with the pore water pressures. It is necessary to check coherence initially enters the values of the modules of compressibility and shearing. It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.
Publications	
Outlines	One proposes to introduce into CAM_CLAY the possibility of choosing to provide G or ν .

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
type "silts, sands and clays sand spreaders, normally consolidated or on-consolidated, serious "	Multicriterion model and elastoplastic multi-mechanisms monotonous and cyclic (4+4). Nonlinear elasticity. Behavior under monotonous and cyclic loading. Capacity to describe the state of material until liquefaction. Taking into account of the right-hand side of critical condition. Taking into account of the right-hand side of dilatancy (or right characteristic). Decomposition on three fixed orthogonal levels (it is the Cartesian reference mark of the model) Anisotropy (orthotropism) induced. Criterion of work hardening evolving of that of Mohr-Coulomb to that of Camwood-Clay (parameter b) in each plan. Phases of dilatancy and contractance of the material (concept of internal friction). In the dilating field, the surface of load narrows. Treatment of cyclic	'HUJEUX' in constraints EFFectives, HP regular criterion evolving of Mohr-Coulomb type to Camwood-Clay in each orthotropic plan Nonassociated law of flow deviatoric. Law of flow of associated consolidation. variables discrete mémoratrices (transition from mechanism). Treatment of the restoration of the variables of work hardening in discharge.	Modelings supported	3D, 2D, THM
			Parameters	keywords ELAS (2) and HUJEUX (16, of which measurable: 6) The parameter b in particular assistance to distinguish the sandy cases from the argillaceous case: form of the surface of load…
			Variable parameters with the temperature	not
			Number of internal variables and significance	50. factors of work hardening of the mechanisms déviatoires and isotropic monotonous and cyclic; voluminal deformation figure cumulated; variables mémoratrices; indicators of state of the monotonous and cyclic mechanisms; criterion of Hill (density of work of the second order), apparent angle of friction.
		Implicit integration of the relations of behavior. Heuristics of management of the predictors. Elastoplastic mechanism of treatment of the cases of traction with a light work hardening.	CAS-tests reproducing the behavior	SSNV197 (Essai triaxial drained), SSNV204 (consolidation cyclic drained), SSNV205 (cyclic shearing drained), SSNV207 (cyclic shearing with microdécharge), SSNV208 (biaxial test drained on sand of Hostun) , WTNV133 (Triaxial compression test not drained cyclic consolidation then), WTNV134 (Triaxial compression test not drained cyclic

	work hardening with several surfaces thresholds. Perfect elastoplastic mechanism of treatment of the cases of traction.			hydromechanics) .
			CAS-tests of physical validation	WTNV132 (construction by layers of one column of ground), WDNP101 (construction by layers of one hydraulic column of ground then earthquake).
			References	Doc. [R7.01.23]. Doc. [U2.04.08].

General opinion	Capacity to model a large range of the features observed of the behavior of the grounds, in particular situations of cyclic loadings. Subjected to repeated cycles, a sand is made denser: the elastic range grows towards the field of rupture: the model of Hujeux makes it possible to represent this phenomenology. This model introduces a dependence of the surface of load according to the deviatoric deformations without modifying the voluminal rule of flow of dilatancy, which makes it possible to better model the deviatoric deformations that the Camwood-Clay model. The function known as of “interlacing” in the regular criterion appears badly selected for granular materials, but more adapted for clays => one could choose in the formulation a function power and not a function log! The curve of critical condition is not right but must be curved as according to what one observes in the tests. Moreover, the ultimate state is not always on the line of critical condition. In addition, this model does not take into account the influence of the intermediate constraint in 3D on resistance peak. The reproduction of the voluminal stabilization observed during the cyclic tests in pure shearing is not correct. It is also observed that this model gives a damping hysteretic overestimated (on the curves $D-\gamma$). Procedures of retiming of the parameters were established, directed according to the type of study concerned (dynamic cyclic for example), using triaxial compression tests, of isotropic compression, and cyclic shearing. The model requires the presence of an initial state of consolidation. Difficulties of calibration because there are ten nonmeasurable parameters directly and nine measurable parameters.
Robustness, developpability	The complexity of the management of the mechanisms makes the resolution expensive in computing times and thus penalizing for industrial studies. Some problems of lack of robustness were raised, but better heuristics of management of local integration is proposed. One observes difficulties of management during the digital integration of the 4 coupled mechanisms. Weak developmental perspectives.
Publications	D. Aubry, JC Hujeux, F. Lassoudière and Y. Meimon. With multiple double memory model with mechanisms for cyclic soil behavior. Int. Symp. one Numerical Models in Geomechanics, Zurich, p.3-13, 1982.
EDF publications	*Memories of doctorate* : Foucault A. Modélisation of the cyclic behavior of the ground works integrating of the techniques of regularization. June 2010. https://tel.archives-ouvertes.fr/tel-00534665. Rapti I. Numerical modeling of liquefaction-induced failure of geostructures subjected to earthquakes. April 2016. https://tel.archives-ouvertes.fr/tel-01329628.

	Articles : Rapti, I., Modaressi, A., Foucault, A., Lopez-Caballero, F., Voldoire F. Coupled S-P wave propagation in nonlinear regularized micromorphic media. Volume 77, July 2016, Pages 106-114. Rapti, I., Lopez-Caballero, F., Modaressi, A., Foucault, A., Voldoire F. Liquefaction analysis and ramming evaluation of structures embankment-type. Recorded Geotechnica, 2/2018, DOI: 10.1007/s11440-018-0631-z. *Conferences* : Kham, Mr., Kolmayer, pH., Lopez-Caballero, F., Mondoloni, A. Numerical Modelling of dynamic answer and pore toilets presses build-up in earthdams subjected to strong seismic loadings. 7^{HT} ICEGE Conference, Roma, 2019. *Benchmarks* : CFBR/JCOLD, Prenolin…
Outlines	Coupling permeability – anisotropy, impoverishment of the soil. Influence of nonsaturation on the modes of rupture and potential of liquefaction. It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms. It is planned to currently introduce an elastoplastic flow in traction with a light artificial isotropic work hardening instead of perfect plasticity in place, in order to facilitate the convergence of difficult increments of loading.

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
"granular" type and clay in a range of loading far away from the ruin	Isotropic material. Cyclic behavior deviatoric and degradation of the modulus of rigidity. Voluminal answer linear rubber band (not of voluminal mechanism, therefore not adapted in the presence of coupling HM) Rheological formulation parallel series from where additive decomposition of the deformations 12 mechanisms of linear kinematic work hardening (Prager), each one for various ranges of deviatoric deformation. Fixed thresholds. Do not represent dilatancy; no line of critical condition. Rule of associated flow.	'IWAN' in effective constraints, HP	modelings supported	3D , D_PLAN
			Parameters	keywords ELAS (2) and IWAN (4, from including the two elastic modules from which one deduces constant compressibility and two which describes the degradation of the modulus of rigidity, from which one deduces the parameters from kinematic work hardening)
			Variable parameters with the temperature	not
			Number of internal variables and significance	103. components of the tensor of elastic strain; scalar plastic multipliers of surfaces of load; components of the tensors of kinematic work hardening; values of 12 surfaces of the load.
		Implicit integration of the relations of behavior. Tangent operator. With Mfront.	CAS-tests reproducing the behavior	COMP012 (cyclic shearing with CALC_ESSAI_GEOMECA), SSNV205 (cyclic shearing drained), SSNV207 (cyclic shearing with microdécharge)
			CAS-tests of physical validation	SDLS128 (column of ground under cyclic shearing)
			References	Doc. [R7.01.38]
General opinion	It is about a simple model of behavior making it possible to reproduce the curves of degradation of the modulus of rigidity during cycles. However, the curves of damping are equivalent are not always satisfactory. Facility of calibration and use. This model does not make it possible to represent the rupture by liquefaction of the grounds: compressibility remains constant. This model does not make it possible to represent cyclic mobility, because there is no function of dilatancy.			
Robustness, developpability	Robust model. The aspects of voluminal behavior and rupture can be developed: for example of model of Prévost.			

Publications	IWAN W.D., One has class of models for the yielding behaviour of continuous and composite systems, Newspaper of Applied Mechanics, 89 (13), pp. 612-617, 1967.
EDF publications	Alves Fernandes, V., Caudron, Mr., Vandeputte, D. Impact of Nonlinear 1D Site Effects Estimated From Measurements And Numerical Simulations At the KiK-Net KSRH10 Site. 16th European Conference one Earthquake Engineering (16^{HT} ECEE), 18-21 June 2018, Thessaloniki, Greece.
Outlines	It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms. It would be possible to take into account average pressure in the function of deviatoric load, with a criterion 3D of the type van Eekelen or Prévost. It would be also useful to improve ergonomics: the moduli of elasticity E and Naked must be provided to two places.

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
type "unsaturated grounds"	Elastoplasticity. In the saturated case, it is the model Camwood-Clay. Two criteria: a mechanical criterion of plasticity (that of Camwood-Clay) and a hydrous criterion controlled by suction (or capillary pressure).	'BARCELONA' in total constraints, HP	modelings supported	KIT_HHM KIT_THHM
			Parameters	keywords ELAS (2), CAM_CLAY (6) and BARCELONA (14)
			Variable parameters with the temperature	not
			Number of internal variables and significance	5. Critical pressure $V1$; indicator of activation of plasticity (1) or not (0) $V2$; hydrous threshold $V3$; hydrous indicator of irreversibility $V4$; cohesion $V5$.
		Implicit integration of the relations of behavior. Tangent operator.	CAS-tests reproducing the behavior	WTNV123 (Triaxial compression test with fixed suction); WTNV124 (Test of désaturation-consolidation);
			CAS-tests of physical validation	WTNV126 (Mixed Ways of saturation-consolidation)
			References	Doc. [R7.01.17]
General opinion	This model functions only in unsaturated. Experience feedback limited.			
Robustness, developpability	There exists in the literature a version in effective constraints, starting from the formulation of the Camwood-clay model.			
Publications	Alonso, E. People, A., Josa, A. "with constitutive Model for Partially Saturated Soils" Geotechnical, 40 (1990), 405-430			
EDF publications				
Outlines	It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.			

2.2 Identification of the parameters of behavior of the grounds

One uses tests on test-tubes of ground: compression tests triaxial (shearing, field of average and high deformations), tests œdometric (measurement of compressibility and the consolidation), tests of compression isotropic (even if they are more difficult to realize), cyclic, alternate and semi-alternate tests, tests with the resonant column (field of the weak deformations $\leq 5.10^{-4}$). It is advisable to establish the link between the parameters of the models of behavior resulting from experimental measurements and the measured parameters of interest in-situ for the engineer such as "the index of plasticity", "the index of the vacuums", cyclic resistance to liquefaction (CSR), resistance to cone (CPT)...

The tests must be realized with varied indices of density D_r (partners with the index of the vacuums e_0) and various confining pressures (for identifying the critical condition well in particular) and drained and not drained condition.

2.2.1 Physical parameters generals

A first class of physical parameters generals characterizes material:

- density of the dry ground ρ_s ,
- density of the water-logged soil,
- initial porosity φ_0 ,
- index of the vacuums $e_0=\frac{\varphi_0}{1-\varphi_0}$ or index of density D_r ,
- grading curve,
- initial degree of saturation S_0 ,
- index of plasticity I_p , related to the natural angle of repose ϕ_{pp} and with the limits of Atterberg,
- permeability to the liquid and/or gas.

2.2.2 Elastic parameters

The second stage consists of the identification of the elastic parameters provided to *Code_Aster* (module of compressibility drained K_0 , modulus of rigidity G_0 in drained situation), very dependent on the confining pressure $P_{réf}$ or average constraint (via the index of vacuums). The data of the coefficient of the grounds at rest k_0 assistance to establish the initial elasticity of material in place.

It is pointed out that the Young modulus and the Poisson's ratio are expressed by:

$$E_0=\frac{9K_0G_0}{3K_0+G_0} \quad \text{and} \quad \nu_0=\frac{3K_0-2G_0}{6K_0+2G_0}$$

expressions in drained situation utilize the coefficient of Biot and distinguish the drained compressibility of the porous environment and the compressibility of the solid matter constituents K_s :

$$\frac{1}{K_s}=\frac{1-b}{K_0}$$

For a ground made up of grains (sands, low registers), it can be necessary to provide a parameter describing the nonlinear dependence between rigidity and the pressure applied.

Note:

- the confrontation of digital predictions to a measurement carried out in-situ on the work, for loadings on low level (in geophysics: exploitation of the ambient noise for example), constitutes a relevant approach for an analysis of existing work.

- it is however difficult to evaluate the initial anisotropic characteristics, related to the geological formation of the grounds in place.

The tests carried out in-situ are carried out for example using a pressure gauge (radial dilation), dynamic penetrometers.

2.2.3 Parameters of nonlinear behavior

The following stages consist of the identification of the parameters associated with the description of cohesion of resistance (criterion of rupture) and of work hardening, of the fields of contractance and dilatancy, dependent on the consolidation (case “normally consolidated”, “on-consolidated”). In particular it is pointed out that the angle of dilatancy ψ is lower or equal to the natural angle of repose ϕ_{pp}. It will be noted that the natural balance of a slope made up of a noncohesive and saturated or dry material imposes that the angle of friction ϕ_{pp} that is to say higher than that of the slope.

Into cyclic, one seeks to identify the curves of *degradation* $G-\gamma$, $D-\gamma$ and the CSR.

Code_Aster propose an ordering specific of assistance to the identification of the parameters of behavior of the grounds: `CALC_ESSAI_GEOMECA` , cf [U4.90.21]. It makes it possible to simulate for a point material various ways of loading characteristic of usual tests géomechanics in laboratory, monotonous/cyclic, drained/not drained, and post-to treat the got results.

For its use, it is advisable to choose the behavior, the parameters material necessary, and the data of loading of the test considered.

2.3 The phenomenology and modelings of the behavior of the rocks

The rocks are primarily classified according to their level of resistance in compression simple (Unconfined Compressive Strength: UCS), itself associated with their geological history (formation) and with porosity. The table below summarizes their phenomenology.

Materials	Phenomenology
Rock, rock solid masses	Elasticity (not) linear. Flow (visco-) plastic (creep) deviatoric and voluminal, cohesion and dilatancy.
Basalt, granite, marble…	Strong resistance in simple compression ($>100\,MPa$)
Limestone, schist…	Resistance in median simple compression ($25-100\,MPa$)
Chalk, faded rock	Resistance in weak simple compression $5-25\,MPa$)
mudstone (quasi rock)	Elasticity (not) linear. Viscoplastic flow (creep) deviatoric and voluminal,

Figure 2.3-1: Phenomenology of intact rocks [28]

The following tables describe the models:

- `‘DRUCK_PRAGER’`
- `‘DRUCK_PRAGER_N_A’`
- `’VISC_DRUCK_PRAG'`

- 'HOEK_BROWN';
- 'LAIGLE';
- 'LETK';
- 'LKR'.

Representative materials	Phenomenologies	Name Code_Aster and type of law	Implementation Code_Aster	
standard "rock"	Isotropic material. Cohesion and work hardening, either linear or parabolic (with ultimate constraint), internal friction (dilatancy). Only one mechanism of associated plastic flow. The criterion of resistance combines the spherical and deviatoric contribution constraints. It is not limited in the direction of the spherical constraints of compression. Linear form of the criterion in $J_2, tr(\boldsymbol{\sigma})$.	'DRUCK_PRAGER ' in effective constraints, HP	modelings supported	3D, 2D, THM
			Parameters	keywords ELAS (2) and DRUCK_PRAGER (6)
			Variable parameters with the temperature	not
			Number of internal variables and significance	3. Cumulated deviatoric plastic deformation $V1$; Cumulated voluminal plastic deformation $V2$; indicator of activation of plasticity (1) or not (0) $V3$.
		Analytical implicit integration of the relations of behavior. Tangent operator.	CAS-tests reproducing the behavior	SSND104 (case in plane deformations, monotonous loading). SSNP124 (Biaxial test drained with a lenitive behavior). SSNV168 (Triaxial compression test drained with a lenitive behavior), WTNA101 (Triaxial compression test not drained with a lenitive behavior).
			CAS-tests of physical validation	
			References	Doc. [R7.01.16]
General opinion	It is about a simple model of behavior, to use for predimensioning before use of more complicated models of checking. The criterion is a cone registered in the pyramid of the criterion of MOHR-COULOMB : it is thus regular, except at the top of the cone (pure hydrostatic state). This model can be employed for rocks, but its rheology is rather far away from the experimental results.			
Robustness, developpability	This model has a rule of associated flow: the incremental problem is thus a convex problem of minimization, which leads to a robust resolution.			
Publications	D.C.DRUCKER, W.PRAGER, *Soil mechanics and plastic analysis for limit design*. Quarterly of Applied Mathematics 10,157-165. 1952.			
EDF publications				

Outlines	It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.

<table>
<tr><th>Representative materials</th><th>Phenomenologies</th><th>Name Code_Aster and type of law</th><th colspan="2">Implementation Code_Aster</th></tr>
<tr><td rowspan="7">Standard “rock”</td><td rowspan="7">Isotropic material. Only one mechanism of nonassociated plastic flow, which makes it possible to better represent dilatancy: the angle of dilatancy varies with the plastic deformation.

The criterion of resistance combines the spherical and deviatoric contribution constraints.

The plastic potential is thus different from the surface of load.

Linear or parabolic work hardening.

Thermal dilation coefficient constant.</td><td rowspan="4">‘DRUCK_PRAGER_N_A’

in effective constraints, HP</td><td>modelings supported</td><td>3D, 2D, THM</td></tr>
<tr><td>Parameters</td><td>keywords ELAS (3) and DRUCK_PRAGER (8)</td></tr>
<tr><td>Variable parameters with the temperature</td><td>not</td></tr>
<tr><td>Number of internal variables and significance</td><td>3.
Cumulated deviatoric plastic deformation $V1$;
cumulated voluminal plastic deformation $V2$;
indicator of activation of plasticity (1) or not (0) $V3$.</td></tr>
<tr><td rowspan="3">Implicit integration of the relations of behavior.

Tangent operator.</td><td>CAS-tests reproducing the behavior</td><td>SSND104 (case in plane deformations, monotonous loading).</td></tr>
<tr><td>CAS-tests of physical validation</td><td></td></tr>
<tr><td>References</td><td>Doc. [R7.01.16]</td></tr>
<tr><td>General opinion</td><td colspan="4">It is about a simple model of behavior, to use for predimensioning before use of more complicated models of checking. Unutilised with the CIH.</td></tr>
<tr><td>Robustness, developpability</td><td colspan="4">This model has a rule of nonassociated flow: the incremental problem can have problems of convergence.</td></tr>
<tr><td>Publications</td><td colspan="4"></td></tr>
<tr><td>EDF publications</td><td colspan="4"></td></tr>
<tr><td>Outlines</td><td colspan="4">It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.</td></tr>
</table>

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
standard “mudstone”	Isotropic material. Only one viscoplastic mechanism. Cohesion, dilatancy and linear isotropic work hardening per pieces (with threshold of peak and ultimate threshold). Nonassociated flow. Potential of viscoplastic flow distinct from viscoplastic surface of load. With viscoplastic law of creep (law power of the Perzyna type).	'VISC_DRUCK_PRAG' in effective constraints, HP	modelings supported	3D, 2D, THM
			Parameters	keywords ELAS (2) and VISC_DRUC_PRAG (14)
			Variable parameters with the temperature	not
			Number of internal variables and significance	4. Viscoplastic deformation deviatoric cumulated $V1$; indicator of activation of plasticity (1) or not (0) $V2$; position of the point of load compared to the threshold $V3$; iteration count local $V4$.
		Implicit integration of behavior. Coherent tangent operator.	CAS-tests reproducing the behavior	SSNV211 (Drained triaxial compression test), WTNV137 (Drained triaxial compression test), WTNV138 (Triaxial compression test not drained).
			CAS-tests of physical validation	
			References	Doc. [R7.01.22]
General opinion	It is about a simple model of behavior, to use for predimensioning before use of more complicated models of checking. Unutilised with the CIH.			
Robustness, developpability				
Publications				
EDF publications				
Outlines	It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms and also the cumulated voluminal plastic deformation.			

<table>
<tr><th>Representative materials</th><th>Phenomenologies</th><th>Name Code_Aster and type of law</th><th colspan="2">Implementation Code_Aster</th></tr>
<tr><td rowspan="7">type “rocks”</td><td rowspan="7">Linear isotropic elasticity, elastoplasticity with positive work hardening then negative (hardening pre-peak then softening post-peak).

Transition contractance-dilatancy earlier than the peak from resistance.

Criteria of rupture written according to the principal constraints major and minor.

Quadratic form of the criterion in $J_2, tr(\boldsymbol{\sigma})$.

Potential of plastic flow nonassociated with Drücker-Prager type.

Effect of thermal dilation.</td><td rowspan="4">'HOEK_BROWN'

HP

Version in effective constraints: 'HOEK_BROWN_EFF',

For a coupling formulated in total constraints, to use the version 'HOEK_BROWN_TOT'</td><td>modelings supported</td><td>3D, 2D D_PLAN, AXI, THM</td></tr>
<tr><td>Parameters</td><td>keywords ELAS (3) and HOEK_BROWN (11)</td></tr>
<tr><td>Variable parameters with the temperature</td><td>not</td></tr>
<tr><td>Number of internal variables and significance</td><td>3
major unrecoverable deformation;
cumulated plastic voluminal deformation;
indicator of activation of plasticity (1) or not (0).</td></tr>
<tr><td rowspan="3">Implicit integration of the relations of behavior.

Coherent tangent operator.</td><td>CAS-tests reproducing the behavior</td><td>SSNA116 (Axisymmetric triaxial compression test);
SSNV184 (Triaxial compression test);
WTNV128 (Test not drained in effective constraints);
WTNV129 (Test not drained in total constraints)</td></tr>
<tr><td>CAS-tests of physical validation</td><td></td></tr>
<tr><td>References</td><td>Doc. [R7.01.18]</td></tr>
<tr><td>General opinion</td><td colspan="4">It is the simplest law in rock mechanics and of which the use is most widespread among the experts. It is noted however that the intermediate constraint principal does not intervene in the criterion of rupture, which is contrary with the experimental observation.</td></tr>
<tr><td>Robustness, developpability</td><td colspan="4"></td></tr>
<tr><td>Publications</td><td colspan="4">E. Hoek and E.T. Brown. The Hoek-Brown failure criterion|1988 update has. In J. Curran, editor, Proceedings of the 15HT Canadian Rock'n'roll Mechanics Symposium, pages 31-38, 1988.</td></tr>
<tr><td>EDF publications</td><td colspan="4"></td></tr>
<tr><td>Outlines</td><td colspan="4">It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.</td></tr>
</table>

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
type "rocks"	Cohesion and dilatancy. Deviatoric plasticity. Work hardening. Taking into account of cohesion and dilatancy. Effect of thermal dilation.	'LAIGLE' in effective constraints, HP	modelings supported	3D, 2D D_PLAN, AXI, THM
			Parameters	keywords ELAS (2) and LAIGLE (14)
			Variable parameters with the temperature	not
			Number of internal variables and significance	
		Implicit integration of the relations of behavior. Tangent operator.	CAS-tests reproducing the behavior	SSNV158 (Drained triaxial compression test); SSNV158 (Triaxial Compression test not drained);
			CAS-tests of physical validation	
			References	Doc. [R7.01.15]
General opinion	This model enriches the phenomenology described by the model 'HOEK_BROWN' (behavior post-peak).			
Robustness, developpability	The experience feedback is correct in Code_Aster.			
Publications	F. Laigle. Conceptual model for the Development of Lois de Comportement adapted to the Design of the Underground Works. PhD thesis, 2004.			
EDF publications				
Outlines	It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms.			

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
rock “massive” type compared to a continuous medium	Viscoplastic behavior élasto: two coupled irreversible mechanisms. Nonlinear elasticity. For a purely hydrostatic way of constraint, the behavior remains elastic nonlinear. Criterion of cleavage. Fragile or ductile according to containment; dilatancy (definition of a characteristic state). positive work hardening in pre peak and a negative work hardening in post-peak with dilatancy. Kinetics of creep. Standard viscoplasticity Perzyna.	'LETK' in effective constraints, HP	modelings supported	3D, 2D D_PLAN, AXI , THM
			Parameters	keywords ELAS (2) and LETK (28)
			Variable parameters with the temperature	not
			Number of internal variables and significance	7. variables of elastoplastic work hardening and élasto viscoplastic; indicator of contractance (0) or dilatancy (1); indicators of plasticity and viscoplasticity.
		Integrations implicit or clarifies relations of behavior. Tangent operator.	CAS-tests reproducing the behavior	SSNV206A (Triaxial compression test); WTNV135A (Drained triaxial compression test).
			CAS-tests of physical validation	
			References	Kleine, Laigle, 2007 Doc. [R7.01.24]
General opinion	This model constitutes the law of behavior of reference, used for the dimensioning instantaneous and differed from the underground works. Dilatancy and viscosity is essential to describe the behavior of the rocks. Form and parameters of surface and the thresholds are based on the model Hoek & Brown, with addition of the intermediate constraint, of a piloting of resistance in shearing by the extension and compression in the expression of the threshold.			
Robustness, developpability	The implicit version is much more robust than the explicit version.			
Publications	A. Kleine. Digital modeling of the Behavior of the Underground Works by a Viscoplastic Approach. PhD thesis, LaEGO, INPL, 2007.			
EDF publications				
Outlines	It would be advisable to develop the calculation of the density of power dissipated by the plastic mechanisms. The model 'LKR' constitute a more advanced version of this model.			

<table>
<tr><th>Representative materials</th><th>Phenomenologies</th><th>Name Code_Aster and type of law</th><th colspan="2">Implementation Code_Aster</th></tr>
<tr><td rowspan="6">rock “massive” type compared to a continuous medium</td><td rowspan="6">Covered phenomenology takes again that of the model ‘LETK’.

The plastic mechanism is characterized by a positive in mode pre-peak and negative work hardening in mode post-peak.
The residual critical condition is purely rubbing: there is no more cohesion and the angle of dilatancy is cancelled.

One can activate or not the coupling between the mechanisms plastic and viscoplastic deviatoric (via the internal variables of work hardening).

The temperature influences work hardenings plastic and viscoplastic.

Thermal dilation coefficient constant.</td><td rowspan="4">‘LKR’

in effective constraints, HP</td><td>modelings supported</td><td>3D, 2D D_PLAN, AXI, THM</td></tr>
<tr><td>Parameters</td><td>keywords ELAS (2) and LKR (27)</td></tr>
<tr><td>Variable parameters with the temperature</td><td>yes</td></tr>
<tr><td>Number of internal variables and significance</td><td>12
variables of work hardening of the mechanisms plastic and viscoplastic; equivalent plastic deformation; indicator of contractance (0) or dilatancy (1); indicator of viscoplasticity; deformations figure and viscoplastic, equivalent and voluminal; indicator of the pre modes or post-peak.</td></tr>
<tr><td rowspan="2">Implicit integration of the relations of behavior.

Complete coherent tangent operator.</td><td>CAS-tests reproducing the behavior</td><td>SSNV206 (triaxial compression test), WTNV135 (drained triaxial compression test),</td></tr>
<tr><td>CAS-tests of physical validation</td><td></td></tr>
<tr><td></td><td></td><td></td><td>References</td><td>Doc. [R7.01.40]</td></tr>
<tr><td>General opinion</td><td colspan="4">This model constitutes the law of behavior of reference for the studies of behaviour of dimensioning instantaneous and differed from the underground works.. Dilatancy and viscosity is essential to describe the behavior of the rocks with dependence at the temperature.
Form and parameters of surface and the thresholds are based on the model Hoek & Brown, with addition of the intermediate constraint, of a piloting of resistance in shearing by the extension and compression in the expression of the threshold.</td></tr>
<tr><td>Robustness, developpability</td><td colspan="4">Good experience feedback in Code_Aster. Rather robust digital convergence because implicit integration of the law.</td></tr>
<tr><td>EDF publications</td><td colspan="4"></td></tr>
<tr><td>Publications</td><td colspan="4">Raude S. Prise in account of the thermal requests on the behaviors instantaneous and differed from the géomatériaux one . PhD thesis, UL, 2015.
Raude, S & Laigle, F & Giot, R & Fernandes, R. (2015). With unified thermoplastic/viscoplastic constitutive model for geomaterials. Geotechnica recorded. 11. 10.1007/s11440-015-0396-6.</td></tr>
<tr><td>Outlines</td><td colspan="4">It would be advisable to develop the calculation of the density of power</td></tr>
</table>

	dissipated by the plastic mechanisms. Taking into account of the anisotropic behavior structural coming from the history of formation from the rock.

2.4 Identification of the parameters of behavior of the rocks

One uses tests on test-tubes of rock: triaxial compression tests (shearing, field of average deformations, carried out on a sample not confined of rock), creep tests and relieving, tests of isotropic compression. These tests are carried out at various temperatures. Other tests on sample of rock are practised: tests of indentation to the cone for example to evaluate the elastic characteristics, prolonged until rupture, tests of extension, cylinder splitting tests. Lastly, certain tests are carried out in-situ, for example the evaluation of *RQD*.

A first class of parameters characterizes material:

- density of the dry rock,
- density of the saturated rock,
- porosity,
- degree of saturation,
- permeability,
- *RQD* (Rock'n'roll Quality Designation index), which evaluates discontinuities present in the rock (deterioration).

One second class of parameters characterizes material mechanically:

- elastic parameters (static, dynamic),
- parameters of creep, parameters of cyclic behavior,
- resistance in uniaxial pressing not confined,
- strength parameter of Hoek-Brown,
- celerities of the waves P and S.

Code_Aster propose an ordering specific of assistance to the identification of the parameters of behavior of the rocks for the models 'DRUCK_PRAGER' : CALC_ESSAI_GEOMECA , cf [U4.90.21]. It makes it possible to simulate for a point material various ways of loading characteristic of usual tests géomechanics in laboratory, monotonous/cyclic, drained/not drained, and post-to treat the got results.

For its use, it is advisable to choose the behavior, the parameters material necessary, and the data of loading of the test considered.

2.5 Modelings of the behavior of the joints

interfaces mediums made up of géomatériaux must also be modelled. One cannot be always satisfied with a perfect modeling by simple continuity of displacements, equivalent to the continuity of the vector-constraint to the interface, supplemented for porous environments by the continuity of the pore water pressures.

The joint is presented in the form of a discontinuity, rough, possibly reinforced by a fill material.

Code_Aster have particular finite elements of *joint* for studies in pure mechanics in 2D and 3D (XXX_JOINT).

Particular finite elements of *joint* for coupled hydraulic studies (XXX_JOINT_HYME in 2D and 3D and XXX_JHMS only in 2D) are also available: to see [R3.06.09] and [R7.02.15]: they represent the displacement and the pressure of fluid in the joint, in particular a flow of fluid inside (cubic law, to see [R7.01.25]). L' introduction of the fluid into the joint modifies the normal mechanical constraint.

Finite elements of *joint* (or fissures) for hydraulic studies coupled (saturated medium) in 2D, with support 1D, to see [R7.02.15], (PLAN_JHMS , AXIS_JHMS) aim at modelling the discontinuity of displacement through the joint and the flow darcéen in along the joint. It is considered that the field of pressure is continuous through the interface, while discontinuities of flow are authorized through the interface (contrary to the finite elements XXX_JOINT _HYME) and a cubic law describes voluminal flow according to the gradient of pressure along the interface: the intrinsic permeability is thus cubic according to the opening of the joint (discontinuity of normal displacement).
Parameters of modeling of the hydraulic behavior of the joint (permeability, porosity, module of Biot, fluid viscosity...) are those of the porous environments, cf [R7.01.11].

One can thus take into account the propagation of the uplifts to an interface concrete-rock, a fluid flow within a crack in a porous environment. The table below indicates for each family of elements the meshs support, degenerated, which have a dimension in more compared to the geometry of the interface, and the degrees of freedom.

Elements stop	Mesh support	Degrees of freedom
XXX_JOINT for linear P1 and quadratic grids P2, in 2D and 3D.	QUAD4 ; QUAD8 HEXA8, PENTA6 ; HEXA20, PENTA15	Displacements of the two walls.
XXX_JOINT _HYME for grids quadratic in hydromechanics, in 2D and 3D.	QUAD8 HEXA20, PENTA15	P2 displacements of the two walls; P2 pressures in the plan of the interface.
XXX_JHMS compatible with elements THM of the solid mass in 2D or with the elements pure mechanics 2D if the solid mass is impermeable. Axisymmetric and plane deformations	QUAD8	Displacements of the two P2 walls; P1 pressures of the two walls. A multiplier of hydraulic Lagrange P0.

The following tables describe the models of behavior of *joint* to assign to interfaces between continuous mediums, modelled by finite elements of *joint* :

- 'JOINT_MECA_RUPT' ;
- 'JOINT_MECA_FROT' ;
- 'JOINT_BANDIS' ;
- 'CZM_LIN_REG' ET 'CZM_EXP_REG'

Representative materials	Phenomenologies	Name Code_Aster and type of law	Implementation Code_Aster	
joints concrete/rock or joined concrete concrete with asperities	elastic behaviour with very weak displacement. Cohesive law and progressive rupture enter the lips of a joint. Not interpenetration of the lips of the joint. Threshold of tangential rupture controlled by the normal rupture. Mode of slip without friction. Pas de tangential rupture under pure shearing. Taking into account of the influence of a fluid on mechanics via pressure. Fluid flow of One tenth of a poise, which is regularized for very weak openings of joint. Taking into account of two industrial processes: keying-up and sawing; for example local pressure of coulis injected.	'JOINT_MECA_RUPT' elastic law cohésiv E lenitive expressed on jump of positive normal displacement . In compression, penalized resilient contact. Coefficient of penalization of the contact. Implicit integration, the tangent matrix is not-symmetrical. The localization due to softening is managed natively by the flattened geometry of the EF of interface.	modelings supported	XXX_JOINT , XXX_JOINT _HYME
			Parameters	keywords SIGMA_MAX (threshold criticizes rupture in traction) and KT, KN (rigidities in requests normal and tangential) parameter of penalization of the contact PENA_CONTACT. keyword PRES_CLAVAGE, which identifies the pressure of coulis injected keyword SAWING, which identifies the thickness of the sawn band. RHO_FLUIDE density and VISC_FLUIDE the dynamic viscosity of the fluidE.
			Variable parameters with the temperature	not
			Number of internal variables and significance	11. Of which: indicator of dissipation, indicators of normal and tangential damage. jumps normal and tangential. 18 in the case XXX_JOINT_HYME : of which: gradient of pressure, hydraulic flow in the total reference mark, pressure of fluid.
			CAS-tests reproducing the behavior	SSNP142 (rupture and slip with under pressures of a joint of stopping, in 2D and 3D). SSNP162 (in pure

				mechanics and hydro-mechanical coupled, 2D and 3D). SSNP143 (processes of keying-up and sawing).
			CAS-tests of physical validation	
			References	Doc. [R7.01.25].
General opinion	Only law available to represent the joints of the concrete dams and the industrial processes associated.			
Robustness, developpability	Possible difficulties of convergence; however several types of application show a good capacity of the model thanks to implicit integration.			
Publications				
EDF publications	CFRAC 2010			
Outlines	Development of a complete energy formulation. Calculation of dissipated energies. Another track: link reinforced with the law of the type CZM_xxx_REG.			

Representative materials	Phenomenologies	Name Code_Aster and type of law	Implementation Code_Aster	
joints concrete/rock or joined concrete concrete	elastic behavior with very weak displacement and elastic remainder for the normal part. not-interpenetration of the lips in contact. friction enters the lips of a joint, in pure slip (with phase of adhesion). Pas de loss of tensile strength. Taking into account of the influence of a fluid on mechanics via pressure. Fluid flow of One tenth of a poise, which is regularized for very weak openings of joint. Normal and tangential viscous damping, if the element of joint is in compression and possibly in the phases of traction.	'JOINT_MECA_FROT' It is an elastoplastic alternative of the law of Mohr-Coulomb, which relates only to tangential part. non-aligned law of flow total. Coefficient of penalization: ensuring the regularization with a parameter of isotropic work hardening. Implicit integration, the tangent matrix is calculated into implicit.	modelings supported	XXX_JOINT, XXX_JOINT_HYME
			Parameters	Keywords DRIVEN (Coefficient of friction of Coulomb) and ADHESION (limit of hasdhésion). normal rigidity, tangential rigidity. RHO_FLUIDE density and VISC_FLUIDE the dynamic viscosity of the fluid. Keywords AMOR_NOR and AMOR_TAN (normal and tangential damping); keyword COEF_AMOR (case where the joint is not in compression).
			Variable parameters with the temperature	not
			Number of internal variables and significance	11. Of which: slip meter, indicator of opening, jump normal and tangential of displacement, normal mechanical constraint. 18 in the case XXX_JOINT _HYME : of which: gradient of pressure, hydraulic flow in the total reference mark, pressure of fluid.
			CAS-tests reproducing the behavior	SSNP142 (rupture and slip with under pressures of a joint of stopping, in 2D and 3D). SSNP162 (in pure mechanics and hydro-mechanical coupled, 2D and 3D). SDNV138 (joined between two studs of stopping in 3D, under earthquake, without

				adhesion nor fluid).
			CAS-tests of physical validation	
			References	Doc. [R7.01.25].

General opinion	
Robustness, developpability	
Publications	
EDF publications	
Outlines	

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
Joints (cracks) rock/rock in a porous environment.	The mechanical behavior of discontinuity is described by the law of Bandis, in effective constraints, between the normal effective constraint and the normal opening of joint. This law is elastic nonlinear. On the tangential direction, the behavior is supposed to be elastic. Can be associated with a law with regularized cohesive zone: propagation of the crack by a lenitive law: CZM_LIN_REG or CZM_EXP_REG, to see [R7.02.11]. Interstitial fluid with hydraulic coupling; mass contributions of fluid. Not-interpenetration of the lips in contact. Fluid flow of One tenth of a poise, which is regularized for very weak openings of joint.	'JOINT_BANDIS ' Coefficient of penalization: ensuring the regularization of the contact of the lips. Parameter of regularization of energy for adherence. Implicit integration, the tangent matrix is calculated into implicit. Use with relations of behavior RELATION_KIT to describe the fluid ('LIQU_SATU','HYDR_UTIL',).	modelings supported	XXX_JHMS
			Parameters	Initial normal rigidity, tangential rigidity. DMAX ouverasymptotic ture joint; GAMMA empirical coefficient of surface roughness. OUV_FICT (parameter of regularization law of One tenth of a poise if it solid mass is impermeable to treat L 'flow in the quasi-closed crack) Keywords (constraint criticizes with the rupture) and (energy of rupture) for the law of cohesive zone.
			Variable parameters with the temperature	not
			Number of internal variables and significance	2 (besides those related to the possible cohesive law): variation of the density, opening of the joint.
			CAS-tests reproducing the behavior	WTNA111 (joint with hydraulic coupling, into axisymmetric). WTNP125 (Déplétion of a tank, in 2D plan). WTNP126 (Igas njection in a fractured porous environment, in 2D plan).
			CAS-tests of physical validation	WTNP128 (test of splitting per corner of the concrete under pressure of fluid, in 2D plan, with law of cohesive zone).
			References	Doc. [R7.02.15].
General opinion				
Robustness,	Weak experience feedback.			

developpability	
Publications	BANDIS, S., et al. "Fundamentals of rock'n'roll joined deformation", 1983, Int. J. Mech Rock'n'roll. mining Sci. Geomech. Abstr., 20(6), 249-68.
EDF publications	Benoît Carrier, Sylvie Granet. Numerical modeling of hydraulic fracture problem in permeable medium using cohesive zone model. Engineering Fractures Mechanics, Elsevier, 2012.79, pp.312-328.
Outlines	

Representative materials	**Phenomenologies**	**Name Code_Aster and type of law**	**Implementation Code_Aster**	
joints concrete/rock or joined concrete concrete in pure mechanics	elastic behaviour with very weak displacement. Cohesive law and progressive rupture enter the lips of a joint. Not interpenetration of the lips of the joint. Even threshold of tangential and normal rupture. Mode of slip without friction. The curve of softening is linear for the model CZM_LIN_REG or exponential for CZM_EXP_REG.	'CZM_xxx_REG' elastic law cohésiv E lenitive associated expressed on the standard with the vector jump of displacement . In compression, penalized resilient contact. Coefficient of penalization of the contact. Implicit integration, the tangent matrix is symmetrical. The localization due to softening is managed natively by the flattened geometry of the EF of interface.	modelings supported	XXX_JOINT on linear meshs QUAD4 in 2D (plan or axis) or 3D (PENTA6 and HEXA8)
			Parameters	Words- keys GC (density of energy of surface criticizes) and SIGMA_C (constraint criticizes) Parameter of penalization of the contact PENA_CONTACT. Parameter of penalization of adherence PENA_ADHERENCE .
			Variable parameters with the temperature	not
			Number of internal variables and significance	9. Of which: indicator of dissipation, value of dissipated energy, value of current residual energy, jumps normal and tangential.
			CAS-tests reproducing the behavior	SSNP118 (in statics, piloting in mode 1, 2D PLAN_JOINT then with 3D_JOINT); SSNP133 (propagation of crack by brittle fracture in statics, with snap-back, in 2D PLAN_JOINT); SSNA115 (wrenching of a rigid reinforcement, in statics, 2D AXIS_JOINT); SSNV199 (propagation of crack by brittle fracture in statics, 3D, 3D_JOINT); SDNS105 (test of wrenching in dynamics, 2D).
			CAS-tests of physical validation	
			References	Doc. [R7.02.11].

General opinion	It is a question of the simplest law and most robust to represent the rupture of a joint in pure mechanics.
Robustness, developpability	
Publications	
EDF publications	J.Laverne doctorate, Energy Formulation of the Rupture by Models of Cohesive Forces: Theoretical considerations and Digital Establishments, UNIVERSITY PARIS XIII, 2004.
Outlines	

2.6 Identification of the parameters of behavior of the joints

It is allowed in general that limit of hasdhésion with the interface is lower or equal to the value of the cohesion of the least resistant material in contact to the interface.

3 What *Code_Aster* cannot (still) make

No model is available in a direct way in *Code_Aster* to represent:
- dependence of the permeability with the state of degradation of the géomatériau;
- dependence of cohesion to the state of saturation.

4 References

1. LEMAITRE J., CHABOCHE J.L.: "Mechanical of solid materials", ED. Dunod (1985).

2. [U2.04.05] Note of use of model THM.

3. [U2.04.08] static and dynamic Calculations of works géomechanics with the law of Hujeux.

4. [U4.51.11] Behaviors nonlinear, § 4.3.8.

5. [U4.90.21] Operator CALC_ESSAI_GEOMECA.

6. [R3.06.09] Finite elements of joint mechanics and finite elements of hydraulic joint coupled.

7. [R5.04.03] Modelings second gradient.

8.[R7.01.11] Models of behavior THHM.

9. [R7.01.13] Law CJS in géomechanics.

10. [R7.01.14] Law of behavior CAM_CLAY.

11. [R7.01.15] Law of behavior of LAIGLE.

12. [R7.01.17] Law of behavior of the porous environments: model of BARCELONA.

13. [R7.01.18] Law of behavior of modified HOEK_BROWN.

14. [R7.01.23] cyclic Law of behavior of Hujeux for the grounds.

15. [R7.01.24] viscoplastic Law of behavior LETK.

16. [R7.01.25] Laws of behavior of the joints of stoppings: JOINT_MECA_RUPT and JOINT_MECA_FROT.

17. [R7.01.28] Law of Mohr-Coulomb.

18. [R7.01.38] Law of Iwan for the cyclic granular material behavior.

19. [R7.01.39] Law of Rankine.

20. [R7.01.40] Model of behavior LKR.

21. [R7.01.41] Law of behavior of the porous environments: GONF_ELAS.

22. [R7.02.11] cohesive Laws of behavior: CZM_xxx_xxx and piloting of the loading.

23. [R7.02.15] Modeling of the cracks with hydraulic coupling in saturated porous environment.

24. ALVES FERNANDES V. "Analysis of the models of cyclic behavior of the grounds for the seismic answer of the works in fill". EDF note, 6125-1714-2017-04046-FR.

25. BUTTON MANUFACTURER L. "hydraulic Behavior of the fine grained soils close to saturation. Case of the ground works: coefficient B, instantaneous and differed strains, withdrawal/swelling". Doctorate INPG, 2007.

26. CAMBOU B., Constitutive Di PRISCO C. "Modelling of Geomaterials". French review of Génie Civil, vol. 4, n°5. ED. Hermes, 2000.

27. LUONG Mr., Phenomena cyclic in the non-cohesive soils. Rev Fr Géotech, (10), 1980.

28. HOEK E., MARINOS P., and BENISSI Mr. "Applicability of the geological strength index (GSI) classification for very weak and sheared rock'n'roll masses. The puts of the Athens schist formation". Bull. Eng. Geol. Approx., 57: 151-160, 1998.

29. VERMEER, P., of BORST, R. Non-Associated Plasticity for Soils, Concrete and Rock'n'roll, HERON 29, pp. 1-64, 1984.

5 Description of the versions of this document

Version *Code_Aster*	**Author (S) Organization (S)**	**Description of the modifications**
14.4	F.Voldoire EDF-R&D/ERMES	Initial text. This document profited from the contributions from V.Alves-Fernandes, S.Granet, K.Kazymyrenko, M.Kham, S.Raude.