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## ► To cite this version:

Guillaume Modeste, Frédéric Masson, Cécile Doubre, François Cornet. Repeated lidar acquisitions in an underground salt gallery in the Alsatian potassic basin (France): Monitoring and geomechanical modelling. *Tunnelling and Underground Space Technology*, 2022, 123, pp.104406. 10.1016/j.tust.2022.104406 . hal-04723638

**HAL Id: hal-04723638**

**<https://hal.science/hal-04723638v1>**

Submitted on 13 Nov 2024

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# **Repeated lidar acquisitions in an underground salt gallery in the** **Alsatian potassic basin (France): monitoring and geomechanical** **modelling**

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## **Abstract**

In the Alsatian potassic basin, located northwest of Mulhouse (eastern France), the deformation of an underground salt gallery is monitored from April 2017 to April 2019 using repeated static lidar acquisitions. This monitoring aims to characterize the rheology of the rock salt. The gallery is situated at 550 m deep in a 20 m thick rock salt layer. At this depth traditional referencing tools such as GPS are not available; and the salt is creeping, which prevents the referencing of the measurements with respect to a stable area. First, we develop a specific acquisition protocol to precisely monitor the deformation affecting the gallery walls over time. After two years, we measure a horizontal deformation between 0.10 and 0.30% all along the gallery with a mean uncertainty of 0.08%. From the low horizontal deformation, a new methodology is developed to set the point clouds in the same coordinate system. By doing so, the gallery closure, or volumetric deformation, is calculated. Then, the horizontal deformation time series of the gallery is used to parametrize the mechanical behaviour law of the rock salt, consistent with parameters from laboratory work on this rock salt. Through our work, in addition to the new methodology, the lidar device is shown to be a useful and polyvalent tool to monitor underground cavities and to mechanically characterize the surrounding medium.

**Keywords:** Lidar, rock salt, underground cavity, geomechanical modelling, methodology

26

## 27 **1. Introduction**

28           Underground galleries might undergo severe deformation induced by the ambient stress  
29 state, especially for deep excavations in materials susceptible to creep. Thus, the measurement of  
30 the deformation of those galleries is necessary to monitor their stability through time. It also allows  
31 improved determination of the rheology of the surrounding medium. Traditional tools, such as an  
32 extensometer or a sliding ruler, offer precise values of deformation. However, those values only  
33 concern specific points. Unlike traditional tools, *Light Detection And Ranging* (lidar) devices offer the  
34 possibility to measure the distance between a large number of points, allowing the determination of  
35 the deformation over a larger spatial extent. During an acquisition or scan, a lidar device derives a  
36 volume depiction using laser technology. By measuring the distance from the sensor to many targets,  
37 the acquisition collects a set of data forming a point cloud in 3D, representing the scanned volume.  
38 Lidar devices have become essential tools for remote sensing and 3D modelling studies, and their  
39 fields of application have widened considerably over the last two decades (Eitel et al., 2016; Telling et  
40 al., 2017; Wang et al., 2014).

41           The use of lidar acquisitions to monitor underground galleries is justified by the millimetric  
42 accuracy of the measurements (Lichti and Licht, 2006). For superficial excavations such as open-pit  
43 mines geo-referencing tools such as GPS are available (Grenon et al., 2017), although not for deep  
44 galleries. When the device cannot be set up in the galleries to achieve continuous acquisitions  
45 (Cecchetti et al., 2017), the referencing of the acquisitions becomes crucial. In some cases, reflective  
46 or optical targets are installed as reference points in a stable area (Kukutsch et al., 2015; Pejić, 2013).  
47 In other cases, the point clouds are set in a same coordinate system with a processing based either  
48 on cross-correlation methods (Han et al., 2013) or on the Iterative Closest Point (ICP) method  
49 (Errington et al., 2010). Moreover, methods based on point clouds cross-correlation result in high  
50 accuracy (Lynch et al., 2017). In particular cases, despite the depth, the position of the lidar for the  
51 acquisition can be geo-referenced with precision (Delaloye et al., 2015). However, these methods

52 might be time consuming due to the point cloud processing or to the protocol of acquisition. In order  
53 to limit the time spent on these geo-referencing issues, 'global fitting approach' methods have been  
54 developed. These methods are based on the comparison of 2D or 3D shapes coming from two point  
55 clouds representing the same area (Walton et al., 2018).

56 The "Mines Domaniales de Potasse d'Alsace" (MDPA) extracted potash from 1910 to 2002  
57 northwest of Mulhouse (eastern France). Due to the depletion of the resource, an underground  
58 waste storage site was then created in 1998 to maintain economic activity in the region. The site is  
59 located at 550 m deep, in a 20 m thick rock salt layer. Several galleries have been dug both in and  
60 around the site to allow the transport and the storage of waste materials. The activity ceased in 2002  
61 due to a fire. The site is currently under observation and is the subject of many studies. Since its  
62 creation, the deformation of the site's gallery has been regularly monitored using sliding rulers. This  
63 monitoring indicates that the galleries of the waste storage site are slowly closing as a result of rock  
64 salt creeping.

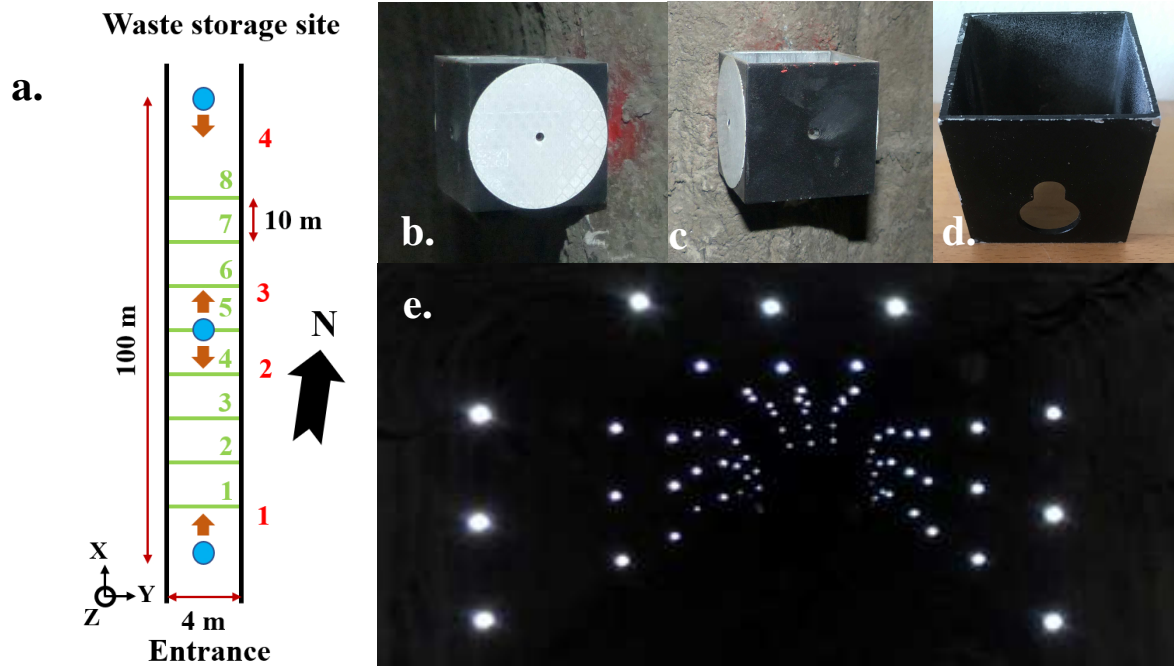
65 Reconnaissance visits have determined that the surface of the rock salt galleries was  
66 delaminating. This is explained by the halokinesis. Inside the rock salt layer, salt crystals develop  
67 within the natural cracks of the layer. In some cases these new crystals press against the crystals on  
68 the surface of the gallery, causing their fall. Thus, we have opposing phenomena: the creeping of the  
69 rock salt (decreasing the distance between opposite walls) and the delamination of the superficial  
70 salt (increasing the distance). As a consequence, we have chosen to work with specific reflectors,  
71 about 70, in order to isolate and measure only the rock salt creeping.

72 Due to both the creeping and the delamination, we have chosen to avoid the use of cloud  
73 point processing in our study such as ICP method (Errington et al., 2010) or 'global fitting approach'  
74 methods (Walton et al., 2018). The first phenomenon modifies the position of the points in respect  
75 to each other and the second in respect to the roughness of the surfaces. The creeping of the rock  
76 salt however prevents the determination and the use of a reference area. Rock salt creeping  
77 therefore makes it difficult to implement a common coordinate system for all acquisitions over time.

78           In this study, we analyse the deformation of an underground salt gallery from April 2017 to  
79 April 2019 connected to the waste storage site. This gallery has been monitored by regular static lidar  
80 acquisitions, every two to three months. From these repeated lidar acquisitions, precise time series  
81 of horizontal deformation or convergence are obtained. Those results are also compared to  
82 measurements realized in the neighbouring waste storage site, attesting to the quality of the results.  
83 Due to the small amplitude of the deformation after two years, a new methodology has been  
84 developed to set the point clouds in the same coordinate system. Thus, the gallery closure, or  
85 volumetric deformation, is computed. These time series are then used to parametrize the mechanical  
86 behaviour law of the rock salt with a geomechanical model. Through this study, in addition to the  
87 new methodology, a lidar device is shown to be a useful and polyvalent tool to monitor underground  
88 cavities and mechanically characterize the surrounding medium.

## 89       **2. Data acquisition**

90           The monitored gallery, oriented N008°W, is 100 m long, 4 m wide, and 2.2 to 3 m high. In  
91 order to enable the determination of the deformation, reflective targets are installed every 10 m  
92 along the gallery (Figure 1.a). These targets are 2.5 cm radius disks glued to aluminium cubes, which  
93 are themselves fixed with a thick vice to the walls and the roof (Figure 1.b-d). For each wall and roof,  
94 three cubes are fixed at one-quarter, at half, and at three-quarters of the length and the height  
95 (Figure 1.e). Unfortunately, the cubes could not be fixed to the floor, making the monitoring of the  
96 vertical deformation more complex.



97

98 **Figure 1 (color)** - Schematic drawing of the gallery (a) and pictures of both the reflectors with their  
 99 **cube (b-d) and the gallery (e)** (Modeste, 2020). Blue points indicate the three positions of acquisition  
 100 and brown arrows the direction of the scan. The acquisition numbers are in red. The reflectors are  
 101 set up in arcs, each arc containing 9 of them and being numbered in green from 1 (entrance of the  
 102 gallery) to 8 (waste storage site).

103 From April 2017 to April 2019, ten campaigns of static lidar acquisitions have been  
 104 conducted, every two to three months. Only one campaign was not undertaken, in August 2018, due  
 105 to the unavailability of the instrument. The lidar device used is a Riegl VZ-2000 (Petrie and Toth,  
 106 2018). This device can scan targets that are at least 2.5 m apart. Each campaign consisted of four  
 107 acquisitions: one at each end and two at the centre, one in both directions (Figure 1.a). A 360°  
 108 acquisition at the centre of the gallery was not possible, since the walls were too close to the device.

109 No area could be considered as stable due to the salt creeping, preventing the presence of a  
 110 reference point reliable for each acquisition. Therefore, at each acquisition campaign, the lidar was  
 111 placed vertically below a hook set up on the roof at the beginning of our experiments. The distance  
 112 between the lidar and the roof is constant over time for each acquisition time. Thus, the lidar is not  
 113 at the exact same position every time, but at a similar position.

114 **3. Methodology**

115 As indicated in the previous section, the point clouds of each acquisition are not in the same  
 116 coordinate system at each campaign. In order to monitor the gallery elsewhere than at the location  
 117 of the reflectors, it is necessary to set the point clouds in the same coordinate system. We have  
 118 developed a new method for this, which requires two assumptions: point clouds acquired from a  
 119 similar point and small displacement of the reflectors between the two acquisition times.

120 In this section, the acquisition realized at the time  $t_i$  is associated with the coordinate system  
 121  $i$ . To transform the coordinates of a point  $M$  from the coordinate system  $i$  into  $j$ , we use the Equation  
 122 1:

$$123 \begin{pmatrix} x_i \\ y_i \\ z_i \\ 1 \end{pmatrix} = s \times \begin{pmatrix} R_{\theta\theta} & R_{\theta\varphi} & R_{\theta\omega} & \frac{T_x}{s} \\ R_{\varphi\theta} & R_{\varphi\varphi} & R_{\varphi\omega} & \frac{T_y}{s} \\ R_{\omega\theta} & R_{\omega\varphi} & R_{\omega\omega} & \frac{T_z}{s} \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} x_j \\ y_j \\ z_j \\ 1 \end{pmatrix} \quad (1)$$

124 with  $(x_j, y_j, z_j)$  the coordinates of the point  $M$  in the coordinate system  $j$ ,  $(x_i, y_i, z_i)$  the coordinates of  
 125 the point  $M$  in the coordinate system  $i$ ,  $s$  a scaling factor,  $(T_x, T_y, T_z)$  the components of the vector  
 126 translation,  $R_{ij}$  the component of the rotation matrix,  $\theta$  the angle of rotation around the x-axis,  $\varphi$  the  
 127 angle around the y-axis and  $\omega$  the angle around the z-axis.

128 Assuming similar orthonormal coordinate systems,  $s$  is equal to 1. This is consistent with test  
 129 measurements giving a value of  $1.0003 \pm 0.0010$  (Habib, 2018). The translation and the rotation are  
 130 geometrical transformations which preserve the distance between two points. Thus, the distance  
 131 measured during an acquisition campaign is comparable to a distance from another acquisition  
 132 campaign.

133 The distance between two points can be written:

$$134 (AB)_j = \sqrt{(x_{bj} - x_{aj})^2 + (y_{bj} - y_{aj})^2 + (z_{bj} - z_{aj})^2} \quad (2)$$

135 with  $(AB)_j$  the distance between the points  $A$  and  $B$  at the time  $t_j$ ,  $(x_{aj}, y_{aj}, z_{aj})$  the coordinates of the  
 136 point  $A$  in the coordinate system  $j$  at the time  $t_j$  and  $(x_{bj}, y_{bj}, z_{bj})$  the coordinates of the point  $B$  in the

137 coordinate system  $j$  at the time  $t_j$ . Using the law of conservation of the distances between two points,  
 138 Equation 2 can be written with the coordinates of the coordinate system  $i$  and the displacement  
 139 vectors (displacements of the reflectors between the acquisition times  $t_i$  and  $t_j$ ):

$$140 (AB)_j$$

$$141 = \sqrt{(x_{bi} - x_{ai} + dx_{bij} - dx_{aij})^2 + (y_{bi} - y_{ai} + dy_{bij} - dy_{aij})^2 + (z_{bi} - z_{ai} + dz_{bij} - dz_{aij})^2} \quad (3)$$

142 with  $dx_{aij}$  and  $dx_{bij}$  the displacement along the x-axis of the points A and B between the times  $t_i$  and  $t_j$ ,  
 143  $dy_{aij}$  and  $dy_{bij}$  the displacement along the y-axis of the points A and B between the times  $t_i$  and  $t_j$ ,  $dz_{aij}$   
 144 and  $dz_{bij}$  the displacement along the z-axis of the point A and B between the times  $t_i$  and  $t_j$ . Here, the  
 145 vector displacement is expressed in the coordinate system  $i$ . In the case of low deformation, with  
 146 variation of distance of a few millimetres, the displacement difference is small compared to the  
 147 coordinate difference. Thus, we can assume that the square of the displacement difference can be  
 148 neglected (Equation 4, 5 and 6):

$$149 (dx_{bij} - dx_{aij})^2 \sim 0 \quad (4)$$

$$150 (dy_{bij} - dy_{aij})^2 \sim 0 \quad (5)$$

$$151 (dz_{bij} - dz_{aij})^2 \sim 0 \quad (6)$$

152 By using and developing Equations 3 to 6, we have:

$$153 (AB)_j^2 = (x_{bi} - x_{ai})^2 + 2(x_{bi} - x_{ai})(dx_{bij} - dx_{aij}) + (dx_{bij} - dx_{aij})^2 + (y_{bi} - y_{ai})^2$$

$$154 + 2(y_{bi} - y_{ai})(dy_{bij} - dy_{aij}) + (dy_{bij} - dy_{aij})^2 + (z_{bi} - z_{ai})^2$$

$$155 + 2(z_{bi} - z_{ai})(dz_{bij} - dz_{aij}) + (dz_{bij} - dz_{aij})^2$$

$$156 \Leftrightarrow \frac{1}{2} [(AB)_j^2 - (AB)_i^2]$$

$$157 = (x_{bi} - x_{ai})(dx_{bij} - dx_{aij}) + (y_{bi} - y_{ai})(dy_{bij} - dy_{aij})$$

$$158 + (z_{bi} - z_{ai})(dz_{bij} - dz_{aij}) + o \left[ (dx_{bij} - dx_{aij})^2 \right] + o \left[ (dy_{bij} - dy_{aij})^2 \right]$$

$$159 + o \left[ (dz_{bij} - dz_{aij})^2 \right] \quad (7)$$

160 Equation 7 can be written with matrix:



$$161 \quad \left( \frac{1}{2} [(AB)_j^2 - (AB)_i^2] \right) = (-\Delta x_{abi} \quad -\Delta y_{abi} \quad -\Delta z_{abi} \quad \Delta x_{abi} \quad \Delta y_{abi} \quad \Delta z_{abi}) \times \begin{pmatrix} dx_{aij} \\ dy_{aij} \\ dz_{aij} \\ dx_{bij} \\ dy_{bij} \\ dz_{bij} \end{pmatrix} \quad (8)$$

162 with  $\Delta x_{abi}$  the coordinates difference along the x-axis between points A and B in the coordinate  
 163 system i,  $\Delta y_{abi}$  the coordinates difference along the y-axis between points A and B in the coordinate  
 164 system i,  $\Delta z_{abi}$  the coordinates difference along the z-axis between points A and B in the coordinate  
 165 system i. This is repeated for each combination of reflectors and the matrix is concatenated. Thus,  
 166 from Equation 8 and for M points, we have:

$$167 \quad \begin{pmatrix} \frac{1}{2} [(AB)_j^2 - (AB)_i^2] \\ \vdots \\ \frac{1}{2} [(LM)_j^2 - (LM)_i^2] \end{pmatrix} = \begin{pmatrix} -\Delta x_{abi} & -\Delta y_{abi} & -\Delta z_{abi} & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \Delta x_{lmi} & \Delta y_{lmi} & \Delta z_{lmi} \end{pmatrix} \times \begin{pmatrix} dx_{aij} \\ dy_{aij} \\ dz_{aij} \\ \vdots \\ dx_{mij} \\ dy_{mij} \\ dz_{mij} \end{pmatrix} \quad (9)$$

168 Equation 9 has the form:  $D = GM$ , with D the data, G the transfer matrix and M the model. In our  
 169 case, M is the reflector displacements to be estimated. We can use Equation 10 to solve Equation 9  
 170 (Tarantola, 2005):

$$171 \quad M = M_0 + (G^T C_D^{-1} G + C_M^{-1}) G^T C_D^{-1} (D + G M_0) \quad (10)$$

172 with  $M_0$  the a priori model,  $C_D$  the covariance matrix of the data and  $C_M$  the covariance matrix of the  
 173 model. By solving Equation 10, we obtain the reflectors displacement between the two acquisitions  
 174 in the coordinate system of our choice. The estimated displacement vectors are in the coordinate  
 175 system i in the previous equation sequence.

176 This method requires the use of at least seven distinct reflectors. These reflectors might be  
 177 placed either within the same arc or all along the gallery. For each reflector, we have three  
 178 unknowns, the three associated components of the displacement vector. We need at least the same  
 179 number of unknowns and distances to have a well-defined system. Thus, with seven reflectors, we  
 180 have 21 unknowns for 21 distances.

181 By applying the displacement to the reflectors at the time  $t_i$ , we obtain the position of the  
 182 reflectors at the time  $t_j$  in the coordinate system  $i$ . Thus, at the time  $t_j$ , we have the position of the  
 183 reflectors in both coordinate systems  $i$  and  $j$ . By concatenating Equation 1 for each reflector, we get  
 184 Equation 11:

$$185 \begin{pmatrix} x_{ai} & x_{mi} \\ y_{ai} & y_{mi} \\ z_{ai} & z_{mi} \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} R_{\theta\theta} & R_{\theta\varphi} & R_{\theta\omega} & T_x \\ R_{\varphi\theta} & R_{\varphi\varphi} & R_{\varphi\omega} & T_y \\ R_{\omega\theta} & R_{\omega\varphi} & R_{\omega\omega} & T_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} x_{aj} & x_{mj} \\ y_{aj} & y_{mj} \\ z_{aj} & z_{mj} \\ 1 & 1 \end{pmatrix} \quad (11)$$

186 By solving Equation 11 with a least-square method, the transfer matrix between the two  
 187 coordinate systems can be estimated and then used to set the point clouds in the same coordinate  
 188 system.

189 Thus, in this method the point clouds are set into the same coordinate system from  
 190 reference points whose position has been corrected for the displacement occurring between the two  
 191 acquisition times. Thus far such a correction was not envisaged to set the point clouds in the same  
 192 coordinate system. This method is less time consuming than methods based on point clouds cross-  
 193 correlation since we do not need to work with the whole point clouds (Lynch et al, 2017). However,  
 194 our method requires installing reflectors to recognize and locate specific points completely during  
 195 each acquisition, in contrast to ‘global fitting approach’ methods (Walton et al., 2018).

## 196 **4. Results**

197 This section is divided into two main parts. First, the uncertainty of distances between  
 198 reflectors and of deformations is determined. Second, the horizontal deformation time series are  
 199 analysed. Due to the small amplitude of the deformation, we can set the point clouds in the same  
 200 coordinate system. Lastly, the closure of the gallery is calculated using the open source software  
 201 CloudCompare (Girardeau-Montaut, 2011).

### 202 **a. Uncertainty of distances between reflectors and of deformations**

203 The scan acquisition 1 is repeated twice during the first campaign of acquisitions (case 1,  
 204 Table 1). Between the two acquisitions, the lidar device is uninstalled and then reinstalled. Each

205 installation followed the described protocol. The aim is to compare the distances between reflectors  
206 inside both collected point clouds. The coordinates of the center of each reflector are extracted from  
207 the first point cloud. The distance between each reflector is then calculated from these coordinates.  
208 This is repeated for the second point cloud. Lastly, both distance sets are compared; i.e., each  
209 distance between reflectors obtained in the first point cloud is compared to its equivalent in the  
210 second point cloud.

211 In this study, the uncertainty is defined as the difference between two distance sets coming  
212 from two different point clouds acquired the same day. Thus, the uncertainty reflects the error  
213 related to the acquisition of the point cloud and the extraction of the reflector coordinates. The  
214 uncertainty is chosen to be greater than 90-92% of the absolute differences between both distance  
215 sets. The uncertainty is low, about 3 mm (Table 1). Then we estimate the uncertainty by using only  
216 reflectors located within a distance smaller than 40 m of the lidar. This distance corresponds to the  
217 maximum distance between each reflecting target and the lidar when it is set up at the centre of the  
218 gallery (Figure 1.a). The uncertainty is lower, about 2 mm (Table 1).

219 In order to assess the importance of the protocol, we realize during the second campaign an  
220 additional acquisition 1 without respecting the protocol (case 2, Table 1). The device is shifted by ~50  
221 cm away from the protocol position. This time the uncertainty is 3 times higher, 9 mm with all  
222 reflectors and 6 mm with reflectors located at less than 40 m from the lidar (Table 1). This result  
223 highlights the importance of respecting the protocol by replacing the device approximately a few  
224 centimetres from the original position.

225 In order to assess the stability of the uncertainty over time, we also repeat the acquisition 1  
226 twice during the tenth campaign in April 2019 (case 3, Table 1). We follow the same procedure for  
227 the comparison. The uncertainty is similar to the one obtained for the first campaign (Table 1). Thus,  
228 the uncertainty is stable over time and we keep a value of 2.1 mm for the uncertainty on the  
229 distance.

230

231

**Table 1** - Estimation of the uncertainty on the measured distance from lidar acquisitions

	Reflectors	Standard deviation [mm]	Uncertainty [mm]	Rate [%]
<b>Case 1</b>	All	1.7	2.9	90.8
	< 40 m	1.0	2.1	90.8
<b>Case 2</b>	All	4.1	9.1	91.1
	< 40 m	2.6	5.8	90.3
<b>Case 3</b>	All	2.5	2.8	90.5
	< 40 m	3.2	1.9	91.2

232

In order to estimate the uncertainty on deformations, we use Equation 12, derived from

233

metrology (JCGM, 2008):

234

$$\Delta\varepsilon(L_i, L_f) = \sqrt{\left(\frac{\partial\varepsilon(L_i, L_f)}{\partial L_i} \times \Delta L_i\right)^2 + \left(\frac{\partial\varepsilon(L_i, L_f)}{\partial L_f} \times \Delta L_f\right)^2} \quad (12)$$

235

with  $\varepsilon$  the deformation,  $L_i$  and  $L_f$  the initial and final distances,  $\Delta$  refers to the uncertainty. Assuming

236

that the uncertainty on distances is constant over time, Equation 12 can be written as follow:

237

$$\Delta\varepsilon(L_i, L_f) = \frac{\Delta L}{L_i} \times \sqrt{1 + \frac{L_f^2}{L_i^2}} \quad (13)$$

238

Taking into account an uncertainty of 2.1 mm on the distances measured with the lidar, the

239

uncertainty on the deformation ranges from 0.05 to 0.10%.

240

#### **b. Horizontal deformation**

241

After two years, the horizontal deformation develops between 0.10 and 0.30% all along the

242

gallery (Figure 2.a-b). To obtain the amplitudes of the horizontal deformation, we look at the

243

variation of distance between two reflectors on opposite walls, at the same height and inside the

244

same arc. These values are higher than the uncertainty which has a mean value of 0.08%. Thus, the

245

monitored deformation is significant and appears linear over two years. Considering a width of 4 m,

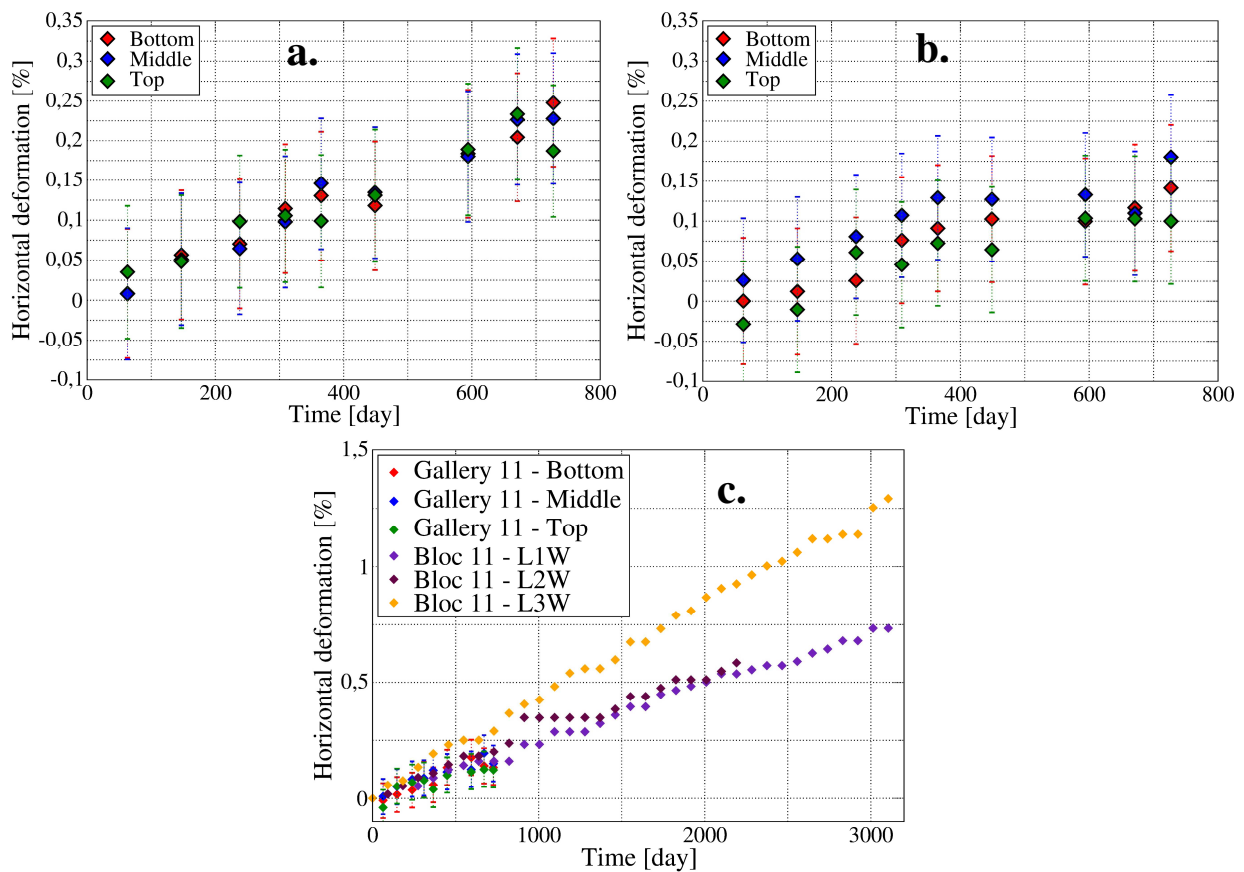
246

the variation of distance between two opposite reflectors ranges from ~4 to 12 mm. Hence, the

247

displacement of each reflector can be considered small.

248 To assess the quality of the results, we compare ours to available measurements of  
 249 horizontal deformation in three neighbouring galleries (Figure 2.c). These measurements were  
 250 carried out by the MDPA with a sliding ruler at reference points marked by nails from June 2007 to  
 251 June 2013. For the comparison, we use the results from arc 8 (Figure 1.a), which is the arc closest to  
 252 the waste storage site. In the manual time series (ruler), we note the presence of offsets due to the  
 253 loss of the initial reference point, the nail falling from the wall. Measurements have been made with  
 254 a point close to the initial reference point. As shown on Figure 2.c, both measurement types are  
 255 consistent.



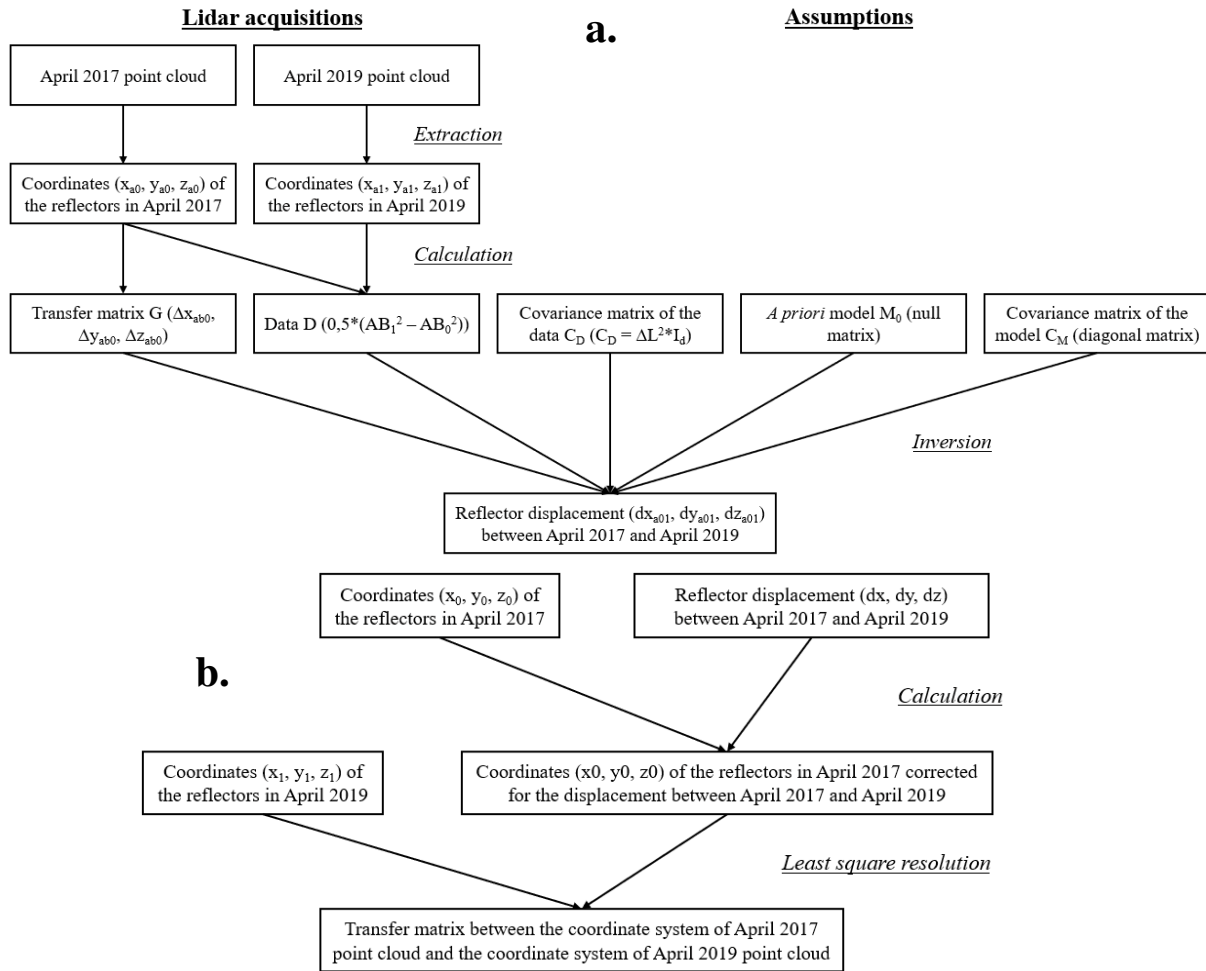
256 **Figure 2 (color) - Horizontal deformation time series from lidar campaigns (a and b) compared to**  
 257 **manual available measurements (c)** (Modeste, 2020). The plotted measurements correspond to arc  
 258 3 (a), 7 (b) and 8 (c). The positive values correspond to a decrease of the distance between the  
 259 reflectors. 'Top' indicates the pair of reflectors fixed at three-quarters height, 'Middle' at halfway,  
 260 and 'Bottom' at one-quarter height. The MDPA data are ruler measurements in three neighbouring  
 261 galleries, associated with the names "Bloc 11 – LXW". The two distinct reference dates of April 2017  
 262

263 and June 2007 have been chosen for the lidar measurements and for the ruler measurements,  
264 respectively.

265 **c. Volumetric deformation**

266 **i. Setting point clouds in the same coordinate system with the new**  
267 **method**

268 Since the deformation between the first and the last campaign is low ( $<0.3\%$ ), we can apply  
269 our methodology to set our point clouds in the same coordinate system. We do the test with the  
270 point clouds coming from acquisitions 2 and 3 (Figure 1.a). The calculation procedure and the  
271 different variables are summarised in Figure 3. After inversion, we obtain the displacement vectors of  
272 the reflectors from April 2017 to April 2019. The norm of the displacement vectors obtained is of the  
273 order of a few millimetres.



274

275 **Figure 3 – Flowcharts to compute the reflector displacement between April 2017 and April 2019**

276 **(a), and then to deduce the transfer matrix between the two coordinate systems (b)**

277 In order to estimate the quality of the inversion, displacement vectors are applied to the

278 position of their respective reflectors in the point cloud acquired in April 2017. We calculate the

279 distance between each reflector with their new coordinates. Then, we calculate the distance

280 between each reflector in the point cloud acquired in April 2019. Lastly, the two distance sets are

281 compared. The differences between the two distance sets are small, at the order of micrometres

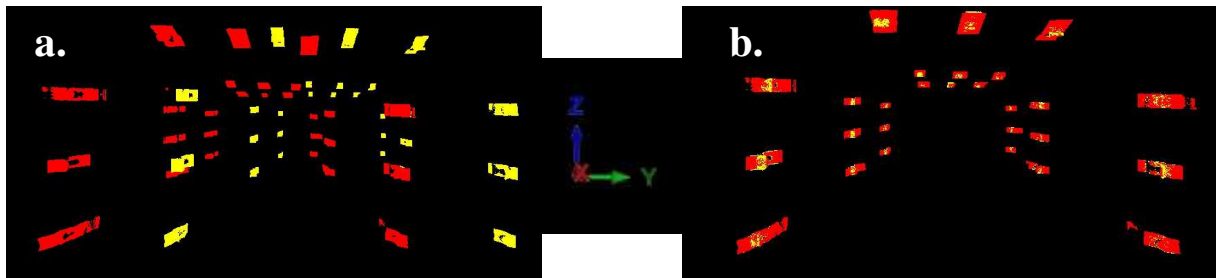
282 (Table 2). Thus, these comparisons validate our methodology. Figure 4 shows reflectors coming from

283 both point clouds before and after being set in the same coordinate system.

284 **Table 2 – Difference of reflectors distance in April 2019 between the original and the adjusted data**

Acquisition point	Maximum difference [ $\mu\text{m}$ ]	Minimum difference [ $\mu\text{m}$ ]	Standard deviation [ $\mu\text{m}$ ]
-------------------	--------------------------------------	--------------------------------------	--------------------------------------

2	48.3	-75.6	10.5
3	95.2	-102	15.9



285

286 **Figure 4 (color)** – Reflectors (arcs 1, 2 and 3) from the April 2017 and the April 2019 point clouds

287 **before (a) and after (b) having set them in the same coordinate system.** The point clouds have been

288 acquired from acquisition point 2. Yellow is associated with the April 2017 point cloud and red with

289 the April 2019 point cloud.

290 **ii. The closure of the gallery**

291 On the open-source software CloudCompare, we study the closure, or volumetric

292 deformation, of four sections of the gallery between the first campaign in April 2017 and the last one

293 in April 2019. To do so, we work only with the point clouds acquired at the centre of the gallery

294 (acquisitions 2 and 3, Figure 1.a). Having the point clouds in a same coordinate system allows us to

295 cut the same section of the gallery at different times. By adding vertical planes on both sides of the

296 selected section, a continuous volume with triangular mesh is created by solving Poisson’s equation

297 (Figure 5.a) (Kazhdan et al., 2006). Then, we compute the volume of the retained section. The April

298 2017 and April 2019 results are finally compared to each other. We repeat this process with three

299 other sections along the gallery (Figure 5.b).

300 Thus, we obtain four values ranging from 0.34 to 0.55% after two years (Figure 5.b). These

301 values are higher than the horizontal deformation results. As the gallery also deforms vertically

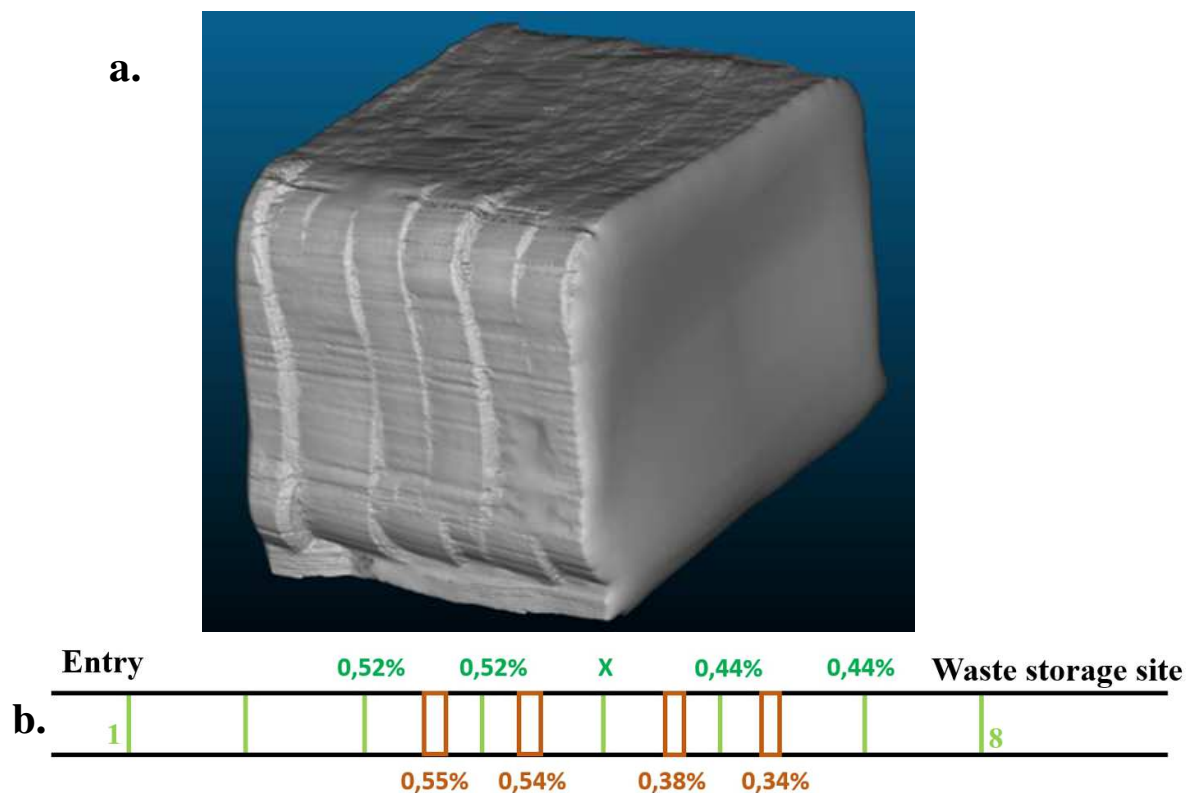
302 (closure), the volumetric deformation is greater than the horizontal deformation. These results are

303 close to the estimations based on the measured displacement of the reflectors. We compare the

304 computed deformation to the variation of the surface of the opening of the gallery, corresponding to



305 a rectangle. To the initial width of 4 m, we subtract the mean reflector displacement of each  
 306 opposing wall. To the initial height of 2.5 m, we subtract two times the mean reflector displacement  
 307 of the roof, since we do not have reflectors on the floor. Then, the product of the initial width and  
 308 height is compared to the product of the reduced width and height. From this comparison, we  
 309 estimate the volumetric deformation from the displacements of the reflectors. The estimated values  
 310 range from 0.44% to 0.52% (Figure 5.b).



311

312 **Figure 5 (color)** - Created volume from the point cloud (a) and its volumetric deformation after two  
 313 years (b) (Modeste, 2020). Positive values correspond to a closure or a loss of volume. Numbers in  
 314 brown are the computed results on CloudCompare while numbers in green refer to the estimation  
 315 based on the displacement of the reflectors.

316 **5. Geomechanical modelling**

317 In this section, the time series of horizontal deformation are geomechanically modelled. The  
 318 model is first set up according to the mechanical characteristics of the Alsatian potassic basin. Then,

319 the deformation of the gallery is modelled to parametrise the mechanical behaviour law of the  
320 medium.

### 321 **1. Model setup**

322 The deformation of two rock salt samples from the Alsatian potassic basin has been studied  
323 in the laboratory under different conditions of temperature and deviatoric stress. Ghoreychi (1991)  
324 shows that the elasto-visco-plastic behaviour of the rock salt follows Norton's Law (Equation 12, 13,  
325 14):

$$326 \quad \dot{\varepsilon}_{ij}^v = \left(\frac{3}{2}\right) \dot{\varepsilon}_{cr} \left(\frac{\sigma_{ij}^d}{\bar{\sigma}}\right) \quad (12)$$

327 where

$$328 \quad \dot{\varepsilon}_{cr} = \begin{cases} A\bar{\sigma}^n & \bar{\sigma} \geq \sigma_1^{ref} \\ 0 & \bar{\sigma} < \sigma_1^{ref} \end{cases} \quad (13)$$

329 and

$$330 \quad A = \frac{A_s}{\sigma_0^n} \exp\left(-\frac{B}{T}\right) \quad (14)$$

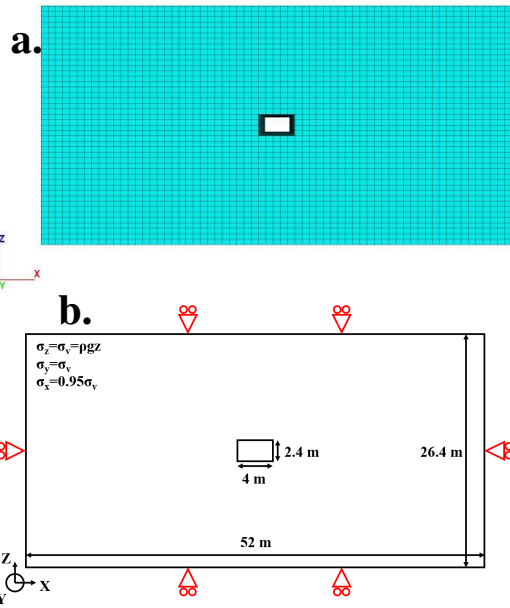
331 where  $\dot{\varepsilon}_{ij}^v$  is the creep strain-rate tensor,  $\dot{\varepsilon}_{cr}$  the creep rate,  $\sigma_{ij}^d$  the deviatoric stress,  $\bar{\sigma}$  the Von Mises  
332 stress,  $\sigma_1^{ref}$  the Von Mises stress threshold,  $n$  the stress exponent,  $A_s$  the rate of reference,  $T$  the  
333 temperature,  $B$  the ratio between the activation energy and the universal gas constant, and  $\sigma_0$  the  
334 normalization stress. Norton's law and modified versions are commonly associated with the  
335 mechanical behaviour law of rock salts (Khaledi et al., 2016; Wang et al., 2010). For rock salts, the  
336 threshold is null, creep occurring as soon as deviatoric stresses are present in the medium (Carter et  
337 al., 1993). Empirical parameters are summarised in Table 3. Previous studies (Camusso and Billaux,  
338 2013; Laouafa et al., 2010) focused on the modelling of the horizontal deformation time series  
339 coming from the ruler measurements. In these studies, the authors used other values of reference  
340 velocity  $A_s$ , between 0.015 and 0.022 %/day instead of 0.005%/day, to retrieve the measurements.

341

**Table 3** - Norton's Law parameters

Parameter	Symbol	Value
Power exponent	n	4.0
Reference velocity	$A_s$	0.005 %/day
Related to the activation energy	B	4700 K
Normalized stress	$\sigma_0$	1.0 MPa

342 In this work, we use Flac3D, which is commercial software developed by Itasca that allows  
343 the study of the mechanical behaviour of a continuous three-dimensional medium (Itasca, 2002).  
344 This modelling aims to determine which value of the reference velocity  $A_s$  in Norton's Law is relevant.  
345 To model the gallery, a rectangular parallelepiped at 26.4 m high, 24 m wide and 52 m long is drawn  
346 with rectangular parallelepipeds at 0.6 m high and 0.8 m long and wide (Figure 6). With those  
347 dimensions, the gallery is made up of five parallelepipeds wide and four in height, either a node at  
348 0.6, 1.2 and 1.8 m of height. These positions are equivalent to those of the reflectors in the gallery.  
349 Since the height of the model (26 m) is similar to the thickness of the salt layer (about 20 m), a single  
350 layer is modelled. In the modelling, the density, the Young's modulus and the Poisson's ratio used are  
351 2.31 gm.cm<sup>-3</sup>, 28.3 GPa and 0.25, respectively (Table 4). The Young's modulus is different from the  
352 laboratory results, 25 GPa (Ghoreychi, 1991), to account for the presence of anhydrite and marls,  
353 which have a Young's modulus of 61 and 5.9 to 7 GPa, respectively (Nguyen-Minh and Bergues, 1995;  
354 Trippetta et al., 2013). These values and the mechanical behaviour law have been estimated  
355 experimentally in laboratory tests on small samples. These results are used here without taking into  
356 account potential scale effects.



357

358 **Figure 6 (color)** – View of th  
359 **(b).**

center (a) and model scheme

360

361

362

363

**Table 4** – Geomechanical parameter of the geomaterial

Parameter	Symbol	Value
Density	$\rho$	2.31 g.cm <sup>-3</sup>
Poisson's ratio	$\nu$	0.25
Young's modulus	$E$	28.3 GPa

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## 2. Comparisons with the model

369

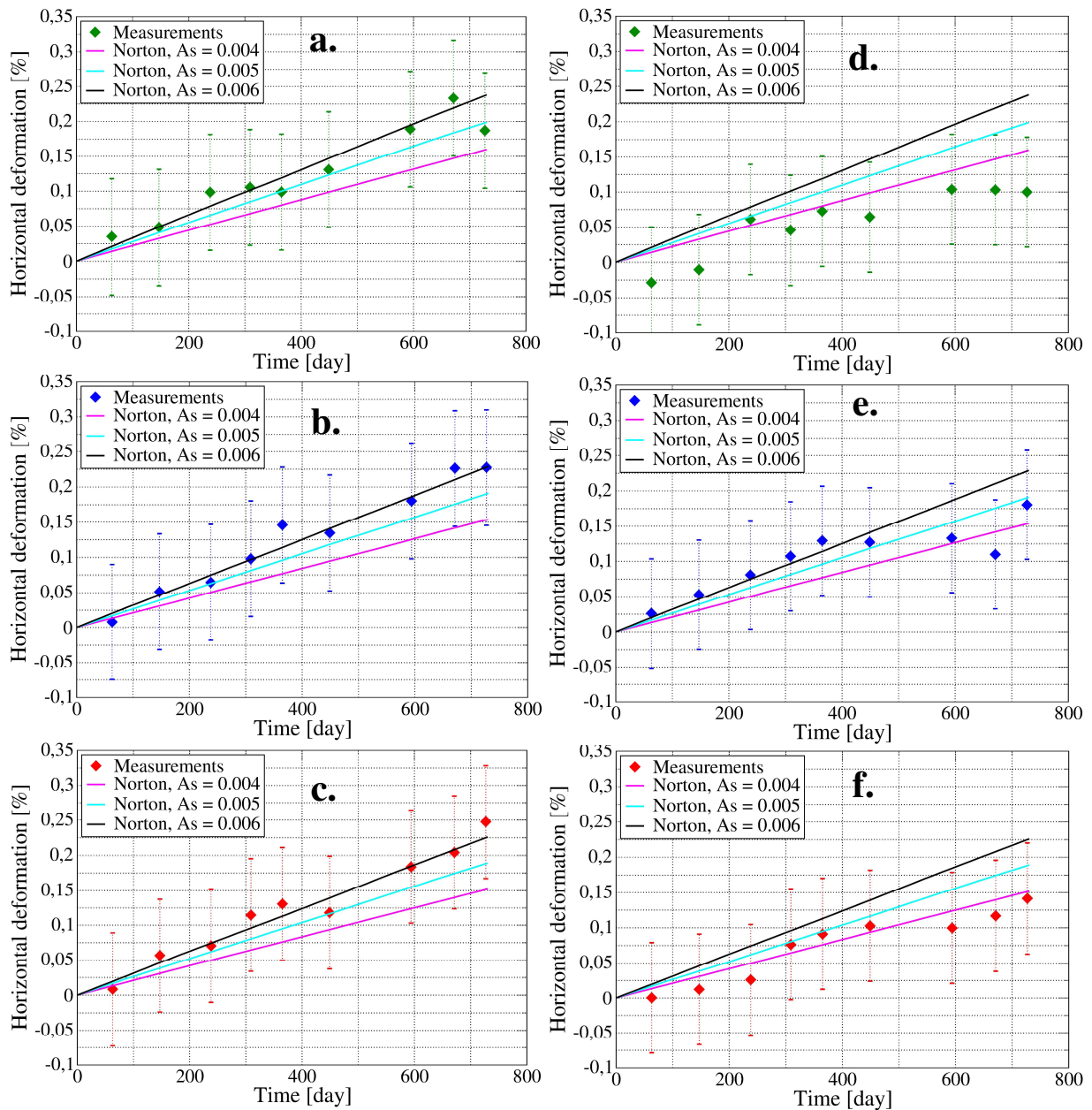
370

371

The gallery is nearly oriented along the maximum horizontal stress direction, which is the North-South axis (Baumann and Illies, 1983; Larroque, 1987). According to in-situ stress measurements in the Alsatian potassic basin (Cornet and Burlet, 1992), the vertical stress  $\sigma_v$  is nearly equal to the maximum horizontal stress  $\sigma_H$  and the minimum horizontal stress  $\sigma_h$  is equal to  $0.95\sigma_v$ .

After setting up the stress field, the closure of the gallery is then modelled. The centre of the parallelepiped, along the Y-axis/N-S direction, is excavated to model the gallery. Norton's Law with the experimental and geomechanical parameters (Table 3 and 4) are associated with each element.

372 In the model, the temperature is set to 298 K, which is the temperature measured during the lidar  
373 campaigns. The modelling is carried out with different values of  $A_s$ . A twenty-year period is first  
374 modelled, which is approximately the time between the excavation of the gallery and the beginning  
375 of our lidar measurement campaigns. Then, the modelling is pursued over a two-year period that  
376 corresponds to our monitoring period. Over this two-year period the distance evolution between  
377 each opposite node of the gallery is extracted from the model. The horizontal deformation is then  
378 deduced and compared to our lidar time series (Figure 7). The comparison is done between the pair  
379 of reflectors fixed at one-quarter height and the pair of nodes at 0.6 m, the pair of reflectors fixed at  
380 half height and the pair of nodes at 1.2 m and so on. Thus, only three pairs of reflectors per arc are  
381 selected for the comparison between the model and the data. With seven arcs, a total of 21  
382 comparisons are made. A  $R^2$  determinant, reflecting the similarity of the model to the  
383 measurements, is calculated for each comparison (Table 5). We used the point clouds coming from  
384 acquisitions 2 and 3 to produce the horizontal deformation time series (Figure 1.a). However, with  
385 these acquisitions, it is not possible to get the time series of arc 5, for it is too close to the lidar. A  
386 mean value of  $R^2$  is obtained for each modelling carried out with a different value of  $A_s$ . The  
387 modelling carried out with a value of 0.005 %/day for  $A_s$  seems to fit our measurements best (Table  
388 5). Here we retrieve results from laboratory experiments, which is 0.005 %/day.



389  
 390 **Figure 7 (color)** - Comparison between the results from campaigns of lidar acquisition and the  
 391 **geomechanical model** (Modeste, 2020). The plotted results correspond to arc 3 (a-c) and arc 7 (d-f).  
 392 The reflectors are associated with the nodes in the model. The horizontal deformation time series of  
 393 the pair of reflectors fixed at three-quarters height is compared to the pair of nodes at 1.8 m (a and  
 394 d), the pair of reflectors fixed at half height to the pair of nodes at 1.2 m (b and e) and the pair of  
 395 reflectors fixed at one-quarter height to the pair of nodes at 0.6 m (c and f).

396 **Table 5** - R-square determinant of the comparison between the lidar measurements and the model.

	$A_s = 0.004 \text{ \%/day}$	$A_s = 0.005 \text{ \%/day}$	$A_s = 0.006 \text{ \%/day}$
--	------------------------------	------------------------------	------------------------------

<b>Top (a)</b>	0.51	0.85	0.89
<b>Middle (b)</b>	0.50	0.83	0.97
<b>Bottom (c)</b>	0.47	0.82	0.96
<b>Top (d)</b>	0.37	0.0	0.0
<b>Middle (e)</b>	0.48	0.56	0.07
<b>Bottom (f)</b>	0.86	0.46	0.0
<b>Mean</b>	0.54	0.62	0.51

397 **6. Conclusion**

398 The deformation of a 500 m deep salt gallery has been monitored from April 2017 to April  
399 2019 by repeated static lidar acquisitions. After two years, the horizontal deformation is estimated  
400 and ranges from 0.10 to 0.30% along the gallery. The detected deformation is higher than the  
401 uncertainty, which has a mean value of 0.08%. The comparisons of measurements conducted in the  
402 waste storage are consistent with our measurements. The horizontal deformation time series are  
403 then used to parametrize the mechanical behaviour law of the surrounding medium in a  
404 geomechanical model. The results confirm the values obtained in laboratory tests.

405 Despite the absence of a stable reference site, the acquisitions have been successfully  
406 referenced to each other. A new methodology was developed for this purpose. At least seven specific  
407 reflectors have to be used as markers and must remain at the same location for the duration of the  
408 monitoring. The methodology relies on two assumptions: point clouds acquired from a similar point  
409 and small displacement of the reflectors between the two campaigns.

410 Through our work, the lidar device is shown to be a useful and polyvalent tool to monitor  
411 underground cavities and to mechanically characterize the surrounding medium. In addition, the new  
412 methodology offers a new way to monitor the deformation of underground galleries, to coincide  
413 with the many existing methods.

414 **Acknowledgement**

415 The authors are grateful to the MDPA and DREAL for their encouraging support, their trust,  
416 and their permission to study the underground gallery. The study is financially supported by the  
417 MDPA. This work is dedicated to François H. Cornet who passed away in 2020. The authors pay  
418 homage to this scientist by acknowledging the tremendous advances in the discipline of  
419 geomechanics he accomplished over the course of his entire career.

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