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► To cite this version:

M. Azabou, Ahmed Rouabhi, Laura Blanco Martín, F. Hadj-Hassen, M. Karimi-Jafari, et al.. Rock salt behavior: From laboratory experiments to pertinent long-term predictions. International Journal of Rock Mechanics and Mining Sciences, 2021, 142, pp.104588. 10.1016/j.ijrmms.2020.104588 . hal-03220133

HAL Id: hal-03220133 https://minesparis-psl.hal.science/hal-03220133

Submitted on 9 May 2023 $\,$

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Rock salt behavior: From laboratory experiments to pertinent long-term predictions

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9 Abstract

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In the energy transition context, salt caverns are probably the most promising storage solution that promotes the development of intermittent renewable energies, due to their flexible and high deliverability. However, their design is still challenging since it should account for their entire lifetime, from rapid cycling exploitation to centuries of abandonment. The key to an optimal design is a constitutive model for rock salt that ensures pertinent short and long-term predictions. In this paper, we confront the results of five experimental campaigns conducted on different salts with existing rheological models. This confrontation proved that the studied models are capable of describing laboratory tests, however their predictions for the long term are either too conservative or overly optimistic. In practice, conservative or optimistic approaches do not ensure the optimal design of the facility. For this reason, we propose a new constitutive model that provides pertinent long-term predictions while interpreting satisfactorily short-term and long-term laboratory tests.

- ¹⁰ Keywords: rock salt, constitutive modeling, long-term creep, laboratory tests, time
- 11 extrapolation

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Preprint submitted to International Journal of Rock Mechanics and Mining Sciences November 13, 2020

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12 1. Introduction

Solution mined caverns in salt formations have proven to be among the most efficient 13 techniques for storage of different energy vectors since the 1960s (Bays, 1963; Ozarslan, 2012; 14 Bai et al., 2014: Iordache et al., 2014: Lord et al., 2014; Michalski et al., 2017: Tarkowski 15 and Czapowski, 2018; Firme et al., 2019; Soubeyran et al., 2019; Lankof and Tarkowski, 16 2020). Today these facilities have an important role in the energy transition context. Their 17 flexible and high deliverability makes them the most promising solution to respond to peak 18 demand for intermittent clean energies. The feasibility studies and the design of these cav-19 erns should account for the exploitation phase and for the decades and sometimes centuries 20 of the abandonment phase. The optimal design of these structures rests upon the use of a 21 constitutive model with pertinent short and long-term predictions. 22

There cannot be a unique rheological model able to describe the behavior of a geological ma-23 terial such as rock salt, under all kinds and within all ranges of thermo-mechanical loadings. 24 What is sought instead, are approximate laws that can provide a close enough description 25 to the real behavior of the rock within a given range of loading conditions. This explains the 26 abundance of rock salt constitutive models in the literature. All the existing models, despite 27 the differences in the phenomena they account for (dilatancy, healing, inverse creep, tran-28 sient, steady state and tertiary creep, damage, extension, strain under tensile loading...), 29 agree on two facts: first, rock salt has a strongly time dependent behavior and second, lab-30 oratory tests are essential for their parameters calibration. The multitude of models proves 31 their limitations and justifies the need for the research on rock salt rheology to continue. 32

Long-term behavior is one of the main challenges for the rheological modeling of rock salt. In fact, it is technically possible to conduct tests under all desired loading conditions (different strain rates, temperatures, mechanical and thermal cycling...). However, contrary to the thermo-mechanical variables, we do not have control over the time of laboratory experiments, which is negligible compared to the lifetime of the underground facilities (a few months or years in the best case scenario, compared to few decades or even centuries in the field). When performing a time-extrapolation of the existing models, three kinds of

responses are obtained: (i) a transient response where the strain rate continuously decreases 40 (Tijani et al., 1983; Labaune et al., 2018; Rouabhi et al., 2019), (ii) a purely steady-state 41 response where the strain rate remains constant and the strain increases linearly over time 42 (Odqvist, 1966) and (*iii*) a transient response that stabilizes into a steady-state regime where 43 the strain starts increasing linearly over time (Munson and Dawson, 1981; DeVries et al., 44 2002; Heusermann et al., 2003; Bérest et al., 2007; Hampel, 2012; Nazary Moghadam et al., 45 2013; Wolters et al., 2012; Günther et al., 2015; Khaledi et al., 2016; Deng et al., 2020; Wu 46 et al., 2020). 47



Figure 1: Time-extrapolation of three models with different creep responses on a uniaxial creep test.

Figure 1 illustrates this point where we show a qualitative comparison of the three 48 responses based on the simulation of a uniaxial creep test over 30 years. As shown, the 49 transient model gives an overly optimistic prediction while the two other models are rather 50 conservative. Bérest et al. (2008) studied the differences in the long-term behavior predicted 51 by these types of models. The study confirmed that the transient models and the steady 52 state ones predict significantly different behaviors on the long term, and suggested that, 53 since in terms of laboratory tests both models give satisfactory interpretations, the most 54 conservative predictions should be selected. However in practice, the optimal design of salt 55 caverns cannot be based on overly conservative approaches. 56

The purpose of this paper is to propose a model with pertinent predictions for long-term 57 creep behavior. We propose an enrichment to the distorsion part of a model that has been 58 detailed in (Rouabhi et al., 2019). The modification consists in adding to the transient 59 component, a second transient mechanism inspired by the Munson-Dawson (Munson and 60 Dawson, 1981) transient creep. This allows to have a compromise between the steady state 61 models and the transient ones in terms of the strain rate and the characteristic time. The 62 added mechanism allows also to describe inverse creep (Julien, 1999; Heusermann et al., 63 2003; Karimi-Jafari, 2007; Günther et al., 2015; Labaune, 2018; Gharbi et al., 2020) and 64 links it to hysteresis loops of the unloading-loading cycles of triaxial compression tests. The 65 authors are aware that in-situ data that covers years of exploitation activity, is needed to 66 fully validate the model and truly assess the pertinence of its time extrapolation. However, 67 acquiring such data and using it for research work is difficult, since -even if they exist- these 68 measurements are destined for exploitation purposes. 69

This paper is structured as follows. In the first section two existing models and the new 70 proposed one are presented. In section 3, we compare these constitutive laws on the basis 71 of five experimental campaigns conducted at Mines ParisTech on rock salts from different 72 geographic locations. The comparison concerns the capability of the three models to fit 73 long-term (creep) and short-term (conventional tiaxial compression) tests with the same 74 parameter set, and the pertinence of their long-term predictions. In section 4 the new 75 model is used to analyze a comprehensive test campaign and the inverse creep phenomenon 76 is discussed in section 5. 77

78 2. Constitutive models

All these constitutive laws agree on the partition of the total strain rate tensor $\underline{\dot{\varepsilon}}_{i}$ into elastic $\underline{\dot{\varepsilon}}_{el}$, thermal $\underline{\dot{\varepsilon}}_{th}$ and viscoplastic parts $\underline{\dot{\varepsilon}}_{vp}$:

$$\underline{\dot{\underline{\varepsilon}}} = \underline{\dot{\underline{\varepsilon}}}_{\text{el}} + \underline{\dot{\underline{\varepsilon}}}_{\text{th}} + \underline{\dot{\underline{\varepsilon}}}_{\text{vp}} \quad ; \quad \underline{\dot{\underline{\varepsilon}}}_{\text{el}} = \frac{1+\nu}{E} \underline{\dot{\underline{\sigma}}} - \frac{\nu}{E} tr(\underline{\dot{\underline{\sigma}}}) \underline{\underline{1}} \quad ; \quad \underline{\dot{\underline{\varepsilon}}}_{\text{th}} = \alpha_{\text{th}} \dot{T} \underline{\underline{1}} \tag{1}$$

where E, ν are the elastic constants, $\underline{\sigma}$ is the Cauchy stress tensor, $\underline{1}$ is the unit tensor, $\alpha_{\rm th}$ is the linear thermal expansion coefficient and T is the temperature. The viscoplastic strain tensor is generally given as a function of the thermodynamic state ($\underline{\sigma}, T$) and internal variables ξ with a rate that depends on $\underline{\sigma}, T$ and the internal variables:

$$\underline{\underline{\dot{\varepsilon}}}_{\mathrm{vp}} = \underline{\underline{\mathscr{F}}}(\underline{\underline{\sigma}}, T, \xi), \quad \underline{\dot{\xi}} = \mathscr{G}(\underline{\underline{\sigma}}, T, \xi)$$
(2)

it is on the definitions of ξ , $\underline{\mathscr{F}}$ and \mathscr{G} that those models differ. In this section we present the following models: Munson-Dawson, Lemaitre and the model developed in this work that we shall call RTL.

⁸⁸ 2.1. The Munson-Dawson constitutive model

This model has been detailed in (Munson and Dawson, 1981) and it states the following 90

$$\underline{\dot{\underline{\varepsilon}}}_{\mathrm{vp}} = F \underline{\underline{\dot{\varepsilon}}}_{\mathrm{ss}} \quad ; \quad \underline{\dot{\underline{\varepsilon}}}_{\mathrm{ss}} = \dot{\varepsilon}_{\mathrm{ss}} \underline{\underline{J}} = \dot{\varepsilon}_{\mathrm{ss}} (\underline{\underline{\sigma}}, T) \underline{\underline{J}} \quad ; \quad \underline{\underline{J}} = \underline{\underline{\sigma}} \mathbf{I} / || \underline{\underline{\sigma}} \mathbf{I} || \tag{3}$$

⁹¹ where $\underline{\sigma}'$ is the deviatoric part of the Cauchy stress tensor $\left(\underline{\sigma}' = \underline{\sigma} - \frac{1}{3}tr(\underline{\sigma})\underline{\underline{I}}\right), \underline{\dot{\varepsilon}}_{ss}$ denotes ⁹² the steady state strain rate tensor and F is defined as follows

$$F = \begin{cases} \exp\left(\Delta(1-\zeta/\varepsilon_t^*)^2\right) & \text{if } \zeta \le \varepsilon_t^* \\ \exp\left(-\delta(1-\zeta/\varepsilon_t^*)^2\right) & \text{if } \zeta \ge \varepsilon_t^* \end{cases}$$
(4)

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$$\dot{\zeta} = (F-1)\dot{\varepsilon}_{\rm ss} \tag{5}$$

⁹⁴ In this work we assume the following

$$\dot{\varepsilon}_{\rm ss}(\underline{\sigma},T) = A \exp\left(A_{\rm M}(\frac{1}{T_{\rm r}} - \frac{1}{T})\right) \langle G \rangle^n \quad ; \quad \varepsilon_t^* = K_0 {\rm e}^{cT} q^m \tag{6}$$

where G is a loading function chosen as G = q, with q the von mises equivalent stress, $\langle \cdot \rangle$ are the Macaulay brackets, i.e., $\langle x \rangle = (x + |x|)/2$, T_r is the reference temperature, A, A_M , n, c, K_0 , m, Δ and δ are material constants. We note that this model accounts for transient creep (via the function F) that saturates at ε_t^* and the steady state flow $\dot{\varepsilon}_{ss}$ takes over.

99 2.2. The Lemaitre constitutive model

This model assumes that rock salt creep is a purely transient flow, the viscoplastic strain rate decreases asymptotically to zero. It states the following

$$\underline{\dot{\varepsilon}}_{\rm vp} = \sqrt{3/2} \dot{\gamma}_{\rm vp} \underline{J} \tag{7}$$

where $\gamma_{\rm vp}$ is the viscoplastic distorsion defined as

$$\dot{\gamma}_{\rm vp} = \gamma_{\rm vp}(\underline{\underline{\sigma}}, T, \gamma_{\rm vp}) = \alpha \exp(A_{\rm L}(\frac{1}{T_{\rm r}} - \frac{1}{T}) \left\langle \frac{G}{K} \right\rangle^{\beta/\alpha} \gamma_{\rm vp}^{1-\frac{1}{\alpha}} \tag{8}$$

¹⁰³ α , β , $A_{\rm L}$ and K and positive rheological constants and $T_{\rm r}$ the reference temperature. Sim-¹⁰⁴ ilarly to the previous model, G is a loading function $G = G(\underline{\sigma}, T, \gamma_{\rm vp})$ and is chosen as ¹⁰⁵ G = q.

106 2.3. The RTL2020 constitutive model

¹⁰⁷ Similar to the model detailed in Rouabhi et al. (2019), for the viscoplastic strain rate ¹⁰⁸ tensor, RTL assumes the following

$$\underline{\underline{\dot{\varepsilon}}}_{\mathrm{vp}} = \sqrt{\frac{3}{2}} \dot{\gamma}_{\mathrm{vp}} \underline{\underline{N}} - \frac{1}{\sqrt{3}} \dot{\zeta}_{\mathrm{vp}} \underline{\underline{I}}$$

$$\tag{9}$$

where $\dot{\zeta}_{vp} = -tr(\underline{\dot{\varepsilon}}_{vp})$ and $\dot{\gamma}_{vp} = \sqrt{2/3}||\underline{\dot{\varepsilon}}'_{vp}||$ are the rates of the volumetric strain and the viscoplastic distorsion, respectively, \underline{N} is a unit tensor defining the deviatoric flow direction and $\underline{I} = \underline{1}/\sqrt{3}$. The general formalism of the viscoplastic distorsion is defined as

$$\dot{\gamma}_{v_{p}} = \dot{\gamma}_{L} + \dot{\gamma}_{R} \quad ; \text{ with } \begin{cases} \dot{\gamma}_{L} = \psi_{L}(\underline{\sigma}, T, \gamma_{L}) \\ \dot{\gamma}_{R} = \psi_{R}(\underline{\sigma}, T, \gamma_{R}) \end{cases}$$
(10)

here $\dot{\gamma}_L$ describes a transient creep mechanism of Lemaitre's type, and $\dot{\gamma}_R$ is an added transient mechanism inspired by the Munson-Dawson model. The first transient mechanism is defined by

$$\psi_L(\underline{\sigma}, T, \gamma_L) = \alpha \exp\left(A_{\rm R}(\frac{1}{T_{\rm r}} - \frac{1}{T})\right) \left\langle \frac{G}{A_2} \right\rangle^{n_2} \gamma_{\rm L}^{1-\frac{1}{\alpha}} \tag{11}$$

where α , $A_{\rm R}$, A_2 and n_2 are material parameters, G is a loading function. The added distorsion mechanism γ_R is defined as

$$\psi_{R}(\underline{\sigma}, T, \gamma_{R}) = \begin{cases} A(1 - \gamma_{R}/\bar{\gamma_{R}})^{n}R(\underline{\sigma}, T) & \text{if } \gamma_{R} \leq \bar{\gamma_{R}} \\ & ; \quad \bar{\gamma_{R}} = \bar{\gamma_{R}}(\underline{\sigma}, T) \\ -B(\gamma_{R}/\bar{\gamma_{R}} - 1)^{m}R(\underline{\sigma}, T) & \text{if } \gamma_{R} \geq \bar{\gamma_{R}} \end{cases}$$
(12)

here A, B, m and n are material parameters such that A > 0, B > 0 and m > 1, n > 1. The model offers enough flexibility in the choice of the functions $\psi_L, \overline{\gamma_R}$ and R. In this work we have made the following considerations:

• $\dot{\gamma}_{\rm L}$ corresponds to the viscoplastic distorsion of Lemaitre model $\dot{\gamma}_{\rm vp}$;

• γ_R is considered to be analogue to the saturation value ε_t^* in Munson-Dawson model, it is given by

$$\bar{\gamma_R} = \left\langle \frac{G}{A_1} \right\rangle^{n_1} \tag{13}$$

where A_1 and n_1 are material parameters.

• As for the definition of the function R, it is considered to be the same as ψ_L in order to link the two mechanisms and ensure that their contributions have the same order of magnitude

$$R(\underline{\sigma}, T) = \exp\left(A_{\rm R}(\frac{1}{T_{\rm r}} - \frac{1}{T})\right) \left\langle\frac{G}{A_2}\right\rangle^{n_2} \tag{14}$$

• We chose the loading function
$$G$$
 such that $G = q$.

As for the volumetric viscoplastic strain, it remains unchanged from the definition given in
RTL (Rouabhi et al., 2019) as

$$\dot{\zeta}_{\rm vp} = \phi\left(\underline{\sigma}, T, \gamma_{\rm vp}\right) \dot{\gamma}_{\rm vp} = z \frac{\langle p/N_z \rangle^{n_z} - \gamma_{\rm vp}}{\langle p/M_z \rangle^{m_z} + \gamma_{\rm vp}} \dot{\gamma}_{\rm vp}$$
(15)

where z, N_z, n_z, M_z and m_z are material parameters and p is the mean pressure $\left(p = -tr(\underline{\sigma})/3\right)$. We note that the RTL model is equivalent to the Munson Dawson model when the following considerations are made:

133 •

• the parameter α from equation 11 is set to 1;

• the parameter A from equation 12 is taken as $A = \exp(\Delta)$;

• the parameter n from equation 12 is linked to the parameter Δ via the following equation

$$n = \begin{cases} -0.0098\Delta^3 + 0.2040\Delta^2 + 0.5622\Delta + 2.0252 & \text{when } \Delta \le 6\\ 1.9987\Delta - 1.4567 & \text{when } \Delta > 6 \end{cases}$$
(16)

• $B = \delta = 0$ (equations 4 and 12).

The advantage of the mechanism $\gamma_{\rm R}$ in this model is that it can be easily integrated compared to the exponential formulation used in Munson-Dawson. Under constant stress and temperature, the analytical solution for equation 11 can be written as

$$\gamma_{\rm R}(t) = \gamma_{\rm R_0} + \left(\bar{\gamma_{\rm R}} - \gamma_{\rm R_0}\right)\xi\tag{17}$$

¹⁴¹ where ξ is given by

$$\xi(t) = 1 - \left(\frac{1}{1 + V(t - t_0)}\right)^{\frac{1}{k-1}}$$
(18)

142 with

$$V = (k-1)U\frac{A_1^{n_1}}{A_2^{n_2}}q^{n_2-n_1}$$
(19)

When $\gamma_{\rm R} \leq \bar{\gamma_{\rm R}}$ we have: $k = n, U = A(1 - \gamma_{\rm R_0}/\bar{\gamma_{\rm R}})^{n-1}$ and if $\gamma_{\rm R} \geq \bar{\gamma_{\rm R}}$ then k = m, $U = B(\gamma_{\rm R_0}/\bar{\gamma_{\rm R}} - 1)^{m-1}$.

In Figure 2 we illustrate the role of each of the parameters $A, B, n, m, A_1, n_1, A_2$ and n_2 . We start from the parameter set given in Table 1 and in each case one parameter is varied, the simulated scenario is one of a uniaxial creep test were the axial stress (q in this case) is held constant at 10 MPa during 15 days and then dropped to 5 MPa for another 15 days. In

the plots we present the evolution of the distorsion $\gamma_{\rm R}$ in time and the value of $\bar{\gamma_{\rm R}}$ in each deviatoric stage (recall that $\bar{\gamma_{\rm R}} = \left(\frac{q}{A_1}\right)^{n_1}$).

A	В	n	m	A_1	n_1	A_2	n_2
0.5	0.05	5	5	0.3	3	0.5	4

Table 1: Initial parameter set used to study the role of the parameters of the distorsion mechanism γ_R (the unit system is such that strain is in $\mu m/m$, stress is in MPa and time in days).



Figure 2: Effect of the parameters of the distorsion mechanism $\gamma_{\rm R}$ in RTL model, predictions of a multistage creep test, note that in the sub-figures describing the effects of parameters A_1 and n_1 , the value of $\bar{\gamma}_{\rm R}$ corresponding to each parameter is plotted in the same color in dashed line.

The parameters A, B, n and m affect the rate at which $\gamma_{\rm R}$ tends to $\bar{\gamma}_{\rm R}$ as shown in the four top sub-figures of Figure 2. Particularly after a load drop, the parameters B and maffect the duration of the observed transient flow. The four sub-figures in the bottom of Figure 2 show that the mechanism is more sensitive to the parameters defining $\bar{\gamma}_{\rm R}$ (A_1 and n_1) and to A_2 and n_2 . As shown in Figure 2, the parameters of the $\gamma_{\rm R}$ distorsion mechanism ¹⁵⁶ give the model a great flexibility to fit different experimental responses.

¹⁵⁷ 3. Models comparison on the basis of laboratory tests

158 3.1. Laboratory tests

We analyzed 5 experimental campaigns conducted at Mines ParisTech between 2012 and 159 2020 on salts from different locations (USA, Europe, Middle East), to which we will refer 160 as salt 1, salt 2, salt 3, salt 4 and salt 5. From each of the campaigns we chose a multistage 161 creep test (considered as a long-term test) and a conventional triaxial compression test 162 (short-term test). The tests of the first four campaigns were all conducted following the 163 same procedure (preconditioning, measurement techniques -strain gauges-, experimental set 164 up and the axial strain rate $\dot{\varepsilon}_{ax}$ for the short-term tests). In addition, in these four series of 165 tests the confining pressure (P) is maintained constant during the creep tests and the changes 166 in the deviatoric stages are applied by modifying the axial stress (Q). However, for salt 5 167 the procedure for the short-term tests was slightly different (duration and confining pressure 168 for specimen preconditioning, measurement techniques -radial extensioneter and global axial 169 displacement-, axial strain rate). Also the creep test on this salt lasted significantly longer 170 compared to the creep tests from the first four campaigns and it differs from them in the 171 testing procedure: the deviatoric stages are obtained by varying both the axial and lateral 172 stresses such that the mean pressure (Q+2P)/3 is held constant at 10 MPa throughout the 173 test. 174

175 3.2. Parameters fitting and time extrapolation

For each salt, the results are analyzed with the three models (Munson-Dawson, Lemaitre and RTL) and the best fitting obtained (with the same parameter set for each model) is provided. Afterwards, these parameters are used to perform a time extrapolation of the models on a virtual scenario of a uniaxial creep test of 10000 days.

In the three models we are studying, the temperature effect is given by the Arrhenius law, and all the creep tests we are analyzing in this section are carried out at constant temperature. For this reason, we have set the parameters $A_{\rm M} = A_{\rm L} = A_{\rm R} = 1725$ K, also the

reference temperature T_r was set to 289 K. In addition, since the stages of deviatoric stress 183 in all the creep tests are ascending, the parameter B from equations 12 was set to 0 and 184 therefore the parameter m was not adjusted. Figures 3 to 7 show the fittings of the three 185 models on the tests from the five campaigns and the results of the time extrapolation. In 186 each of these figures, the top graph represents the analysis of a triaxial compression test (at 187 a constant confining pressure and a constant strain rate that are specified on the graph), the 188 middle graph corresponds to a multistage creep test (the test temperature and conditions 189 are indicated on the graph) and the bottom figure is a time extrapolation of the three models 190 for a uniaxial creep test at $T = 40^{\circ}$ C. The fitting parameters are provided in Table 2. 191

We can see that the three models give satisfactory interpretations to both the short-term 192 and the long-term tests, they are all able to describe the behavior of rock salt at the labo-193 ratory scale for this specific type of tests (time and loading ranges). As for the long-term 194 predictions, the transient creep phase described by Munson-Dawson model is practically 195 inexistent compared to the steady state flow and it has the same time span of laboratory 196 tests durations (a few days), the time extrapolation of this model is rather conservative since 197 the steady state flow is dominant and the strain increases linearly over time. However, the 198 Lemaitre model is overly optimistic as it assumes that the strain rate keeps on decreasing 199 infinitely and the strain almost tends to stabilize. On the other hand, in all the studied cases 200 RTL gives predictions that are between these two extremes, the strain increases in time but 201 neither linearly nor with an almost-zero rate. Besides, in RTL time extrapolation we dis-202 tinguish a characteristic time (for the mechanism $\gamma_{\rm R}$) that is comparable to the duration of 203 the prediction. 204



Figure 3: Fittings of tests on salt 1 and time extrapolation of the three fitted models.



Figure 4: Fittings of tests on salt 2 and time extrapolation of the three fitted models.



Figure 5: Fittings of tests on salt 3 and time extrapolation of the three fitted models.



Figure 6: Fittings of tests on salt 4 and time extrapolation of the three fitted models.



Figure 7: Fittings of tests on salt 5 and time extrapolation of the three fitted models.

Parameters	Salt 1	Salt 2	Salt 3	Salt 4	Salt 5			
Elasticity								
E	29518	27499	28567	32172	22126			
ν	0.32	0.32	0.30	0.31	0.2			
Munson-Dawson								
A	4.636×10^{-8}	2.713×10^{-3}	0.5882	0.5513	4.46×10^{-4}			
n	8.0975	3.7	1.	1.01	3.936			
m	1.387	2.3	2.8075	2.6922	2.7062			
K_0	159.5602	69.6769	31.2385	18.5017	5.8505			
Δ	14.0464	9.3	11.1551	11.6182	15.3698			
Lemaitre								
α	0.1363	0.2288	0.1746	0.1801	0.1904			
β	2.4189	2.6356	2.0518	2.265	3.4854			
K	0.4938	0.4832	0.16	0.3034	1.4091			
RTL								
α	0.5072	0.3601	0.2601	0.3201	0.6709			
A_1	0.4896	0.061	0.0181	0.04107	0.2937			
n_1	2.5093	1.473	1.162	1.3711	2.2839			
A_2	0.1916	1.0945	0.3986	0.868	4.5478			
n_2	2.7967	9.2482	9.6768	9.1676	6.3023			
A	36.055	6.81×10^{-3}	0.01	2.94×10^{-2}	684			
n	11.5263	9.2644	13.5	12.11	8.8926			

Table 2: Parameters used to fit the experimental data in Figures 3 to 7. The unit system is such that strain is in μ m/m, stress is in MPa and time in days.

²⁰⁵ 4. Analysis of a comprehensive testing campaign with RTL

In order to show the capabilities of RTL to fit simultaneously short and long-term tests, with different and relatively complicated loading paths, we use this constitutive model to analyze a comprehensive testing campaign performed on specimens from salt 5 at Mines ParisTech.

210 4.1. Laboratory tests

In addition to the triaxial compression and the creep tests shown in Figure 7, we conducted the following tests on specimens from salt 5:

• a typical triaxial compression test under a confining pressure P = 5 MPa and an constant axial strain rate of $\dot{\varepsilon}_{ax} = 10^{-5}$ s⁻¹, performed at room temperature;

• a constant mean stress triaxial compression test, where the confining and the axial pressures (respectively P and Q) vary with the respective rates of $\dot{P} = -1$ MPa/d and $\dot{Q} = 2$ MPa/d in order to maintain a constant mean stress of (Q + 2P)/3 = 17 MPa (at room temperature);

• a multistage creep test at room temperature, where the effect of the mean pressure is investigated: during some of the stages the axial and lateral stresses are changed in order to maintain a constant deviatoric stress and change the mean pressure;

• a multistage creep test similar to the last one, but performed at T = 70 °C.

This testing campaign is comprehensive as it is includes tests with different and non-classic
loading paths, also all the creep tests last over 200 days.

225 4.2. Parameters fitting

Since some of the tests have different temperature stages, the parameters $A_{\rm R}$ and $\alpha_{\rm th}$ were fitted. The elastic parameters E and ν were fitted using the unloading/reloading cycles of the triaxial compression tests. The remaining parameters were fitted in two independent steps: those related to the deviatoric part and those related to the volumetric part. The experimental measurements of the distorsion were used to fit the volumetric strain part; this ensures the independence of the two fittings. The fittings of the analyzed tests are given in Figure 8 and the corresponding single parameter set in Table 3. As can be seen, RTL allows a satisfactory matching to the experimental measurements and it describes correctly the deviatoric and the volumetric behavior. The quality of the fittings shown in Figure 8 proves the robustness of RTL as a rock salt constitutive law.



Figure 8: Fitting of three short-term tests (top) and three creep tests (bottom) with a single parameter set. Note that for the second creep test, an isothermal (room temperature), isotropic phase (at (Q + 2P)/3 = 12 MPa) was applied.

Elasticity and Temperature effect								
E	ν	A_{R}	$lpha_{ m th}$					
22126	0.2	4457	3.27×10^{-5}					
Distorsion								
a	A_1	n_1	A_2	n_2	A	n	В	m
0.5812	0.1854	2.1012	3.7009	6.7562	155.6582	11.989	0.01918	2.2195
Dilatancy								
z	nz	$N_{\rm z}$	mz	$M_{\rm z}$				
0.4523	1.2644	0.0241	1.028	0.024				

Table 3: Parameters used to fit both short-term and creep tests on Landes salt (the unit system is such that strain is in μ m/m, stress is in MPa and time in days).

²³⁶ 5. Inverse creep

When the deviatoric stress level decreases during a classic creep test, the specimen's 237 length increases for a brief duration before it starts decreasing again. This phenomenon 238 assumes that the viscoplastic strain rate can be negative following a loading drop (inverse 239 creep). Observing this during classic creep tests is delicate due to its small magnitude and 240 brief duration. However this phenomenon is exhibited during the unloading-loading cycles 241 of classic triaxial compression tests, in fact we observed that during these tests the decrease 242 of the deviatoric stress comes with an irreversible strain and the creation of a hysteresis loop. 243 We select the first triaxial compression test and the third creep test presented in Figure 8, 244 we fit the two data sets with RTL and a single parameter set twice: the first fitting does 245 not allow a change in the direction of the viscoplastic strain (i.e., the parameter B is set to 246 0) and the second fitting is performed with $B \neq 0$. The results are respectively shown in 247 Figure 9 and 10 and the corresponding parameters are listed in Table 4. 248

Both fittings qualities are satisfactory, in Figure 9 the loading drop during the two analyzed tests is purely elastic as it can be seen in the zoomed plots. However, activating the inverse creep mechanism ($B \neq 0$) allows to describe the hysteresis loop observed during the shortterm test; it characterizes correctly the viscoplastic flow that comes with this unloading-

loading cycle. Also, following the load drop in the creep test, the model describes a very 253 small and hardly distinguishable inverse creep: the strain rate decreases and then starts 254 increasing again. We would like to highlight the fact that in the experimental measurements 255 inverse creep was not observed, which is almost always the case during creep tests. This 256 phenomenon has a very small order of magnitude (as predicted by the model in Figure 10), 257 yet this fitting proves that it is directly linked to the loops of the unloading-loading cycles 258 of triaxial compression tests. In Figure 11 we detail the fitting of the creep test in Figure 10 259 and we explicit the contributions of the distorsion mechanisms of RTL. We can see that 260 following the load drop $\gamma_{\rm R}$ decreases and tends to the new $\bar{\gamma}_{\rm R}$ but with a very small rate, 261 which is why $\gamma_{\rm L}$ (steadily increasing) prevails and this results in a very discreet inverse creep 262 phenomenon. 263



Figure 9: Fitting of a conventional triaxial test (left) and a multistage creep test (right) with a single parameter set without accounting for inverse creep.



Figure 10: Fitting of a conventional triaxial test (left) and a multistage creep test (right) with a single parameter set accounting for inverse creep.

Elasticity and Temperature effect									
E	ν	A_{R}	$lpha_{ m th}$						
22126	0.2	4457	3.27×10^{-5}						
Distorsion without accounting for inverse creep									
a	A_1	n_1	A_2	n_2	A	n	В	m	
0.5812	0.1854	2.1012	3.7009	6.7562	155.6582	12.11	0	_	
Distorsion accounting for inverse creep									
a	A_1	n_1	A_2	n_2	A	n	В	m	
0.3840	0.2136	2.0581	2.4199	9.9698	0.2223	12.11	$3.72\!\times\!10^{-5}$	4.5795	

Table 4: Parameters used for the fittings shown in Figures 9 to 11 (the unit system is such that strain is in μ m/m, stress is in MPa and time in days)



Figure 11: Fitting of a the multistage creep test shown in Figure 10 and detailing of the contributions of the distorsion mechanisms in RTL.

²⁶⁴ 6. Conclusion

In this paper we discussed the aptitude of rock salt constitutive models to provide per-265 tinent short and long-term predictions, since they are crucial for the optimal design of salt 266 caverns. Our discussion was based on the confrontation of existing models with five ex-267 perimental campaigns conducted on salts from different geographic locations. We found 268 that the studied models gave satisfactory interpretations to laboratory tests. However, their 269 long-term predictions were either too conservative or very optimistic. A new model was 270 developed and included in this confrontation. It also allowed correct interpretations for lab-271 oratory tests but unlike the existing models, it gave pertinent predictions for the long term. 272 This new model was also tested against a comprehensive testing campaign that comprises 273 short-term, long-term and non-classic creep tests. It provided a valid fitting for the cam-274 paign with a single parameters set. 275

We note that an absolute validation of the model and the pertinence of its long-term predictions, requires confrontation with in-situ data over years of the cavern's lifetime. This can be done when a continuous monitoring of the underground facilities is performed and in-situ measurements are used to re-calibrate the model parameters and update the predictions.

280 7. Acknowledgments

This work has been performed in the framework of the projects CITEPH and STOPIL-H2, the authors thank the sponsors and partners of the projects. The authors would also like to acknowledge Michel Tijani from Mines ParisTech and Nicolas Gatelier from Geostock, for their constructive discussions.

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