

Evaluating the subsidence above gas reservoirs with an elasto-viscoplastic constitutive law. Laboratory evidences and case histories

*Original*

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4 **Evaluating the subsidence above gas reservoirs with an elasto-**  
5 **viscoplastic constitutive law: laboratory evidences and case histories**

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19

20

21 **Abstract**

22

23 Reliable modelling of subsidence is an important objective for companies and regulators interested in safe and  
24 environmentally sustainable development of hydrocarbon fields. Subsidence is triggered by the depletion of reservoirs  
25 and connected aquifers, which causes the compaction of the geologic layers. A fundamental requirement of models is the  
26 correct prediction of the pore pressure changes taking place during the production; but capturing the mechanical  
27 behaviour of the reservoir material and its proper constitutive modelling are equally important. In some cases, the geologic  
28 materials show a time-dependent (viscous) behaviour, which might lead to creep strains at constant stress conditions. As  
29 a consequence, subsidence might be delayed with respect to hydrocarbon production, or continue even when production  
30 has stopped.

31 This paper refers to the case of two gas reservoirs from the Adriatic basin. Numerical simulations based on elasto-plastic  
32 constitutive models, even if relying on very accurate reconstructions of the pore pressure histories, did not provide a  
33 satisfactory match of subsidence history. This motivated a further insight into the time-dependent behaviour of the sandy  
34 reservoir materials. The results of an exhaustive laboratory investigation were interpreted in light of an existing elasto-  
35 viscoplastic model, recently implemented by the authors in a commercial Finite Element code. Numerical predictions are  
36 compared to field data, which include both measurements of compaction, taken in the reservoirs with radioactive markers,  
37 and surface settlements recorded with GPS and bathymetric surveys. A very good agreement was obtained between  
38 simulation results and field data, in terms of maximum settlements, settlement history and extent of the subsidence bowl.

39 **Keywords:**

40 Subsidence; time-dependent mechanical behaviour; creep; elasto-viscoplastic constitutive law; gas reservoir; case  
41 history

42

43        **1. Introduction**

44        Land subsidence is a potential undesired effect of underground fluid extraction, which in some cases can seriously affect  
45        the environment and human activities. Subsidence can increase the risk of flooding along coastal and estuarine areas, as  
46        in New Orleans with the Katrina Hurricane<sup>1</sup> and in Bangkok in 2011<sup>2</sup>. In extreme cases, anthropic subsidence can cause  
47        the ground floor to sink below the water level, which in proximity of populated or environmentally relevant lands can  
48        impact on social or ecological equilibria<sup>3</sup>, requiring the building of new dykes (see e.g. Refs. 4, 5) or rising the height of  
49        old ones<sup>6</sup>. In offshore fields, subsidence due to hydrocarbon extraction can reduce the air gap between the lower platforms  
50        deck and the sea, exposing platforms to waves inundation and requiring very costly extraordinary maintenance to keep  
51        the production activities ongoing<sup>7</sup>. Both regulators and energy companies are then deeply interested in reliable predictive  
52        models, which allow foreseeing the magnitude and extent of the ground settlements, ultimately leading to early  
53        implementation of mitigation strategies whenever necessary.

54        Factors that can lead to appreciable subsidence are highly compressible reservoir rocks, considerable decrease of pore  
55        pressure during hydrocarbon production, thick or shallow reservoirs and low contrast between the stiffness of the  
56        reservoir and that of the overburden<sup>8</sup>.

57        Saturated soils and rocks have a coupled hydro-mechanical behaviour and, in principle, both the flow and the mechanical  
58        problems should be solved simultaneously through coupled hydro-mechanical analyses. This is seldom done, because of  
59        the demanding numerical issues and computational efforts required for large scale problems such as the one under  
60        consideration (e.g. Ref. 9). However, for gas reservoirs, very little hydro-mechanical coupling is expected because the  
61        pore fluid has a very high compressibility compared to the rock. A one-way coupling procedure, where the pore pressure  
62        distribution at different times is first estimated by means of reservoir fluid dynamic simulations and then used to simulate  
63        the mechanical response, is accepted in these cases, provided that the mechanical characterization of reservoir rocks is  
64        consistent in both flow and mechanical models. The first mathematical model for the prediction of subsidence was  
65        formulated by Geertsma<sup>10</sup> on the basis of the 'strain nuclei' approach. This model considers the subsurface as a poro-  
66        elastic half space, and it provides the analytical solution of the displacement caused by the pore pressure drop occurring  
67        within a material point (nucleus of strain) having some specific coordinates. The analytical solution can be readily  
68        extended to real cases by discretizing the reservoir with a proper number of grid blocks (strain nuclei) and integrating the  
69        effects of the pressure decrease of each grid block over the whole reservoir, thus predicting the subsidence bowl due to  
70        the development of the field. The solution for the simplified case of an axisymmetric disc-shaped reservoir with a uniform  
71        pressure can be found in Geertsma<sup>11</sup>.

72 The Geertsma model introduces the very stringent assumptions of a homogeneous material with a linear isotropic elastic  
73 behaviour. Other analytical models (see e.g. Refs. 12, 13) relaxed the homogeneity and the isotropy assumptions, while  
74 maintaining linear elasticity. However, it is well known that the mechanical behaviour of most of the geologic materials  
75 is elastic only at very small strains, and that it is generally not linear.

76 A significant improvement in subsidence modelling was obtained accounting for plastic strains occurring along  
77 compression stress paths, by implementing volumetric hardening elasto-plastic models such as the Modified Cam Clay  
78 Model<sup>14</sup> into Finite Element (FE) codes. Simulations based on these models proved to be satisfactory for several field  
79 cases<sup>15-17</sup>, but failed in detecting the correct values and trends of subsidence for others<sup>18-21</sup>, where an increase in subsidence  
80 was appreciated even after production had stopped or reduced significantly.

81 Two major mechanisms are considered to be responsible for the delayed subsidence and for the discrepancy between the  
82 simulations and field measurements. The first one is the delayed depletion of low permeability layers, such as shales or  
83 clays, both within and outside the reservoir (see e.g. Ref. 22). Pore pressure decrease, originating in the gas bearing layers,  
84 diffuses very slowly through shales or clays, because of their low permeability. As such, shale compaction will continue  
85 after suspending or even stopping production. Such a compaction adds up to the one of the reservoir and induces a delayed  
86 increase of subsidence, which can be observed only in later stages of the productive life of the field. However, delayed  
87 subsidence has been observed also in the first years of production, without any relationship to stop of production<sup>23</sup>.

88 Delayed subsidence might also depend on the time-dependent behaviour of the materials. For soils, volume strains are  
89 well known to increase with time even under a constant effective stress, a creep phenomenon known as secondary  
90 compression<sup>24,25</sup>. A similar behaviour has been observed with reservoir sands<sup>26</sup> and shales<sup>27</sup> loaded to high effective  
91 stresses. Chang et al.<sup>20</sup> studied the subsidence history of onshore gas fields by summing the elastic subsidence of a disc-  
92 shaped reservoir (evaluated according to Geertsma<sup>11</sup>) to the compaction of the shale layers surrounding the reservoir. The  
93 hydraulic behaviour of the shales was modelled with the one-dimensional diffusion equation whereas the mechanical  
94 behaviour was modelled with a one-dimensional viscoplastic law. Notwithstanding the simplifying assumptions,  
95 introduced both with respect to the geometry and the hydro-mechanical behaviour, they obtained a good qualitative match  
96 of the subsidence history, suggesting that creep and delayed depressurization of shales are key aspects to be taken into  
97 account for the improvement of subsidence predictions (see also Ref. 28).

98 This paper aims at discussing the impact of the time-dependent behaviour of reservoir sands on the subsidence of gas  
99 fields. After briefly introducing some elasto-viscoplastic models of use for soils and rocks, the main results of a laboratory  
100 investigation on the time-dependent behaviour of sands from two reservoirs of the Adriatic basin are provided. The

101 adequacy of the elasto-viscoplastic model of Vermeer and Neher<sup>29</sup> (VNM in the following) in reproducing the laboratory  
102 results is discussed, justifying its implementation into a commercial FE code. Laboratory tests served also to determine  
103 the VNM parameters to be used for the numerical simulations of the subsidence of the two fields. The pressure history  
104 and related compaction of clay layers were taken into account in the simulations where appropriate. Model predictions  
105 are finally compared to real field data, based upon the extensive subsidence and compaction monitoring campaigns  
106 performed.

107

## 108 **2. Elasto-viscoplastic models for soils and reservoir rocks**

109 Several models have been formulated in past years to reproduce the time-dependent behaviour of soils and rocks (see e.g.  
110 Ref. 30) and both viscoelastic and viscoplastic relationships have been proposed. Elasto-plastic laws with volumetric  
111 hardening are currently used by the oil industry for geomechanical simulations. Elasto-viscoplastic models can be seen  
112 as an enhancement of elasto-plastic ones. It is then of interest to check their performance in subsidence prediction, since  
113 they might ensure an improvement in the cases where the ones obtained using elasto-plasticity are not accurate enough.

114 A brief description of the families of constitutive models which enhance hardening plasticity to account for time-  
115 dependent behaviour, with special reference to elasto-viscoplastic models with volumetric hardening, is given below.  
116 These models share the assumption that the total strain can be decomposed into the sum of an elastic and of a viscoplastic  
117 component:

$$118 \quad \boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^{vp} \quad (1)$$

119 where  $\boldsymbol{\varepsilon}$  is the small strain tensor, while  $\boldsymbol{\varepsilon}^e$  and  $\boldsymbol{\varepsilon}^{vp}$  are its elastic and viscoplastic components.

120 The elastic strains are time independent and they are related to stress increments through some generalized Hooke's law.  
121 Viscoplastic strains are time-dependent, and they are usually evaluated either in the frame of the theory of the Non  
122 Stationary Flow Surface (NSFS) or in the frame of the Overstress Theory.

123

### 124 *2.1 Models formulated in the frame of the Non Stationary Flow Surface*

125 The theory of the Non Stationary Flow Surface has been originally developed by Naghdi and Murch<sup>31</sup> and by Olszak and  
126 Perzyna<sup>32</sup> and it is based on the assumption that the yield surface evolves with time, even when the stress is constant.

127 In volumetric hardening plasticity, the yield function has the expression:

128 
$$f = f(\boldsymbol{\sigma}', p'_c(\boldsymbol{\varepsilon}^p, \gamma)) \quad (2)$$

129 where  $\boldsymbol{\sigma}'$  is the effective stress tensor and  $p'_c$  is the hardening parameter, related to the plastic strain tensor  $\boldsymbol{\varepsilon}^p$  and, where  
 130 required, to other variables  $\gamma$  accounting for effects such as grain bonding, saturation, temperature, chemical composition  
 131 of the pore fluid, etc. In the NSFS models, the yield function depends on the same variables used in elastic-hardening  
 132 models, but it also depends on some time-dependent function  $\beta$ :

133 
$$f = f(\boldsymbol{\sigma}', p'_c(\boldsymbol{\varepsilon}^{vp}, \gamma), \beta) \quad (3)$$

134 The effect of time is often introduced through the viscoplastic strain rate  $\dot{\boldsymbol{\varepsilon}}^{vp}$  and specifically imposing that the hardening  
 135 parameter depends both on the viscoplastic strain and on the viscoplastic strain rate:

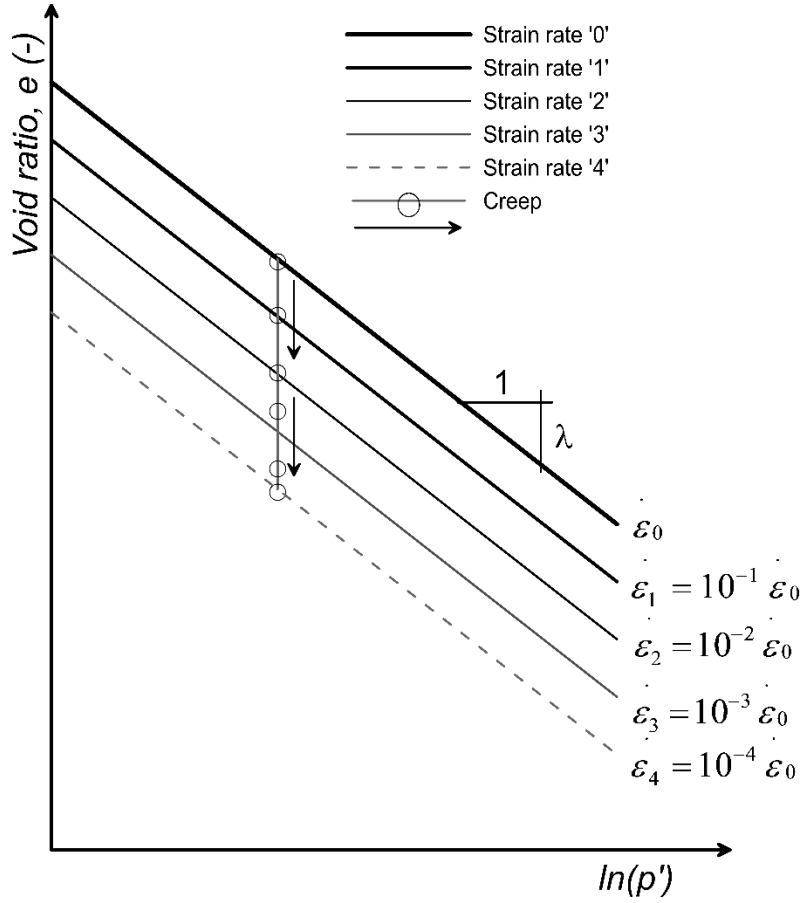
136 
$$p'_c = p'_c(\boldsymbol{\varepsilon}^{vp}, \dot{\boldsymbol{\varepsilon}}^{vp}, \gamma) \quad (4)$$

137 Equation 4 is consistent with the isotach concept proposed by Šuklje<sup>33</sup>, which states that the state of a volume of soil can  
 138 be described by a single  $(p', e, \dot{e})$  relationship, where  $p'$  is the mean effective stress,  $e$  and  $\dot{e}$  are the void ratio and the  
 139 rate at which it changes. Under the hypothesis of incompressible solid grains, the volume strain is

140 
$$\varepsilon_v = -\frac{\Delta e}{1+e_0} \quad (5)$$

141 where  $\Delta e$  is the change in void ratio and  $e_0$  is the void ratio at some reference conditions. The isotach concept implies  
 142 then that the position of the Normal Compression Line (describing first time compression of the soil volume) in the  
 143 compression plane  $(p', e)$  depends on the applied strain rate: first time compressions at different strain rates are described  
 144 by different Normal Compression Lines. During a creep phase, the stress remains constant and the strains increase but  
 145 their velocity decreases with time. Therefore, as remarked by De Gennaro and Pereira<sup>34</sup> “soils may experience both  
 146 compression under constant strain rate (i.e. following a rate-line) or delayed compression under sustained constant load  
 147 (i.e. decreasing the strain rate and crossing multiple rate-lines)” (see Fig. 1). The yield stress increases then with the strain  
 148 rate (see e.g. Ref. 35).

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**Fig. 1.** Isotach concept: Normal Compression Lines at different constant strain rates are parallel lines on the

compression plane. During a creep process the stress remains constant while the volume decreases at decreasing rates,

thus crossing the NCL of different strain rates

de Waal and Smits<sup>36</sup> presented results of one-dimensional compression of sandstones, interpreted with a stress rate

dependent model, which have been also reproduced with a strain rate NSFS model by Cassiani et al.<sup>37</sup>. By introducing

the assumptions of eq. (4) into eq. (3), it follows:

$$f = f(\sigma', p'_c(\epsilon^{vp}, \dot{\epsilon}^{vp}, \gamma)) \quad (6)$$

The yield function  $f$  of the Modified Cam Clay Model:

$$f = q^2 - M^2 p'(p'_c - p') \quad (7)$$

is usually adopted (see e.g. Refs 37-38). In (7)  $q$  is the deviatoric stress and  $M$  the slope of the critical state line in the  $p', q$

plane:

$$p' = \frac{1}{3} \sigma'_{ii}, \quad q = \sqrt{3} \sqrt{J_2}, \quad J_2 = \frac{1}{2} s_{ij} s_{ij}, \quad s_{ij} = \sigma'_{ij} - p' \delta_{ij}, \quad M = \frac{6 \sin \phi'_{cv}}{3 - \sin \phi'_{cv}} \quad (8)$$

163 with  $\phi'_{cv}$  friction angle at constant volume conditions.

164 A NSFS model for unsaturated conditions, relying of the yield and plastic potential functions of the Barcelona Basic  
165 Model<sup>39</sup>, is discussed in Ref. 34.

166 The infinitesimal increment of viscoplastic strains  $d\boldsymbol{\varepsilon}^{vp}$  is given by:

$$167 \quad d\boldsymbol{\varepsilon}^{vp} = \Lambda \frac{\partial g}{\partial \boldsymbol{\sigma}'_c} \quad (9)$$

168 where  $g$  is the plastic potential function and  $\Lambda$  the plastic multiplier. As in hardening plasticity, the stress state is not  
169 allowed outside of the yield surface and the constraint  $f \leq 0$  applies. Very often an associated flow rule is assumed and  
170  $f = g$ .

171 The value of  $\Lambda$  is then determined by introducing eq. (9) into the consistency condition  $df=0$ :

$$172 \quad df = \frac{\partial f}{\partial \boldsymbol{\sigma}'_c} : d\boldsymbol{\sigma}'_c + \frac{\partial f}{\partial \alpha} d\alpha + \frac{\partial f}{\partial p'_c} \left( \frac{\partial p'_c}{\partial \varepsilon_v^{vp}} d\varepsilon_v^{vp} + \frac{\partial p'_c}{\partial \dot{\varepsilon}_v} d\dot{\varepsilon}_v \right) = 0 \quad (10)$$

173 In eq. (10), the two hardening mechanisms are made evident. The first one is related to the magnitude of the viscoplastic  
174 volume strain, and it is usually assumed to be the same of the Modified Cam Clay Model:

$$175 \quad \frac{\partial p'_c}{\partial \varepsilon_v^{vp}} = \frac{1+e_0}{\lambda-\kappa} p'_c \quad (11)$$

176 where  $\lambda$  is the elasto-viscoplastic logarithmic compliance and  $\kappa$  is the elastic logarithmic compliance, defined in terms of  
177 void ratio. The second hardening mechanism is related to the strain rate, which is usually expressed by a power law  
178 relating  $p'_c$  to  $\dot{\varepsilon}_v$ .

179

## 180 *2.2 Models formulated in the frame of the Overstress Theory*

181 The Overstress Theory was originally developed by Malvern<sup>40</sup> for one-dimensional conditions and extended to the three-  
182 dimensional case by Perzyna<sup>41,42</sup> and Olszak and Perzyna<sup>32</sup>. It requires a static yield surface  $f_s$ , which separates the non-  
183 viscous regime from the viscoplastic regime, thus defining the size of the purely elastic domain, and a dynamic loading  
184 surface  $f_d$ , related to the current stress state. The Overstress Theory aims at predicting the strain rates, decomposed into  
185 elastic and viscoplastic components:

$$186 \quad \dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^e + \dot{\boldsymbol{\varepsilon}}^{vp} \quad (12)$$

187 The stress state can be within, on, or outside the static yield surface  $f_s$  and the consistency condition does not apply. The  
 188 viscoplastic strain rate  $\dot{\epsilon}^{vp}$  is then given by a flow rule with respect to the dynamic loading surface  $f_d$ :

189 
$$\dot{\epsilon}^{vp} = \mu \langle \phi(F) \rangle \frac{\partial f_d}{\partial \sigma'} \quad (13)$$

190 where  $\mu$  is a fluidity parameter and  $\phi(F)$  is the overstress function, expressing the distance between  $f_d$  and  $f_s$ . According  
 191 to the original Overstress Theory:

192 
$$\langle \phi(F) \rangle = \begin{cases} 0 & \text{if } F \leq 0 \\ \phi(F) & \text{if } F > 0 \end{cases} \quad (14)$$

193 with  $F > 0$ ,  $F < 0$ , and  $F = 0$  when the state of stress  $P$  is outside, within, or on  $f_s$ <sup>30</sup>.

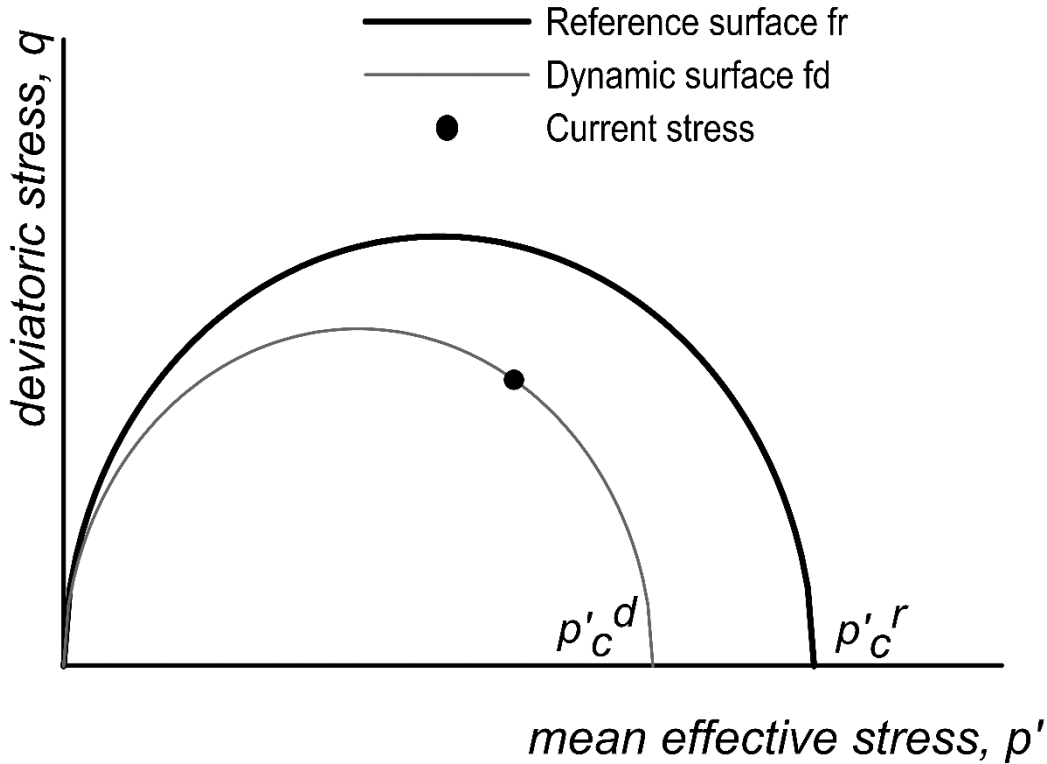
194 Determination of the static yield surface is problematic: experimental studies generally remarked the dependency of the  
 195 yield stress on the strain (or loading) rate, but there are no experimental data proving the existence of a threshold rate  
 196 below which the yield surface does not depend on the rate anymore<sup>43</sup>. To overcome this issue, recent models ('Extended  
 197 Overstress Theory') adopt a reference yield surface  $f_r$  (Fig. 2) instead of the static yield surface  $f_s$ , and viscoplastic strains  
 198 are anticipated also for  $F < 0$ <sup>29,44-46</sup>. Equation (12) is then replaced by expressions such as<sup>41</sup>:

199 
$$\dot{\epsilon}^{vp} = \mu \left\langle \left( \frac{p'_c}{p'_c^d} \right)^N \right\rangle \frac{\partial f_d}{\partial \sigma'} \quad (15)$$

200 where  $\left( \frac{p'_c}{p'_c^d} \right)$  is the ratio the of intercepts of the two yield surfaces with the  $p'$  axis and  $N$  is a material parameter, or a  
 201 combination of material parameters. As it can be appreciated through eq. 15, the reference yield surface is associated to  
 202 a reference strain rate.

203 The size of the reference yield surface, and therefore the value of  $p'_c$ , only depends on the viscoplastic strains.  
 204 Accordingly, the evolution of  $p'_c$  is governed by the hardening rule of the reference hardening plasticity model, which  
 205 is usually given by an expression such as eq. (11).

206



207

208

**Fig. 2.** Dynamic and reference surfaces. Depending on the current stress state, the dynamic surface can either be smaller or bigger than the reference surface.

209

210

211

212 *2.3 Vermeer and Neher Model*

213 ‘Creep models’ are models of the Extended Overstress Theory built on experimental evidences gathered at constant  
 214 effective stress (creep tests)<sup>43</sup>. The isotropic models described in Refs. 29 and 44 and the anisotropic model of Leoni et  
 215 al.<sup>47</sup> are all ‘creep models’. The formulation of the VNM<sup>29</sup> takes advantage of the results of standard oedometer tests,  
 216 where the axial stress is increased stepwise and maintained constant for at least 24 hours. In such conditions, after pore  
 217 pressure dissipation and consolidation, a creep phase takes place. When the applied stress is high enough, the viscoplastic  
 218 strains grow linearly with the logarithm of time, and a creep index  $\mu^*$  can be defined as:

219

$$\mu^* = \frac{\Delta \varepsilon_v^{vp}}{\Delta \ln(t)} \quad (16)$$

220 where  $\Delta \varepsilon_v^{vp}$  is the increase in the viscoplastic volume strain and  $t$  is time. By writing the viscoplastic volume strain at time  
 221  $\tau = 24$  hours as  $\bar{\varepsilon}_v^{vp}$ , it follows:

222 
$$\mu^* = \frac{\varepsilon_v^{vp} - \bar{\varepsilon}_v^{vp}}{\ln(t) - \ln(\tau)} \quad (17)$$

223 so the relationship between time and viscoplastic strain is:

224 
$$\frac{t}{\tau} = \exp\left(\frac{\varepsilon_v^{vp} - \bar{\varepsilon}_v^{vp}}{\mu^*}\right) \quad (18)$$

225 The viscoplastic volumetric strain rate is then:

226 
$$\dot{\varepsilon}_v^{vp} = \frac{\mu^*}{\tau} \exp\left(\frac{\varepsilon_v^{vp} - \bar{\varepsilon}_v^{vp}}{\mu^*}\right) \quad (19)$$

227 In the VNM, the reference yield function  $f_r$  describes the state of the material which has been loaded for the reference  
 228 time  $\tau$ . However, in light of eq. 18, it is also related to a constant strain rate  $\dot{\varepsilon}_v^{vp} = \frac{\mu^*}{\tau}$ .

229 The viscoplastic volume strains occurring during a creep phase induce hardening, *i.e.* the hardening parameter  $p'_c{}^r$   
 230 evolves, with  $p'_c{}^r = p'_c{}^d$  when  $t = \tau$  and  $p'_c{}^r > p'_c{}^d$  when  $t > \tau$ . Adopting the hardening rule of the Modified Cam Clay:

231 
$$\varepsilon_v^{vp} - \bar{\varepsilon}_v^{vp} = (\lambda^* - \kappa^*) \ln\left(\frac{p'_c{}^r}{p'_c{}^d}\right) \quad (20)$$

232 with  $\lambda^* = \frac{\lambda}{1+e}$  and  $\kappa^* = \frac{\kappa}{1+e}$ . By introducing eq (20) into eq. (19) the volumetric viscoplastic strain rate can be related to  
 233 the ratio between the dynamic and the reference surfaces:

234 
$$\dot{\varepsilon}_v^{vp} = \frac{\mu^*}{\tau} \left(\frac{p'_c{}^d}{p'_c{}^r}\right)^{\frac{\lambda^* - \kappa^*}{\mu^*}} \quad (21)$$

235 Consistency between eq.(15) and eq.(21) implies  $N = \frac{\lambda^* - \kappa^*}{\mu^*}$  and  $\mu = \frac{\mu^*}{\tau \frac{\partial f}{\partial p'}}$  and the substitution that follows into eq. (15)

236 provides the full viscoplastic strain rate tensor for the VNM.

237 Eq. (21) predicts that any loading process occurring at a certain constant strain rate is characterized by a fixed  $\left(\frac{p'_c{}^d}{p'_c{}^r}\right)$  ratio.

238 Therefore Normal Compression Lines at different strain rates are expected to be parallel lines, and also the VNM is  
 239 consistent with the isotach concept. The reference yield function  $f_r$  describes then the combination of stress states for  
 240 which a Normal Consolidated type of behaviour applies whenever the load increments are imposed every 24 hours. The

241  $\left(\frac{p'_c{}^d}{p'_c{}^r}\right)$  ratio is a measure of the ‘distance’ from this state, and its inverse can be used to define an apparent Over

242 Consolidation Ratio (OCR). Differently from elasto-plastic models, the apparent OCR does not depend only on the

243 loading sequence and then on the maximum stress that had been applied. For instance, during a prolonged creep phase,  
244 the OCR grows since  $p'_c{}^d$  remains constant while  $p'_c{}^f$  increases with the accumulated viscoplastic strains, in virtue of the  
245 hardening rule (eq (11)).

246

### 247 **3. Experimental behaviour of clastic materials from the Adriatic basin and comparison with VNM** 248 **predictions**

249 A previous experimental characterization of the time-dependent behaviour of clastic materials from the Adriatic basin has  
250 been described in Ref. 48. Sandy and clayey samples were loaded in the oedometer until reaching some stress higher than  
251 the *in-situ* one, which was maintained constant for 2 weeks. Creep strains were appreciated, while when resuming the  
252 monotonic loading the compressibility of these samples was initially smaller than the one of analogous samples that had  
253 not been exposed to creep. At higher stresses, the behaviour of the two types of samples was comparable again. Some  
254 preliminary data suggested that the stress range over which the compressibility is reduced because of creep depends on  
255 the OCR and on the duration of creep. The OCR also impacted on the creep rate. These evidences are similar to the ones  
256 found for various soils or rocks (e.g. Refs. 35,36,49-53) and confirm that Adriatic sediments show appreciable viscoplastic  
257 effects, such as those that might be taken into account by the VNM through the hardening law relating the yield stress to  
258 the viscoplastic volume strains.

259 The present work, based on the results of a new comprehensive set of experimental tests, is aimed at:

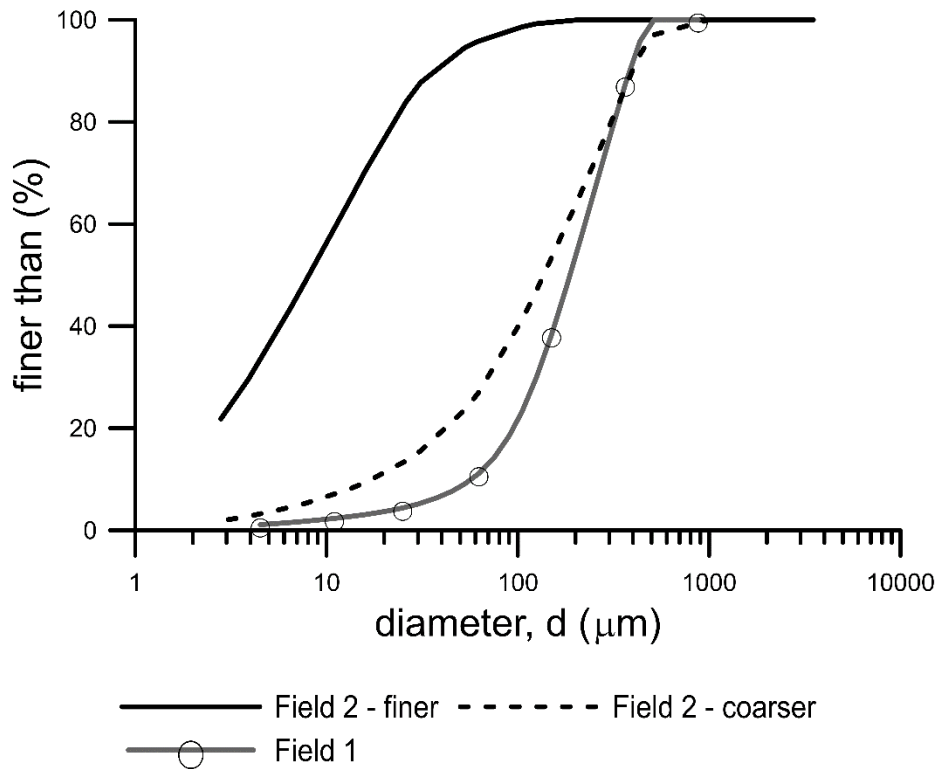
- 260 - gaining a further insight on the mechanical behaviour of the Adriatic offshore sediments, accounting for different  
261 loading histories and creep times;
- 262 - comparing the experimental findings with the results of simulations based on the VNM model;
- 263 - defining robust experimental protocols for the determination of the model parameters;
- 264 - providing the parameters for subsidence simulations for the fields of concern.

265

#### 266 *3.1 Materials*

267 The experimental study was performed on clastic samples from the reservoirs of two fields (for confidentiality reasons  
268 defined as Field 1 and Field 2 in the following), focusing on the evaluation of the viscoplastic behaviour. The grain size  
269 distribution, obtained through laser diffractometry, and the related classifications are provided in Fig. 3 and Table 1.  
270 While all the samples from the Field 1 reservoir were classified as silty sand and have about the same grain size

271 distribution, the samples from the Field 2 reservoir fall into two classes, one being a clayey silt and the other being a silty  
 272 sand.



273

274

**Fig. 3.** Grain size distributions of studied samples

275 **Table 1**

276 Grain size fractions according to British standard 5930.

	Clay ( $d < 2 \mu\text{m}$ )	Silt ( $2 \mu\text{m} \leq d < 60 \mu\text{m}$ )	Sand ( $60 \mu\text{m} \leq d < 2 \text{mm}$ )
Field 1	1	10	89
Field 2 (finer)	22	74	4
Field 2 (coarser)	2	25	73

277

278 *3.2 Testing protocols*

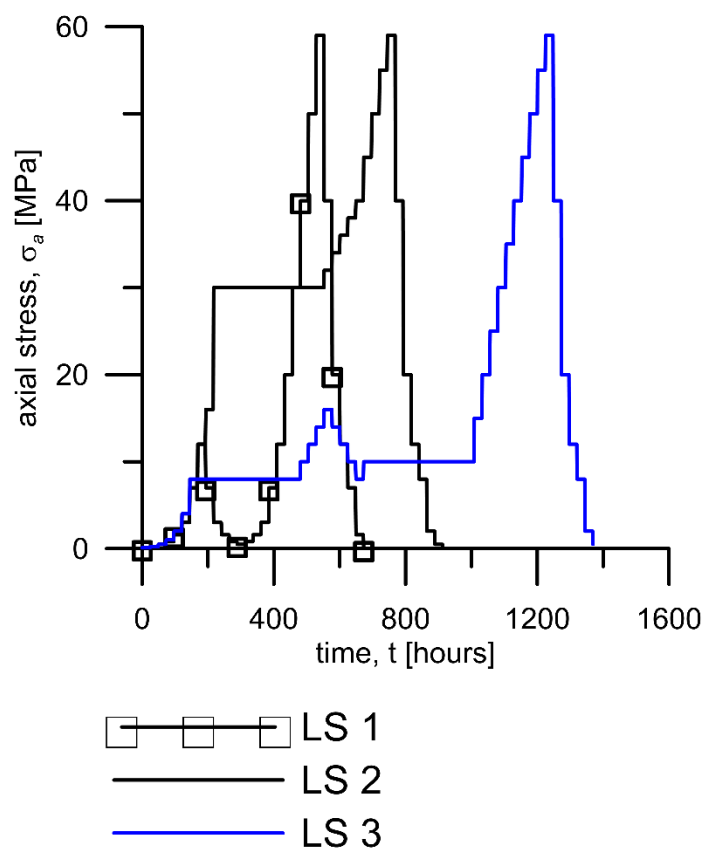
279 Samples were water saturated and tested under oedometer conditions. For each material, three different multistage step

280 Loading Sequences (LS) were adopted (Fig. 4):

281 LS 1: the axial stress  $\sigma_a$  was increased every 24 hours as in ‘conventional’ oedometric tests. No prolonged creep phases  
282 were imposed. A comparison of the results of this procedure with other sequences was made, to verify the possibility of  
283 determining the parameters of the VNM with relatively quick, standard procedures;

284 LS 2: the axial stress  $\sigma_a$  was increased every 24 hours up to a value higher than the geostatic one (equal to 10.2 MPa for  
285 Field 1 and 9.3 MPa for Field 2).  $\sigma_a$  was then kept constant for two weeks to induce a well developed secondary  
286 compression. The stress increments which followed were applied in small steps to appreciate possible hardening due to  
287 creep, detected as an increase of the apparent preconsolidation stress;

288 LS 3: the axial stress was first increased every 24 hours up to  $\sigma_a = 8$  MPa, a stress which is smaller than the geostatic  
289 one for all samples, where a first creep phase of two weeks was imposed. They were then further loaded up to 16 MPa  
290 with increments of 2 MPa imparted every 24 hours, and unloaded back to 8 MPa with the same progression. The axial  
291 stress was then increased to  $\sigma_a = 10$  MPa and a second creep phase of two weeks was imposed. A final loading – unloading  
292 cycle up to 58 MPa applying the load increments every 24 hours was then imposed. This loading sequence was aimed at  
293 checking the relevance of creep from Over Consolidated states. Since the loading history is an important information for  
294 proper modelling with the VNM, the loading – unloading sequence imposed before the creep stage at  $\sigma_a = 10$  MPa was  
295 chosen to make at least the recent history available for modelling.



296

297 **Fig. 4.** Loading sequence adopted in the multistage oedometer loading tests

298 Constant strain rate triaxial with null lateral strain tests (CRS- $K_0$ ) previously performed on dry Field 1 samples<sup>54</sup> were  
299 also reinterpreted. In these tests, the axial stress was first increased at a constant strain rate up to  $\sigma_a = 15$  MPa, and it was  
300 then kept constant while recording the creep strains. Subsequently, loading and unloading were applied by imposing again  
301 constant strain rates.

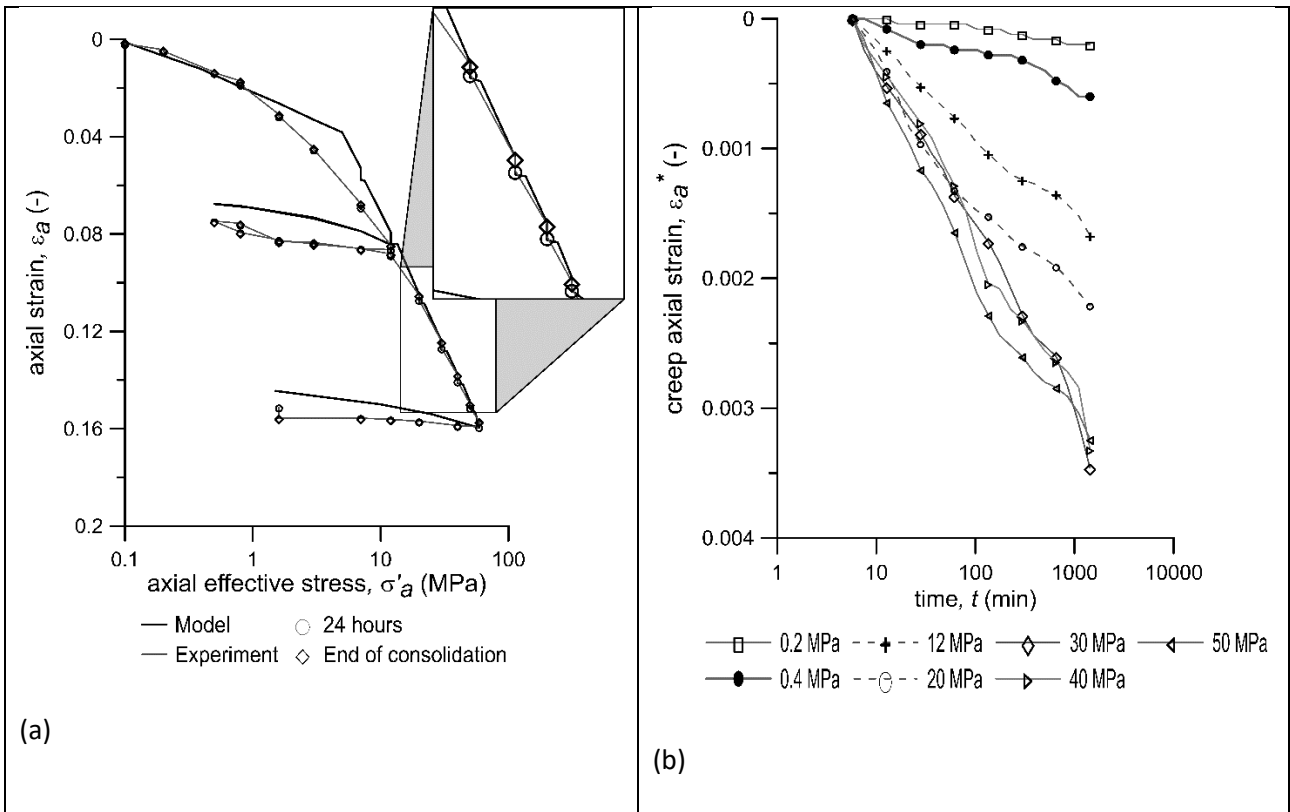
### 302 3.3 Experimental results and model predictions

303 This section presents the results of laboratory tests together with the predictions of the numerical modelling performed  
304 using the VNM model. The same type of mechanical response was obtained with all the materials and the discussion is  
305 here limited to the Field 2 samples. In the simulations the specimens were treated as a reference elementary volume, eq.  
306 (15) was discretized in time and solved numerically with the software Matlab<sup>®</sup>. The numerical implementation was done  
307 accounting for the constraints of null radial and circumferential strains which hold in oedometer conditions. In the LS  
308 tests the axial stress was increased by steps and the saturated samples also experienced mechanical consolidation, which  
309 according to the interpretation in the frame of the Terzaghi's one-dimensional equation occurred within 10 minutes from  
310 each load increase. Consistently, the experimental creep strains, labeled as  $\varepsilon_a^*$  in the following, are determined as the  
311 difference between the current axial strain  $\varepsilon_a$  and the axial strain at the end of consolidation, *i.e.* 10 minutes after imposing  
312 the load. In the numerical analyses the consolidation process was approximated by adopting load ramps of 10 minutes.

313 Fig. 5a shows the experimental stress-strain curve and the model predictions for the LS1 test. The figure provides the  
314 axial strain  $\varepsilon_a$  at the end of the consolidation and 24 hours from loading for each step. The model reproduces quite well  
315 the experimental results, in particular for stresses higher than about 12 MPa and along the unloading – reloading sequence.

316 Fig. 5b provides the time history of the creep strains  $\varepsilon_a^*$  for selected stresses.  $\varepsilon_a^*$  increases about linearly with the logarithm  
317 of time, with a rate that at first increases with the stress and becomes about constant for  $\sigma'_a \geq 30$  MPa. The slope of  $\varepsilon_a^*$   
318 vs.  $\ln(t)$  at high stresses was used to evaluate the  $\mu^*$  parameter of the VNM, while the slopes of the loading and of the  
319 unloading – reloading lines, defined for the 24 hours strains  $\bar{\varepsilon}_a$ , were used to determine  $\lambda^*$  and  $\kappa^*$ , respectively. The  
320 dependency of the experimental strain rate on the stress is in agreement with the predictions of the VNM model. According  
321 to eq. (21), the strain rate grows with the  $p'^d/p'^r$  ratio. At lower stresses the specimen is overconsolidated and this ratio  
322 is surely smaller than one, which justifies small strain rates. At high stresses the  $\left(\frac{p'^d}{p'^r}\right)$  ratio at 24 hours is equal to one  
323 which justifies identical strain rates for each step.

324



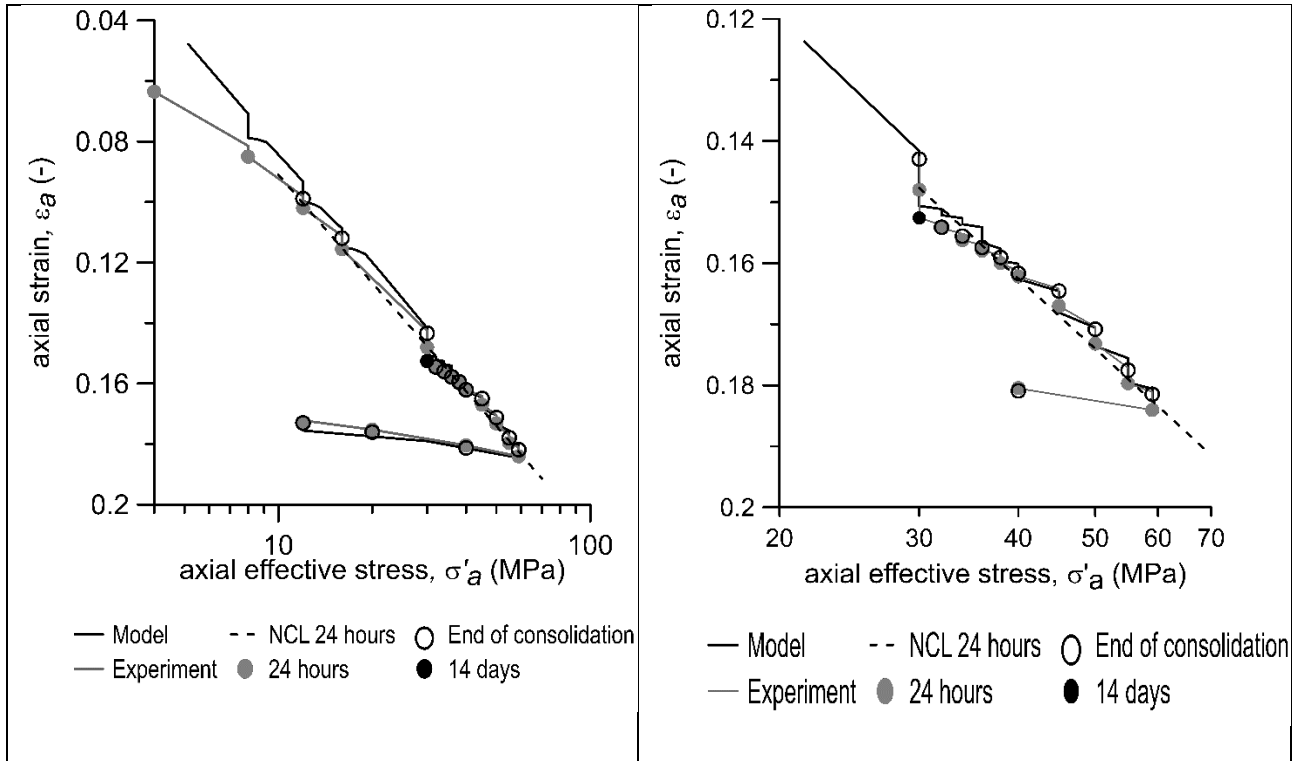
**Fig. 5.** LS1 test on coarse Field 2 sample. a) stress – strain curves. b) creep strains vs. time

325

326

327 The impact of 14 days of creep, such as the one occurring when  $\sigma_a = 30$  MPa in the LS2 tests, is shown in Fig. 6. Besides  
 328 causing larger axial strains, the long creep phase impacts on the behaviour in two ways, which become clear when the  
 329 axial stress is furtherly increased. For one, the material is stiffer than before. For another, the creep strains accumulating  
 330 during 24 hours in the following load steps are reduced with respect to the ones occurring at the stresses which precede  
 331 the long creep stage. In Fig. 6, the 24 hours creep strains are appreciated as the vertical distance between empty and grey  
 332 circles. The dashed line provides the position of the Normal Compression Line under oedometer conditions for the 24  
 333 hours strain, which gives the relationship between the axial stress on the reference surface and  $\varepsilon_a$ . After the 14 days creep,  
 334 the state of the specimen plots to the left of the NCL, justifying an apparent overconsolidation effect and the stiffer  
 335 behaviour. However, under very high stresses ( $\sigma'_a \geq 45$  MPa) the experimental points align again very well with the NCL  
 336 and the creep strains attained during 24 hours are comparable with the initial ones.

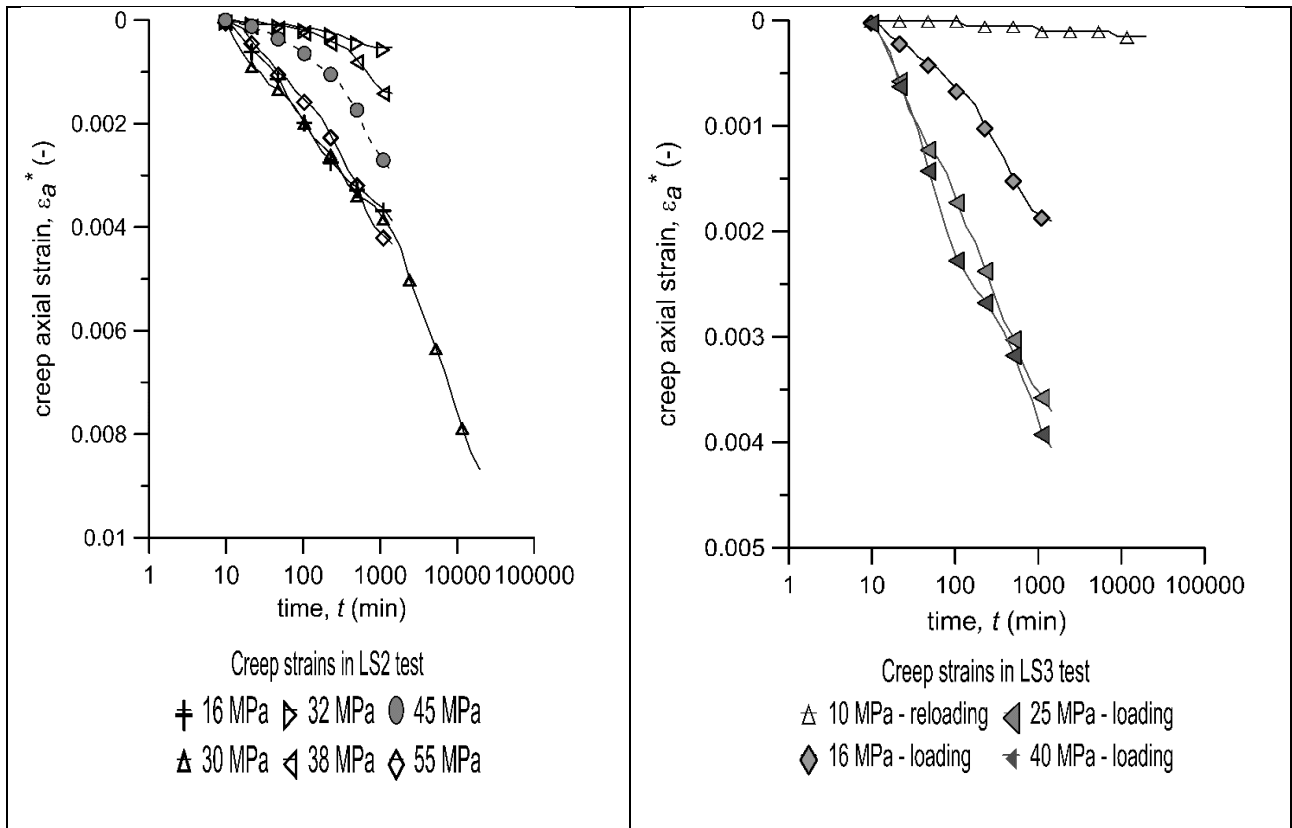
337



338 **Fig. 6.** LS2 test on coarse Field 2 sample. a) stress – strain curve, b) zoom on the hardening due to 14 days of creep

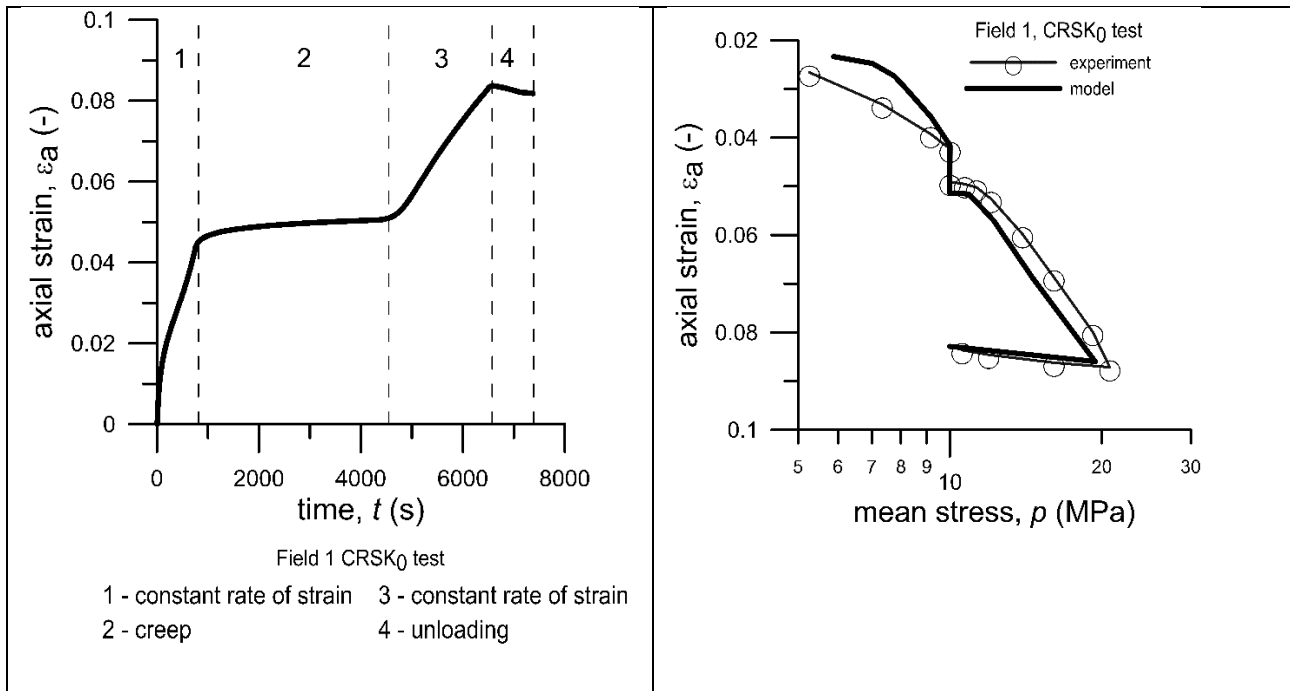
339 This effect can be further appreciated by observing the time history of the creep strains under different loads in Fig. 7a.  
 340  $\sigma'_a = 16$  MPa and  $\sigma'_a = 30$  MPa were both applied starting from a physical state which plots on the oedometer NCL, *i.e.*  
 341 with  $\frac{p'_c^d}{p'_c^r} = 1$  and consistently with eq (21) the strain rate developing under these loads is the same. However, because of  
 342 the large strains accumulating during the 14 days of creep, the loads ranging from  $\sigma'_a = 32$  MPa to 38 MPa are imparted  
 343 from physical states on the left of the NCL, *i.e.* with  $\frac{p'_c^d}{p'_c^r} < 1$ . When these loads are applied the sample has then developed  
 344 some apparent OCR, which, in light of eq. (21), justifies smaller strain rates. At higher stresses the experimental points  
 345 plot on the NCL and the previous strain rate is obtained again when  $\sigma'_a = 55$  MPa. Fig. 7b examines the effects on the  
 346 creep strains of a loading - unloading – reloading sequence (LS3 test). Following a reloading step, such as under the  $\sigma'_a$   
 347 = 10 MPa imposed for 14 days in LS3, the creep strain rate is highly reduced. However, as a first loading condition is  
 348 approached, the strain rates increases ( $\sigma'_a = 16$  MPa) and it gets to a quite constant value at higher stress ( $\sigma'_a = 25$  MPa  
 349 and  $\sigma'_a = 40$  MPa). It is interesting to note that the strain rate does not depend on the duration of the current creep phase,  
 350 as in Fig. 7a the strain rates for 16 MPa, 30 MPa and 55 MPa are all the same, so that it can be concluded that a creep  
 351 phase of 24 hours should be enough for a reliable characterization, provided that it is imparted from a condition such that  
 352  $\frac{p'_c^d}{p'_c^r} = 1$ .

353



354 **Fig. 7.** Effect of history on strain rates. a) creep strains from a monotonous loading sequence, with a long creep at  $\sigma_a^* =$   
 355 30 MPa (LS2); b) creep strains from a loading – unloading – reloading sequence (LS3).

356 Model capabilities were also checked against conditions of imposed strain rate. Fig. 8 shows the strain history (a) and the  
 357 stress – strain relationship (b) for one of the CRS- $K_0$  tests on a Field 1 sample. The hardening effect of creep is well  
 358 evident both in the experiment and in the simulations, which prove to be adequate also for the different material and  
 359 testing conditions.



**Fig. 8.** CRS-K<sub>0</sub> test on Field 1 sample. (a): strain history. (b): stress - strain curve.

360

361

362 Table 2 provides the ranges of parameter values estimated from each test, which were also used in their simulations. As  
 363 for the Field 1 case, no significant influence of testing procedure on parameters was found.

364 **Table 2**

365 Range of parameter values determined from the laboratory tests.

	$\lambda^*$ (-)	$\kappa^*$ (-)	$\mu^*$ (-)
Field 1 – step load oedometer	$6.1 \div 6.8 \cdot 10^{-2}$	$0.5 \cdot 10^{-2}$	$1.5 \div 1.7 \cdot 10^{-3}$
Field 1 – CRS-K <sub>0</sub>	$5.0 \div 6.8 \cdot 10^{-2}$	$0.7 \div 1.1 \cdot 10^{-2}$	$1.1 \div 1.5 \cdot 10^{-3}$
Field 2 – coarse	$4.8 \div 7.6 \cdot 10^{-2}$	$0.2 \div 0.8 \cdot 10^{-2}$	$0.5 \div 1.3 \cdot 10^{-3}$
Field 2 – fine	$6.8 \div 7.0 \cdot 10^{-2}$	$1.1 \div 1.2 \cdot 10^{-2}$	$1.4 \div 1.8 \cdot 10^{-3}$

366

367 **4. Case Histories**

368 The experimental campaign and related numerical simulations suggested that the VNM can provide a quite good  
 369 reproduction of the behaviour in oedometer conditions of reservoir samples from two gas fields. This section presents the  
 370 results of the studies of the real field cases for the two fields, carried out through Finite Element simulations and adopting  
 371 the VNM as described in section 2.3. As stated, the two fields are located in the northern and central portions of the

372 Adriatic Sea. In this area, gas reservoirs are generally constituted by alternances of sandy and shaly layers, deposited  
373 during the Pliocene and Pleistocene ages (Carola formation till Porto Garibaldi formation) that form multilayered systems  
374 in which every layer may have its own gas-water contact and a thickness variable from a metric scale to thin layers of  
375 few centimeters. The shaly layers are the source rocks of the biogenic gas while the trapping mechanism can be  
376 structural/mixed structural or stratigraphic type. Porosity of hydrocarbon bearing sandy layers is very variable, from very  
377 low values in thin beds environments up to more than 25% in conventional reservoirs. Gas from Adriatic Sea fields is  
378 generally withdrawn through several wells whose production is gathered toward one or more platforms per field. Most of  
379 these platforms are equipped with a continuous GPS station for the monitoring of subsidence evolution. In several fields,  
380 a well is equipped with radioactive markers for the measurements of the compaction of the reservoir rock in time<sup>6,55,56</sup>.  
381 The companies operating the gas fields are in charge of providing, and periodically updating, subsidence forecasts for  
382 each field based on detailed 3D numerical fluid-dynamic and mechanical models in order to demonstrate the  
383 environmental sustainability of their activities. The results of these models have to correctly reproduce the historical  
384 monitoring data acquired in the field: the two real cases presented in this section aim at highlighting the improvement in  
385 the accuracy of these studies achieved through the adoption of the VNM model, whose implementation in a FE code was  
386 previously tested against synthetic cases<sup>57-58</sup>.  
387 Herein, all subsidence values for each field were normalized with respect to the maximum subsidence obtained in the  
388 simulation performed with the VNM constitutive model at the GPS station location.

#### 389 *4.1 Workflow*

390 First, a 3D geological model was built starting from reflection seismics and populated with petrophysical properties from  
391 well logs and laboratory analysis of core samples. Next, the geological model was converted into a Finite Difference  
392 fluid-dynamic model of the reservoir, that evaluates the time evolution of pore pressures in the whole computational  
393 domain. Pore pressure fields at selected time steps were finally provided, in a one-way coupled framework, to the 3D  
394 finite element geomechanical model, built using the commercial software Abaqus®.

395 To correctly evaluate the evolution of the stress state above and around the reservoir and, consequently, correctly predict  
396 the evolution of land subsidence, the geomechanical model also includes the rocks surrounding the reservoir, namely the  
397 overburden, underburden and sideburden regions. The reservoir rocks were described by means of appropriate elasto-  
398 plastic or elasto-viscoplastic constitutive laws (e.g. Modified Cam-Clay - MCCM - and VNM for the present cases,  
399 whose parameters were derived from the laboratory tests described in section 3), while the rocks surrounding the reservoir  
400 were considered as linear elastic. Appropriate stress-dependent rock compressibilities were used in the fluid-dynamic  
401 model to ensure consistency with the mechanical behaviour in the geomechanical model. Because of the non linear,

402 anelastic behaviour of the reservoir rock, the geomechanical predictions depend on the initial stress state, which must be  
 403 identified adequately (see e.g. Refs. 59-60). Here it was determined as follows: the total vertical stress was obtained by  
 404 integrating the bulk density profile versus depth, while the horizontal stress was obtained combining drilling information,  
 405 stress tests and regional data when available. Boundary conditions imposed to the model prescribe null horizontal  
 406 displacements of the lateral faces and no displacement in the three directions at the bottom face. Initial geostatic  
 407 equilibrium is achieved by imposing the gravity force at the model elements. The simulations were then carried out  
 408 allowing the model to evolve, following the time variation of pore pressure values derived from the fluid-dynamic  
 409 simulation at each time step. Simulations were continued for 30 years after the end of production, in order to evaluate the  
 410 effect of pore pressure equilibration after shut down.

411 While for elasto-plastic models like the MCCM, the initial position of the yield surface, determined by the parameter  $p'_c$   
 412 in eq. (2), only depends on the maximum stress ever experienced by the material, in the case of elasto-viscoplastic models  
 413 like the VNM, the definition of the initial position of the reference yield surface, *i.e.* of  $p'_c^r$ , requires a more elaborated  
 414 approach that also takes into consideration time and strain rates. In fact, the initial viscoplastic strain rate of the model  
 415 must be consistent with the one of the material *in situ*, which in light of eq. (21) provides a constraint on the initial value  
 416 of the  $\left(\frac{p'_c^d}{p'_c^r}\right)$  ratio. For the Adriatic basin it is reasonable to assume a constant strain rate induced by the sedimentation  
 417 process, given by:

$$418 \quad \dot{\epsilon}_v^{sed} = -\frac{\Delta e}{(1+e_0)\Delta t} \quad (22)$$

419 where  $e_0$  is the void ratio at the beginning of sedimentation and  $\Delta t$  is the age of the sediments. The viscoplastic component  
 420 of the sedimentation strain rate was obtained by subtracting the elastic component from the total one, *i.e.* as  $\frac{\lambda^* - \kappa^*}{\lambda^*} \dot{\epsilon}_v^{sed}$

421 The initial value of the apparent OCR, *i.e.* the  $\left(\frac{p'_c^d}{p'_c^r}\right)$  ratio, can then be obtained by inverting eq. (21):

$$422 \quad OCR = \left(\frac{\lambda^* - \kappa^*}{\lambda^*} \frac{\tau}{\mu^*} \dot{\epsilon}_v^{sed}\right)^{-\frac{\mu^*}{\lambda^* - \kappa^*}} \quad (23)$$

#### 423 4.2 Field 1

424 Field-1 is an off-shore gas field located in the Adriatic Sea at about 20 km from the Italian coastline, with an average  
 425 water depth of about 20 m. The reservoir is included in the Lower Pliocene sequences, situated from 1000 to 2200 mssl,  
 426 characterized by an alternation of metric and plurimetric sandy, clayey and silty layers with variable proportions and  
 427 thicknesses, classified as a proximal turbidite deposit in submarine fan facies. The field is bounded by a lateral facies  
 428 variation toward north and east and by a NW-SE fault in the south west direction. Fourteen wells have been drilled in the

429 field and connected to the same production platform. A GPS station, located on the platform, was installed about 10 years  
430 after the start of production and has been recording data for more than 11 years.

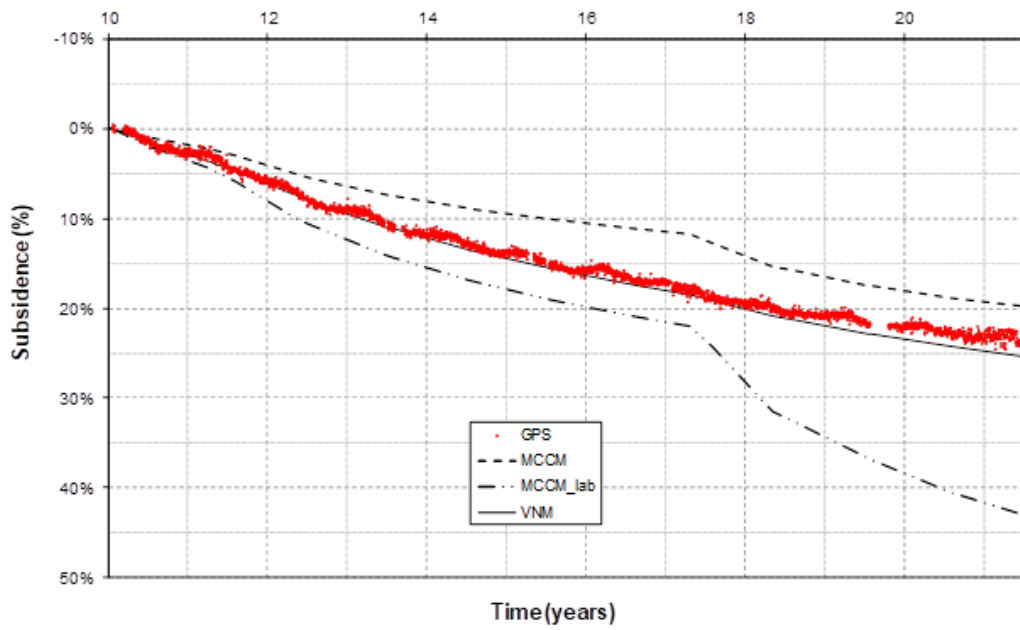
431 The FE geomechanical grid of Field 1 consists of about 300,000 cells, resulting in more than one million degrees of  
432 freedom. Subsidence induced by production was simulated with alternative constitutive laws for reservoir rocks, *i.e.*  
433 elasto-plastic (MCCM) and elasto-viscoplastic (VNM). The simulation results were then compared to the vertical  
434 displacements recorded by the GPS station. As a first attempt, the  $\lambda$  and  $\kappa$  parameters for the MCCM introduced in the  
435 simulations were imposed as the mean values determined with all the laboratory tests on Field 1 samples (Table 2). For  
436 the eleven years of GPS recording, the MCCM predictions obtained following this approach ("MCCM\_lab" in Fig. 9),  
437 are far from the GPS data. A further simulation was then performed with MCCM constitutive law, tuning  $\lambda$  and  $\kappa$   
438 parameters (assuming different values in each geological layer) in order to better reproduce the GPS data: in this case the  
439 simulated evolution of subsidence ("MCCM" curve in Fig. 9) is much closer to the GPS series, but the subsidence trend  
440 is not correctly reproduced. The simulated curves show a slope change after about 7 years from the start of GPS recording  
441 (year 10 in the figure), which is not present in the GPS data. In both the MCCM models, the subsidence velocity increases  
442 because of a fast pressure drop due to a sharp increase in production rates, which however did not impact immediately on  
443 the recorded subsidence. This suggests that an elasto-plastic model may not be appropriate to describe the behaviour of  
444 the reservoir rocks, since it instantaneously responds to pressure changes, while the role of a viscous component cannot  
445 be neglected. The elasto-viscoplastic characterization of the reservoir rock enabled to better capture the subsidence history  
446 recorded by the GPS ("VNM" curve in Fig. 9). The VNM simulations were carried out using the mean values of  $\lambda^*$  and  
447  $\kappa^*$  from the laboratory tests (Table 3), analogously to the first MCCM case, while only the creep index  $\mu^*$  was calibrated  
448 within the admissible range from the experiments. The initial value of the apparent OCR was computed through the  
449 procedure described in section 4.1 and subsequently tuned on the basis of GPS data: the age of sediments was assumed  
450 equal to 3.8 millions of years according to previous sedimentological studies, the average value of the intercept of the  
451 NCL line determined from all oedometric tests (0.74) has been considered representative of the void ratio at the beginning  
452 of sedimentation and the current void ratio has been set equal to 0.3 according to current in situ porosity. Fig. 10 shows  
453 the modelled evolution of subsidence for the three cases, during the whole time-span from the start of production to the  
454 end of the simulation.

### 455 **Table 3**

456 Adopted mechanical parameters for "MCCM\_lab" and calibrated "VNM" simulations of Field 1. All parameters are  
457 dimensionless.

$\lambda$	elasto-plastic compliance ("MCCM_lab" case)	$7.96 \cdot 10^{-2}$
$\kappa$	elastic compliance ("MCCM_lab" case)	$8.61 \cdot 10^{-3}$
$\kappa^*$	elastic compliance (strain)	$6.63 \cdot 10^{-3}$
$\nu$	Poisson's ratio	0.3
$\lambda^*$	elasto-viscoplastic compliance	$6.13 \cdot 10^{-2}$
M	CSL slope	1.33
$\mu^*$	creep index	$1.30 \cdot 10^{-3}$
OCR	apparent Over Consolidation Ratio	1.53

458

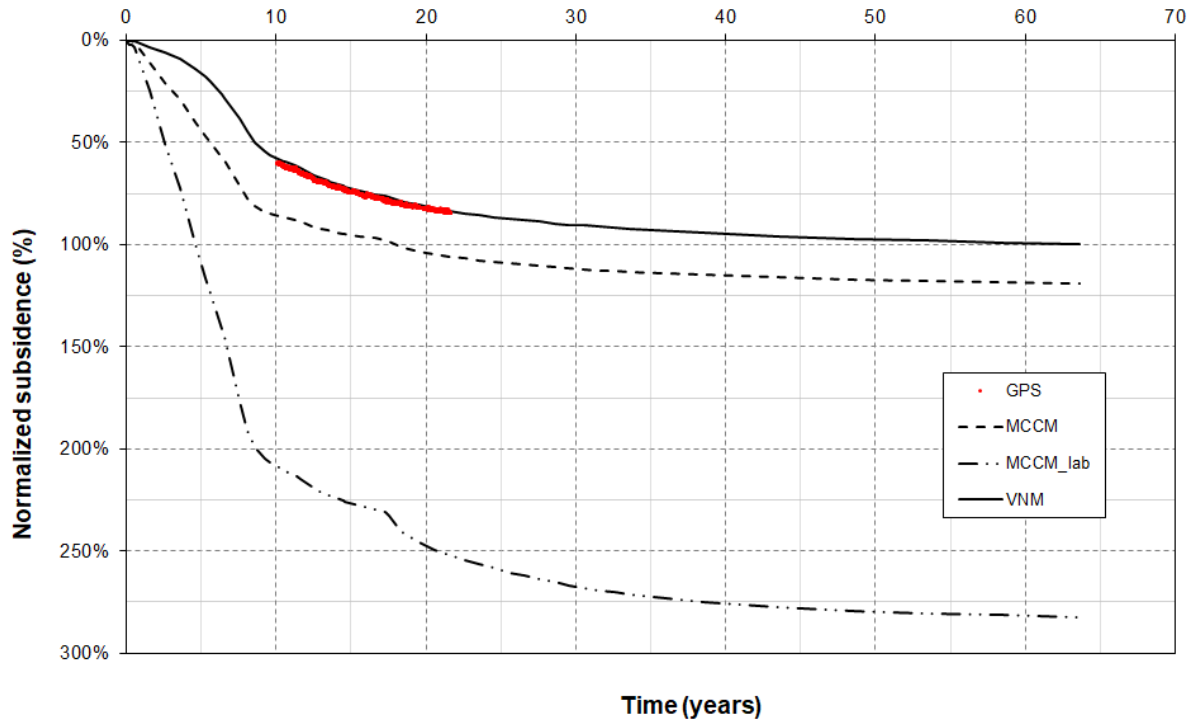


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460

**Fig. 9.** Field 1: Comparison between evolution of measured and modelled vertical displacements from start of GPS recording

461



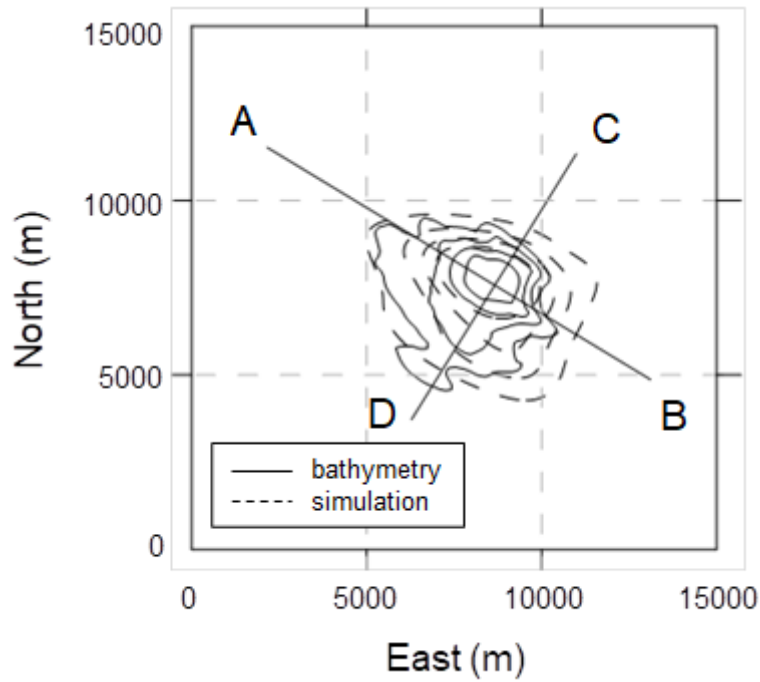
462

463 **Fig. 10.** Field 1: Evolution of modelled vertical displacement from the start of production to the end of the simulation, with  
 464 comparison with GPS series.

465

466 A bathymetric survey was carried out around 10 years after the start of production, *i.e.* approximately at the same time  
 467 when the platform was equipped with the GPS station. This survey allowed to build a map of the subsidence bowl, as the  
 468 difference between the assumed undisturbed sea bottom regional trend and the bathymetry measured by the survey. The  
 469 resulting map is shown in Fig. 11, together with the position of two sections of interest. In Fig. 11, the iso-subsidence  
 470 lines predicted with the VNM are overlaid to the measured ones.

471

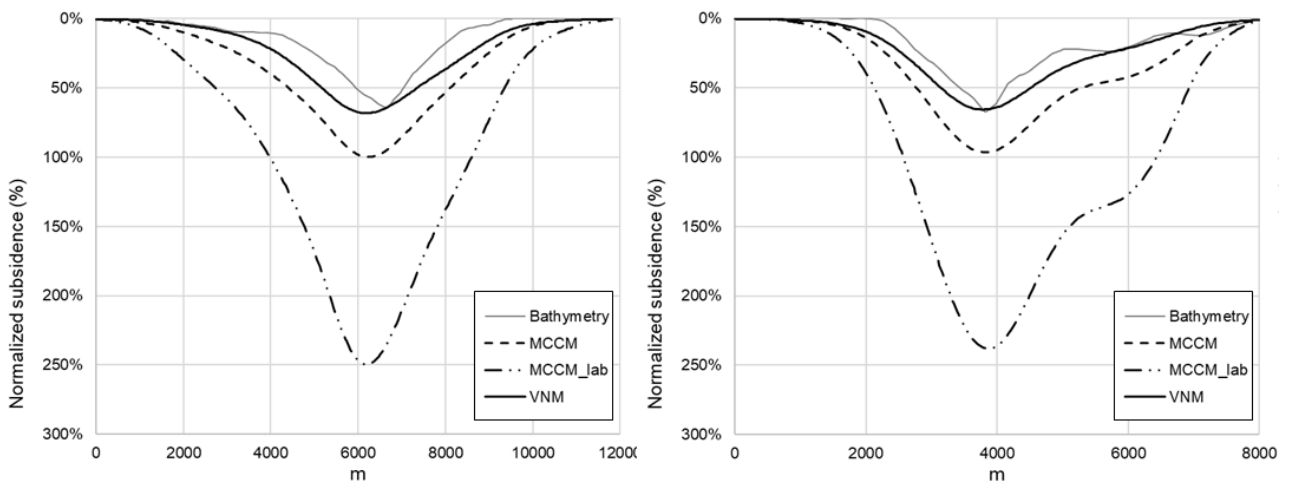


472

473 **Fig. 11.** Field 1: Subsidence from bathymetric survey and from model (contour lines 10%, 20%, 30%, 40%) and position of AB and  
 474 CD sections.

475

476 A comparison between the results of the geomechanical studies and the subsidence after the first 10 years of production,  
 477 as obtained from the bathymetric survey along the sections highlighted in Fig. 11, is shown in Fig. 12. Despite the fact  
 478 that, for the following 11 years of GPS monitoring, subsidence is overestimated by the MCCM\_lab simulation and it is  
 479 slightly underestimated by the MCCM with GPS calibrated parameters (Fig. 9), at the time of the bathymetry the two  
 480 elasto-plastic simulations are coherent in overestimating both the depth and extent of the subsidence bowl. Remarkably,  
 481 the VNM simulation is able to accurately reproduce both the depth and the extent of the subsidence bowl directly using  
 482 the laboratory derived parameters.



483

484

485 **Fig. 12.** Field 1: Subsidence from bathymetric survey and modelled subsidence along sections AB (a) and CD (b).

486

#### 487 *4.3 Field 2*

488 This off-shore gas field is located in the Adriatic Sea, at about 60 km from the Italian coastline, where the average water  
489 depth is around 60 m. Its structure is made up by an anticline with two culminations. The proximal turbiditic sand lobes  
490 of the pleistocenic Carola Formation represent the shallowest and most recent reservoir layers, while the deepest reservoir  
491 layers (pliocenic Porto Garibaldi Formation) are composed by distal turbidite sand lobes and fringes. These sandy  
492 reservoir layers lie from 900 to 1800 mssl and gas is withdrawn by 28 wells, connected to platforms A and B. The two  
493 platforms are equipped with GPS stations that have been acquiring data since the early production phases. GPS records  
494 highlight a delay between gas production rate and vertical displacement rate variations, as shown in Fig. 13 for platform  
495 B. One well of platform B has been equipped with markers for the monitoring of reservoir compaction and bathymetric  
496 surveys have been performed before the start of production of Field 2 and after 7 years.

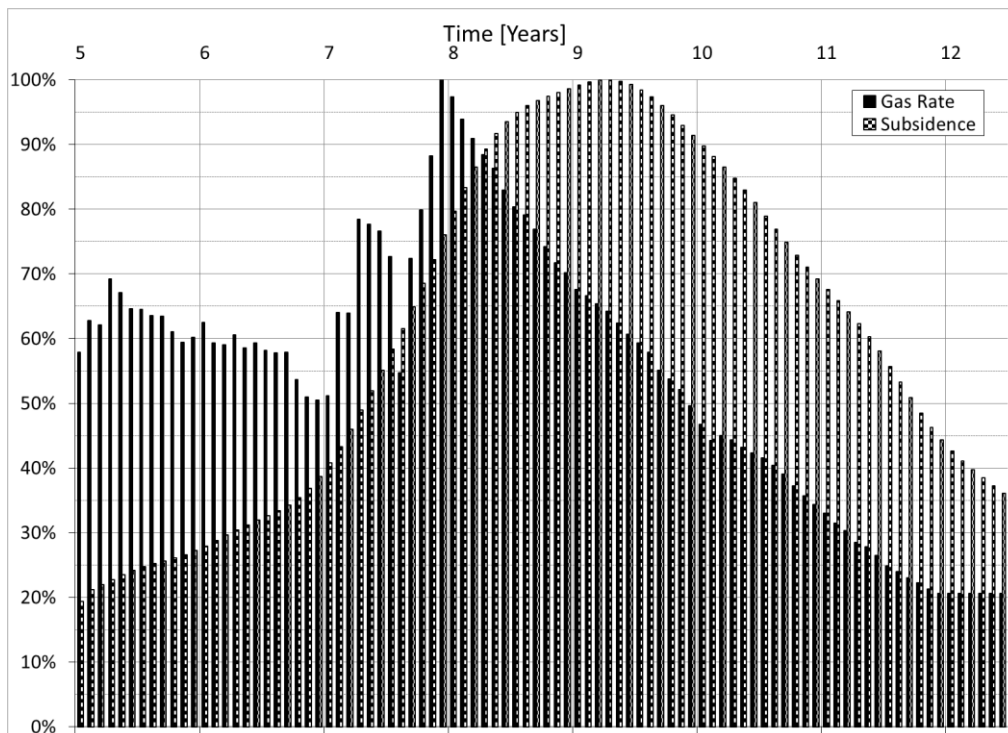
497 The simulation domain was extended to the North-East of Field 2 to include two nearby gas reservoirs that are potentially  
498 interacting hydraulically and mechanically, thus resulting in an extent of the model of about 88 km x 73 km x 5 km. The  
499 model was discretized with about  $5.5 \cdot 10^5$  finite elements, for a total of around  $2 \cdot 10^6$  degrees of freedom.

500 Initial simulations were performed with VNM material properties from average experimental values (tests described in  
501 section 3), while the initial value of the apparent OCR was defined according to the procedure proposed in section 4.1  
502 and by adopting the same hypotheses described for Field 1 case (age of sediments equal to 1.4 millions of years, void ratio  
503 at the beginning of sedimentation equal to 0.63 and current void ratio equal to 0.28). Then, a tuning of the VNM  
504 parameters allowed to accurately reproduce the GPS data recorded at platform B (Fig. 14). This step involved only minor  
505 changes of the creep index  $\mu^*$  (less than 4%) and of the apparent OCR (around 1%), while  $\lambda^*$  and  $\kappa^*$  were left unchanged  
506 (see Table 4).

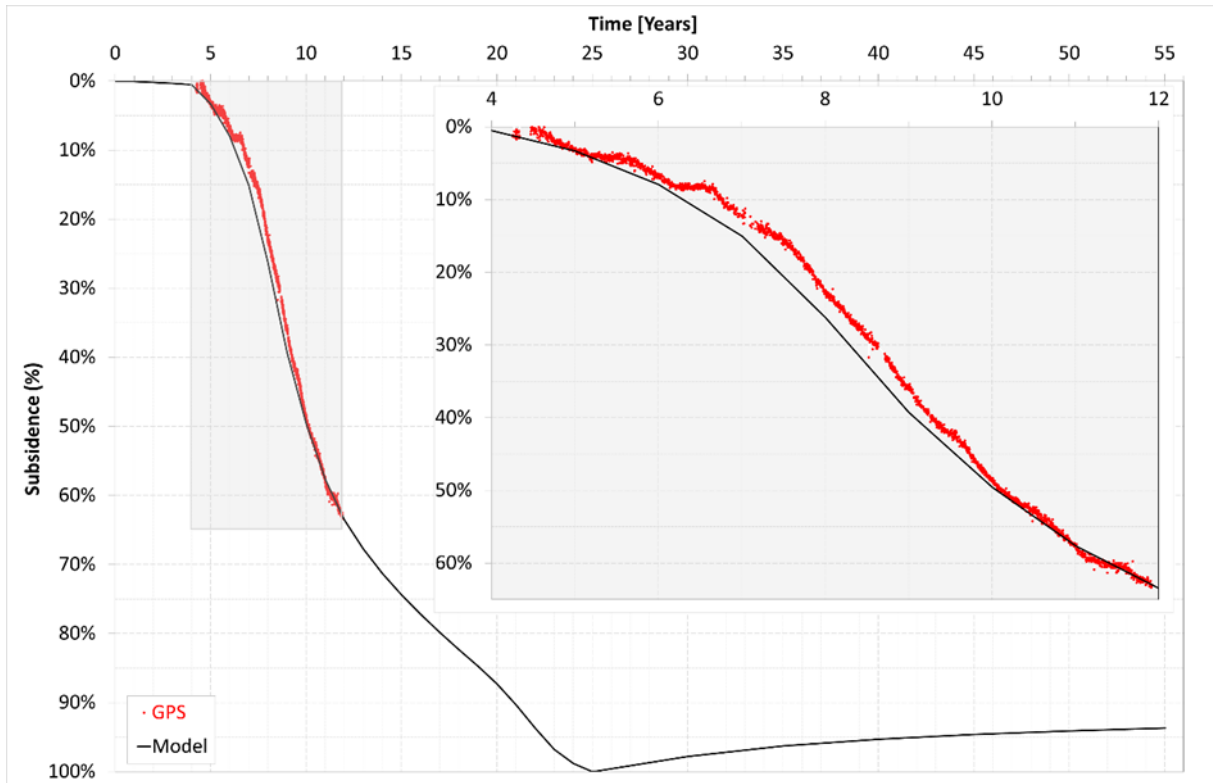
507 In Fig. 15 the results of the simulation performed with the VNM are compared to those obtained using the MCCM whose  
508 parameters ( $\lambda$  and  $\kappa$ ) are derived from laboratory experiments according to the well known expressions in section 2.3 and  
509 reported in Table 4. The OCR of the MCCM simulation was set equal to the ratio between the maximum vertical stress  
510 reasonably compatible with the tectonical and sedimentological history of the area and the current stress (OCR = 1.20) as  
511 higher values would not be justifiable. This comparison highlights that VNM is able to provide an excellent match of  
512 monitoring data by directly using laboratory derived parameters and reasonable assumption on the consolidation state of  
513 the material.

514 While GPS data from platform B were used to tune the VNM parameters, other available data (markers, bathymetry and  
515 GPS on platform A) were used to validate the geomechanical model. To this purpose, Fig.s 16 and 17 show comparisons

516 of model results in terms of reservoir compaction from markers and iso-subsidence lines from bathymetries, respectively.  
 517 In particular, Fig. 16 shows the good agreement between cumulative compaction observed at the monitoring well and the  
 518 VNM model estimates. All the measurements are reproduced within the confidence interval ( $\pm 3$  standard deviation) or  
 519 slightly overestimated, except for the measure acquired at year 11.7, which is out of trend and might be affected by  
 520 acquisition uncertainties. The subsidence developed in the 7 years between the two bathymetric surveys is well reproduced  
 521 by the model results (Fig. 17). Even if calibrated on data from platform B, the model properly reproduces also the  
 522 subsidence rate recorded at the GPS station installed on platform A (Fig. 18).  
 523 Finally, Fig. 19 shows the time evolution of the 2 cm iso-subsidence line, the minimum distance from the coastline and  
 524 the maximum extent at simulation-end, which is set 30 years after the production-end. It is apparent that the extent of the  
 525 subsidence bowl after end of production tends to stabilize with time, especially in the direction of the coastline.  
 526  
 527  
 528



529  
 530 **Fig. 13.** Monthly data for platform B: gas production rate (black bars) versus subsidence GPS rate filtered from  
 531 seasonal components (black and white bars).  
 532



533

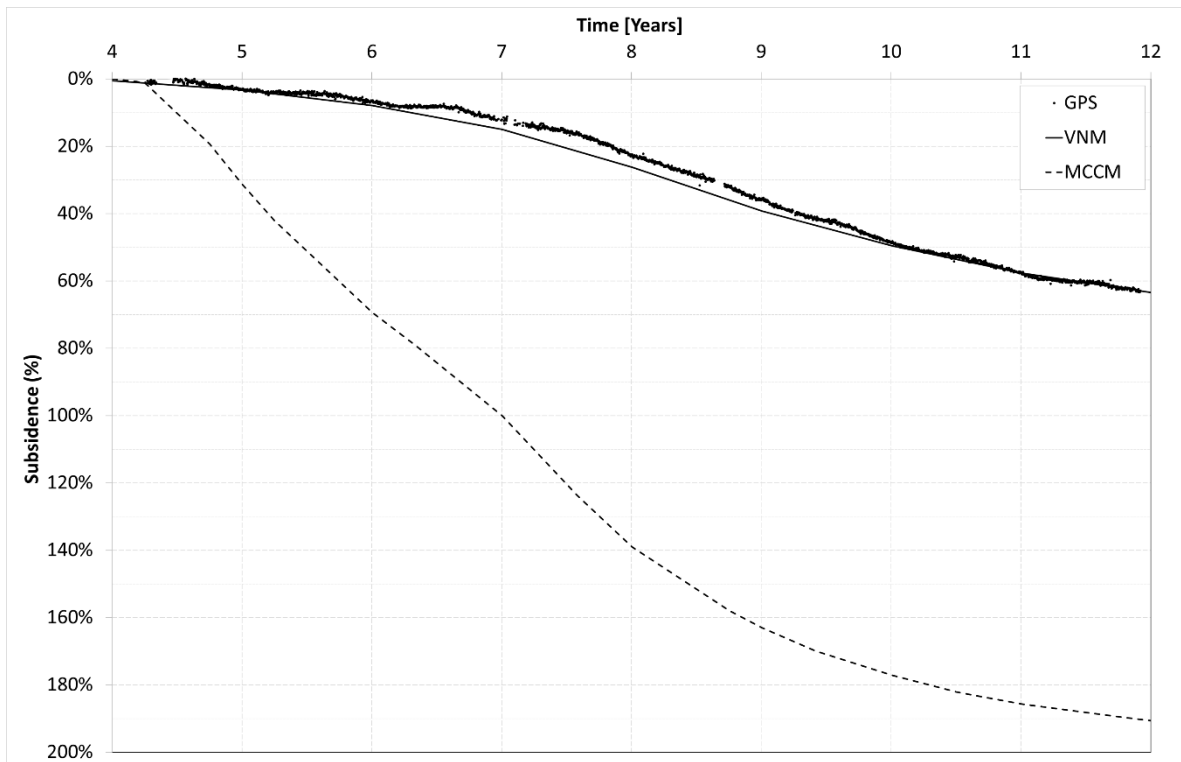
534 **Fig. 14.** Time evolution of subsidence at platform B (Field 2): GPS data versus model estimate, with magnification.

535 **Table 4**

536 Adopted mechanical parameters for “MCCM” and calibrated “VNM” simulations of Field 2. All parameters are  
 537 dimensionless.

$\lambda$	elasto-plastic compliance	$7.76 \cdot 10^{-2}$
$\kappa$	elastic compliance	$8.40 \cdot 10^{-3}$
$\kappa^*$	elastic compliance (strain)	$6.19 \cdot 10^{-3}$
$\nu$	Poisson's ratio	0.3
$\lambda^*$	elasto-viscoplastic compliance	$5.75 \cdot 10^{-2}$
$M$	CSL slope	1.33
$\mu^*$	creep index	$1.06 \cdot 10^{-3}$
OCR	apparent-OCR	1.34

538



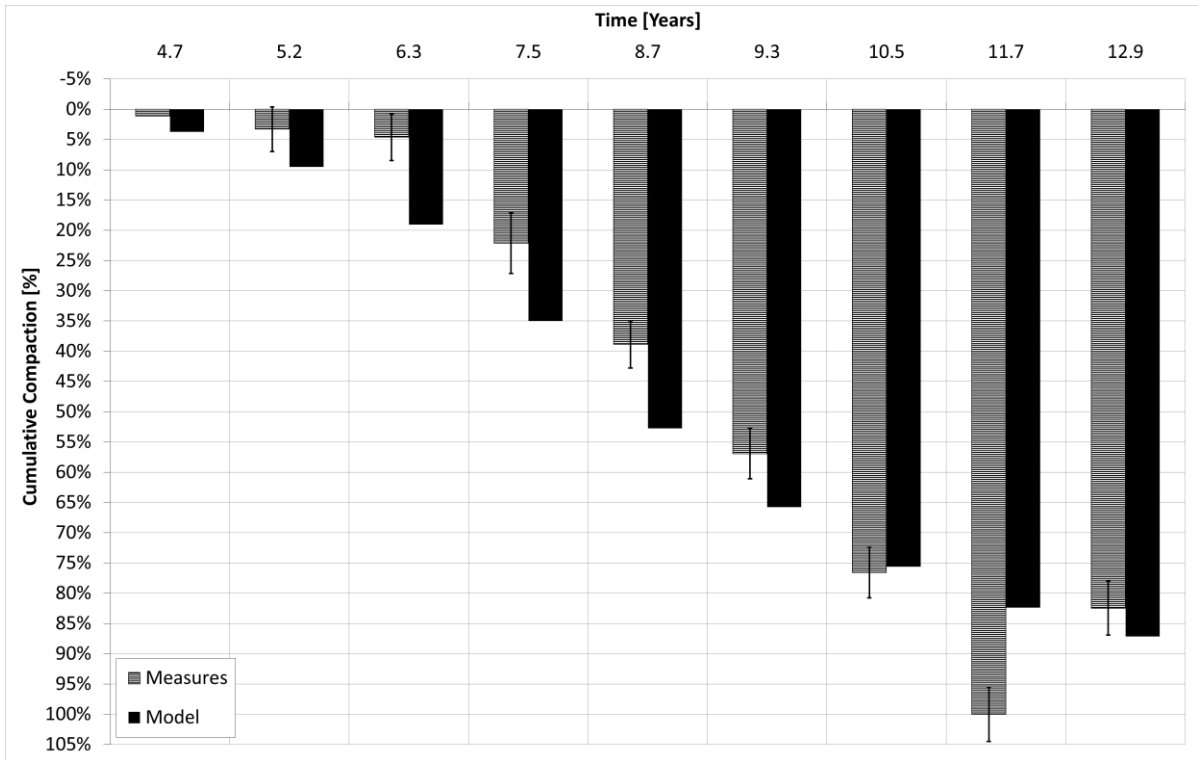
539

540 **Fig. 15.** Field 2: Comparison between evolution of measured and modelled vertical displacement in the period of GPS  
 541 recording.

542

543

544

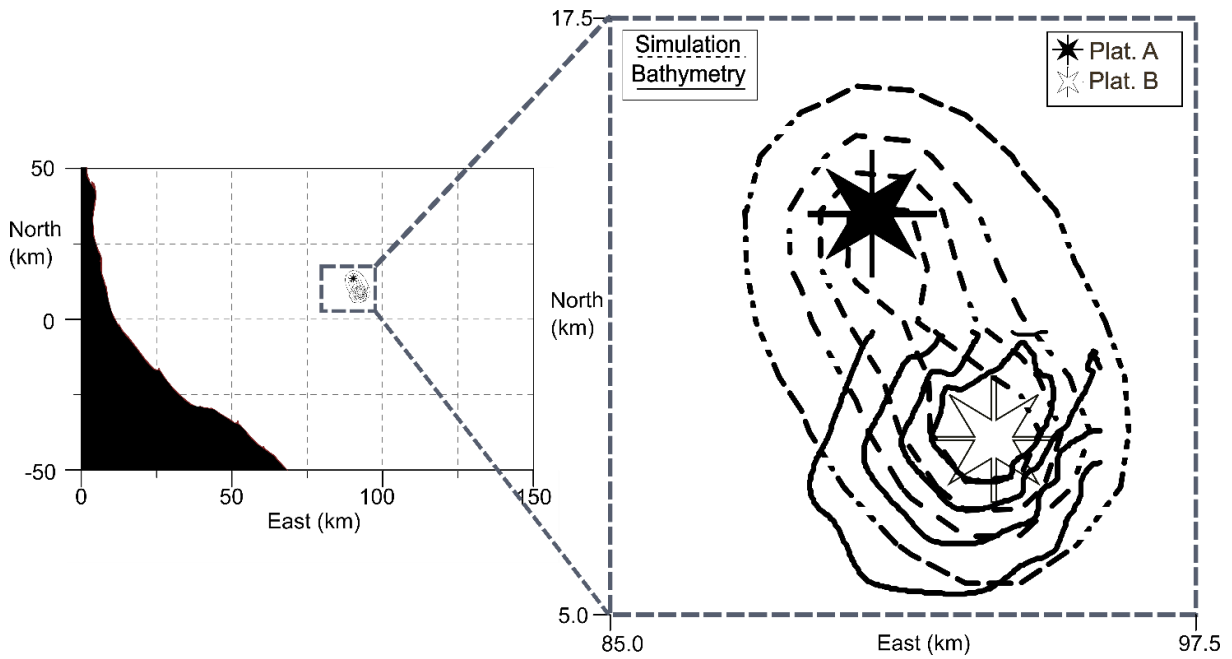


545

546 **Fig. 16.** Time evolution of compaction along the monitoring well of platform B (Field 2): markers data versus model  
 547 estimates.

547

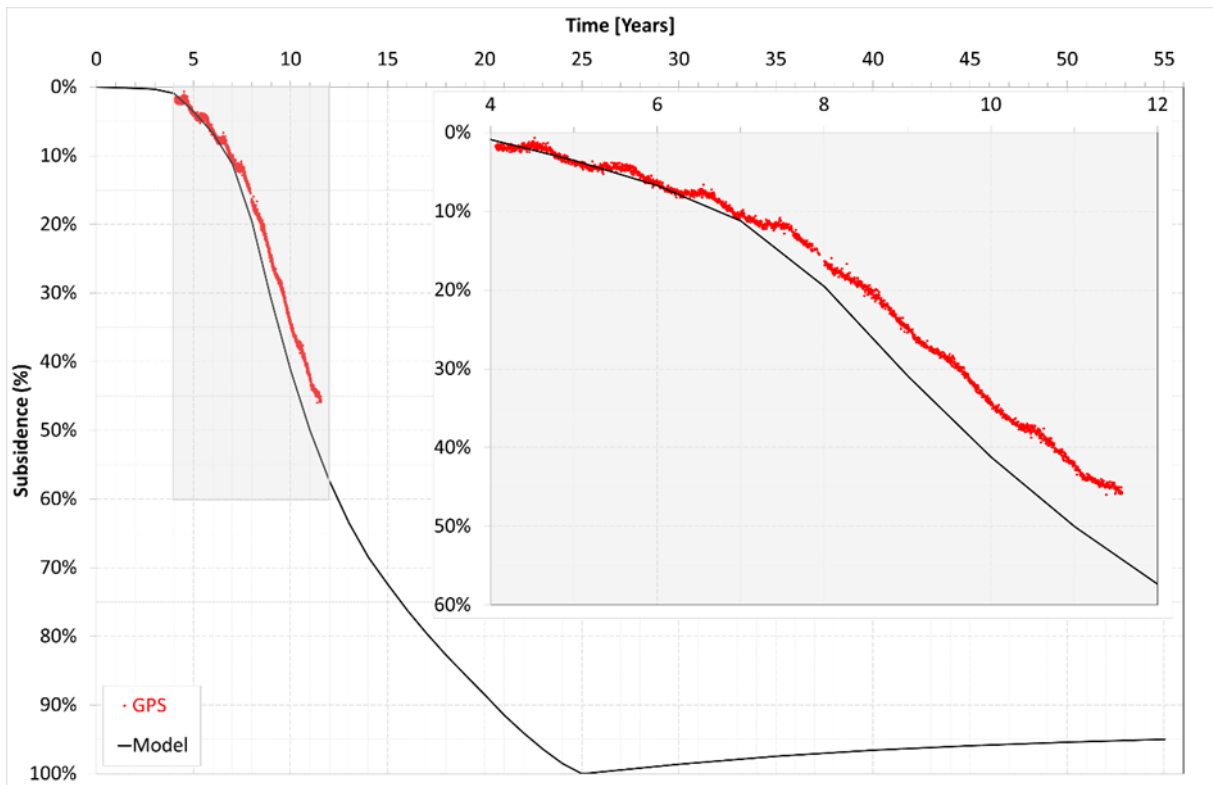
548



549

550 **Fig. 17.** Field 2: Contour lines (10%, 20%, 30% and 40%) of subsidence developed during the 7-year time interval  
 551 between the two bathymetric surveys: model estimates (dotted lines) versus measured data (solid lines).

552

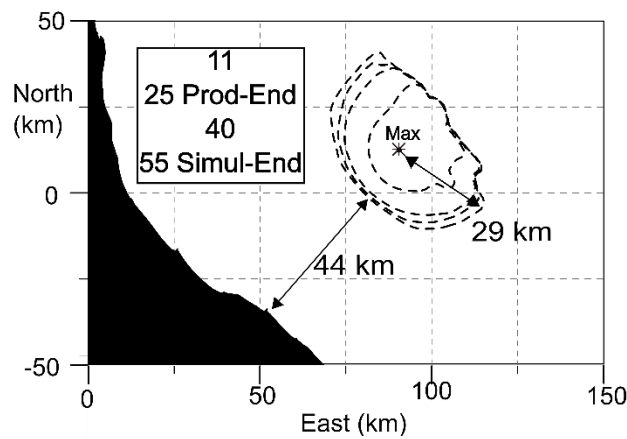


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**Fig. 18.** Time evolution of subsidence at platform A: GPS data versus model estimate, with magnification.

555



556

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**Fig. 19.** Map with time evolution (after 11, 25, 40 and 55 years from start of production) of subsidence bowl extent. At simulation end (30 years after the production-end), the subsidence bowl gets minimum distance from coastline and maximum areal extent.

559

560

561       **5. Conclusions**

562       The evaluation and prediction of subsidence induced by hydrocarbon production is a complex task that involves advanced  
563       monitoring and modeling techniques. The long time series of monitoring data currently available highlighted that, in many  
564       cases, subsidence does not respond instantaneously to variations of fluids production rates. This ‘delay’ in subsidence  
565       response could be captured by adopting ‘time dependent’ models to describe the mechanical behaviour of the geological  
566       materials. Elasto-viscoplastic laws in the frame of the Overstress Theory offer a good compromise between simplicity  
567       and accuracy when modeling time dependent behaviour. Among them, the Vermeer Neher model is of particular interest,  
568       since model parameters can be derived from standard laboratory tests. The model was exploited to simulate the results of  
569       laboratory tests done on samples of reservoir sands and silts from two gas reservoirs from the Adriatic Basin. It adequately  
570       reproduced the main experimental outcomes, such as the dependency of the creep strain rates on the apparent OCR and  
571       the reduced compressibility upon loading after creep. At regional scale, Finite Element simulations of the subsidence of  
572       the two considered fields were also run using the VNM. A very good match of the monitoring data was obtained, both in  
573       terms of maximum subsidence value and areal extent. Interestingly, this was achieved using the compliance and creep  
574       parameters directly determined in the laboratory, while the apparent OCR was defined to be consistent with the geological  
575       history of the basin.

576

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579

580       **References**

- 581       1. Dixon TH, Amelung F, Ferretti A, Novali F, Rocca F, Dokka R, et al.. Space geodesy: Subsidence and flooding  
582       in New Orleans. *Nature*. 2006; 441(7093): 587–588.
- 583       2. Chan FKS, Mitchell G, Adekola O, McDonald A. Flood risk in Asia's urban mega-deltas: Drivers, impacts and  
584       response. *Environment and Urbanization ASIA*. 2012; 3(1): 41–61.
- 585       3. Dijkema K. Impact Prognosis for Salt Marshes from Subsidence by Gas Extraction in the Wadden Sea. *Journal*  
586       *of Coastal Research*. 1997; 13, 4: 1294-1304.
- 587       4. Murria J. Subsidence Due to Oil Production in Western Venezuela: Engineering Problems and Solutions. In  
588       *Land Subsidence (Proceedings of the Fourth International Symposium on Land Subsidence, May 1991)*. 1991.  
589       IAHS Publ. no. 200:129-140.

- 590 5. Takagi H, Fujii D, Esteban M, Yi X. Effectiveness and Limitation of Coastal Dykes in Jakarta: The Need for  
591 Prioritizing Actions against Land Subsidence. *Sustainability*. 2017; 9, 619.
- 592 6. Doornhof D, Kristiansen TG, Nagel NB, Pattilo PD, Sayers C. Compaction and Subsidence. *Oilfield Review*,  
593 Autumn 2006; 50-68.
- 594 7. Sulak RM. Ekofisk field: the first 20 years. *J. of Petroleum Technology, SPE*, 43(10). 1991; SPE Paper SPE-  
595 20773-PA.
- 596 8. Fjaer E, Holt RM, Raaen AM, Risnes R, Horsrud P. *Petroleum related rock mechanics*. 2<sup>nd</sup> ed. Development in  
597 Petroleum Science, Vol. 53. Amsterdam, Holland: Elsevier; 2008.
- 598 9. Kim J, Tchelepi HA, Juanes R. Stability, Accuracy, and Efficiency of Sequential Methods for Coupled Flow and  
599 Geomechanics. Paper SPE-119084-PA. 2009.
- 600 10. Geertsma J. Problems of rock mechanics in Petroleum Production Engineering. *Proceedings of the First*  
601 *Congress of the International Society of Rock Mechanics*. 1966; 585-584
- 602 11. Geertsma J. Land Subsidence Above Compacting Oil and Gas Reservoirs. *Journal of Petroleum Technology*.  
603 1973; 25: 06.
- 604 12. Mehrabian A, Abousleiman N. Geertsma's subsidence solution extended to layered stratigraphy. *Journal of*  
605 *Petroleum Science and Engineering*. 2015; 130: 68-76.
- 606 13. Tempone P, Fjær E, Landrø M. Improved solution of displacements due to a compacting reservoir over a rigid  
607 basement. *Applied Mathematical Modelling*. 2010; 34: 3352- 3362.
- 608 14. Roscoe K, Burland JB. On the generalized stress-strain behaviour of wet clay. *Engineering Plasticity*. 1968.  
609 Cambridge Univ. Press, 535-609
- 610 15. Abdulaheem A, Zaman M, Roegiers JC. A finite-element model for Ekofisk field subsidence. *Journal of*  
611 *Petroleum Science and Engineering* 1994; 10 (4); 299-310.
- 612 16. Capasso G, Mantica S. Numerical simulation of compaction and subsidence using Abaqus. *Proc. Abaqus Users'*  
613 *Conference*, Boston (USA). 2006: 125-144.
- 614 17. Gemelli F, Monaco S, Mantica S. Modelling methodology for the analysis of subsidence induced by exploitation  
615 of gas fields. *Proc. Second EAGE Workshop on Geomechanics and Energy, Celle (Germany)*. 2015.. cp-466-  
616 00001.
- 617 18. van Thienen-Visser K, Breunese JN, Muntendam-Bos AG. Subsidence due to gas production in the Wadden  
618 Sea: How to ensure no harm will be done to nature. *49th US Rock Mechanics / Geomechanics Symposium held*  
619 *in San Francisco, CA, USA, 28 June-1 July 2015*.

- 620 19. Morton RA, Bernier JC. Recent subsidence-rate reductions in the Mississippi Delta and their geological  
621 implications. *Journal of Coastal Research*. 2010; 26, 3: 555–561.
- 622 20. Chang C, Mallman E, Zoback M. Time-dependent subsidence associated with drainage induced compaction in  
623 Gulf of Mexico shales bounding a severely depleted gas reservoir. *AAPG Bulletin*. 2014; 98, 6: 1145–1159
- 624 21. Gemelli F, Corradi A, Volonté G, Mantica S, De Simoni M. Elasto-viscoplastic modeling of subsidence above  
625 gas fields in the Adriatic Sea. *Proceedings of the International Association of Hydrological Sciences*. 2020;  
626 382:463.
- 627 22. Mossop A. An explanation for anomalous time dependent subsidence. *46th U.S. Rock Mechanics/Geomechanics*  
628 *Symposium, 24-27 June, Chicago, Illinois* 2012. Paper ARMA 2012-518
- 629 23. Hettema M, Papamichos E, Schutjens PMTM. Subsidence delay: field observations and analysis. *Oil & Gas*  
630 *Science and Technology*. 2002; 57(5): 443-458
- 631 24. Mesri G. Coefficient of secondary compression. *J. Soil Mech. Found. Div., ASCE*. 1973; 99 (1): 123-137.
- 632 25. Mesri G, Godlewski PM. Time and stress-compressibility interrelationship. *J. Geotech. Eng.* 1977; 103(5): 417-  
633 430.
- 634 26. Hagin PN, Zoback MD. Viscous deformation of unconsolidated sands – Part 1: Time-dependent deformation,  
635 frequency dispersion, and attenuation. *Geophysics*. 2004; 69, 3: 732-741.
- 636 27. Chang C, Zoback MD. Viscous creep in room-dried unconsolidated Gulf of Mexico shale (I): Experimental  
637 results. *Journal of Petroleum Science and Engineering*. 2009; 69: 239-246
- 638 28. Voyiadjis G Y, Zhou Y. Time-dependent modeling of subsidence due to drainage in bounding shales:  
639 Application to a depleted gas field in Louisiana. *Journal of Petroleum Science and Engineering*. 2018; 166: 175-  
640 187.
- 641 29. Vermeer PA, Neher HP. A soft soil model that accounts for creep. In *Proc. Int. Symp. “Beyond 2000 in*  
642 *Computational Geotechnics”*. 1999; 249-261, Balkema, Rotterdam.
- 643 30. Liingaard M, Augustesen A, Lade PV. Characterization of models for time-dependent behavior of soils. *Int.*  
644 *Journal of Geomechanics*. 2004; 4, 2: 157–177.
- 645 31. Naghdi PM, Murch SA. On the mechanical behavior of viscoelastic/plastic solids. *J. Appl. Meteorol.* 1963; 30:  
646 321–328.
- 647 32. Olszak W, Perzyna P. Stationary and nonstationary viscoplasticity. 1970. McGraw-Hill, New York.
- 648 33. Šuklje L. The analysis of the consolidation process by the isotache method. In: *Proc. 4th Int. Conf. on Soil Mech.*  
649 *and Found. Engng., London*. 1957; 1:200–6.

- 650 34. De Gennaro V, Pereira JM. A viscoplastic constitutive model for unsaturated geomaterials. *Computer and*  
651 *Geotechnics*. 2013; 54:143–51.
- 652 35. Leroueil S, Kabbaj M, Tavenas F, Bouchard R. Stress strain-strain rate relation for the compressibility of  
653 sensitive natural clays. *Géotechnique*. 1985; 35 (2): 159–180.
- 654 36. de Waal J, Smits R. Prediction of reservoir compaction and surface subsidence: field application of a new model.  
655 *SPE Form Eval*. 198; 83:347–56.
- 656 37. Cassiani G, Brovelli A, Hueckel T. A strain-rate-dependent modified Cam-Clay model for the simulation of  
657 soil/rock compaction. *Geomechanics for Energy and the Environment* 2017; 11:42-51.
- 658 38. Qiao Y, Ferrari A, Laloui L, Ding W. Nonstationary flow surface theory for modeling the viscoplastic behaviors  
659 of soils. *Computers and Geotechnics*. 2016; 76: 105-119.
- 660 39. Alonso EE, Gens A, Josa A. A constitutive model for partially saturated soils. *Géotechnique* 1990; 40(3):405–  
661 30.
- 662 40. Malvern LE. The propagation of longitudinal waves of plastic deformation in a bar of metal exhibiting a strain  
663 rate effect. *J. Appl. Mech.*. 1951; 18: 203–208.
- 664 41. Perzyna P. The constitutive equations for rate sensitive plastic materials. *Q. Appl. Math.* 1963; 20, 4: 321–332.
- 665 42. Perzyna P. Fundamental problems in viscoplasticity. *Advances in Applied Mechanics*. 1966; 9: 243–377.
- 666 43. Yin Z-Y, Chang CS, Karstunen M, Hicher PY. An anisotropic elastic–viscoplastic model for soft clays.  
667 *International Journal of Solids and Structures*. 2010; 47, 5: 665-677.
- 668 44. Kutter BL, Sathialingam N. Elastic–viscoplastic modelling of the ratedependent behaviour of clays.  
669 *Géotechnique*. 1992; 42 (3): 427–441.
- 670 45. Yin JH, Zhu JG, Graham J. A new elastic–viscoplastic model for time dependent behaviour of normally and  
671 overconsolidated clays: theory and verification. *Canadian Geotechnical Journal*. 2002; 39 (1): 157–173.
- 672 46. Hickman RJ, Gutierrez MS. Formulation of a three dimensional rate dependent constitutive model for chalk and  
673 porous rocks. *Int. J. of Numerical and Anal. Meth. in Geomechanics*. 2006; 31 (4): 583-605.
- 674 47. Leoni M, Karstunen M, Vermeer PA. Anisotropic creep model for soft soils. *Géotechnique*. 2008; 58 (3): 215–  
675 226.
- 676 48. Hueckel T, Cassiani G, Tao F, Pellegrino A, Fioravante V. Aging of oil/gas-bearing sediments, their  
677 compressibility and subsidence. *Journal of Geotechnical and Geoenvironmental Engineering*. 2001; 127, 11:  
678 926 – 938.
- 679 49. Leonards GA, Altschaeffl AG. Compressibility of clay. *J. Soil Mech. and Found. Div., ASCE*. 1964; 90(5): 133–  
680 155.

- 681 50. Bjerrum L. Embankments on soft ground. *Proc. of ASCE Spec. Conf. on Performance of earth and earth*  
682 *supported structures* 1972; 2: 1–54.
- 683 51. Bjerrum L. Problems of soil mechanics and construction on soft clays. *8th International Congress of Soil*  
684 *Mechanics and Foundation Engineering* 1973; 3: 111–159.
- 685 52. Mesri G, Feng TW, Benak JM. Postdensification penetration resistance of clean sands. *J. Geotech. Engrg.,*  
686 *ASCE*. 1990; 116(7): 1095–1115.
- 687 53. Schmertmann JH. The mechanical aging of soils. *J. Geotech. Engrg., ASCE*. 1991; 117(9): 1288–1330.
- 688 54. Brignoli M, Fanuel P, Holt RM, Kenter CJ. Effects on core quality of a bias stress applied during coring.  
689 *SPE/ISRM Eurock 98, Trondheim (Norway)*. 1998; SPE47262.
- 690 55. Pemper R, Fjell L, Gold R. Field examples with a new compaction monitoring instrument. *38<sup>th</sup> SPWLA Annual*  
691 *Logging Symposium, June 15-18, Houston, Texas*. 1997; SPWLA-1997-MM.
- 692 56. Macini P, Mesini E. Radioactive markers technique application to evaluate compaction in environmentally  
693 sensitive areas. *SPE international petroleum conference and exhibition. February 10-12, Villahermosa, Mexico*.  
694 2002; SPE74411.
- 695 57. Nguyen SK, Volonté G, Musso G, Brignoli M, Gemelli F, Mantica S. Implementation of an elasto-viscoplastic  
696 constitutive law in Abaqus/Standard for an improved characterization of rock materials. *Abaqus Users’*  
697 *Conference, Boston (USA), Natural Resources*. 2016; 710: 710–724.
- 698 58. Cremonesi M, Ghisi A, Perego U, Corradi A, Gemelli F, Mantica S. A Numerical Study on Explicit vs Implicit  
699 Time Integration of the Vermeer-Neher Constitutive Model. In: Carcaterra A, Paolone A, Graziani G, eds.  
700 *Proceedings of XXIV AIMETA Conference 2019*. AIMETA 2019.
- 701 59. Della Vecchia G, Pandolfi A, Musso G, Capasso G. An analytical expression for the determination of in situ  
702 stress state from borehole data accounting for breakout size. *International Journal of Rock Mechanics and*  
703 *Mining Sciences*. 2014; 66, 64-68, ISSN 1365-1609.
- 704 60. Scelsi G, De Bellis ML, Pandolfi A, Musso G, Della Vecchia G. A step-by-step analytical procedure to estimate  
705 the in-situ stress state from borehole data. *Journal of Petroleum Science and Engineering*. 2019; 176: 994-1007.