

# 1 Calibration of Strain Gauged Square Tunnels for Centrifuge 2 Testing

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14  
15 **Abstract:** A series of dynamic centrifuge tests was conducted on square aluminum tunnel-  
16 models embedded in dry sand. The tests were carried out at the Schofield Centre of the  
17 Cambridge University Engineering Department, aiming to investigate the dynamic response  
18 of these type of structures. An extensive instrumentation scheme was employed to record the  
19 soil-tunnel system response, which comprised of miniature accelerometers, total earth  
20 pressures cells and position sensors. To record the lining forces, the model tunnels were strain  
21 gauged. The calibration of the strain gauges, the data from which was crucial to furthering our  
22 understanding on the seismic performance of box-type tunnels, was performed combining  
23 physical testing and numerical modelling. This technical note summarizes this calibration  
24 procedure and highlighting the importance of advanced numerical simulation in the  
25 calibration procedure of complex construction models.

26  
27 **Keywords:** Centrifuge modelling; Calibration; Strain Gauges; Numerical analysis

## 28 29 **1. Introduction**

30 Large underground structures (e.g. subways, metro stations, underground parking lots, utility  
31 tunnels) have a vital socio-economic role - being a crucial part of the transportation and utility  
32 networks in an urban area. To prevent disruption arising from earthquake induced damage,  
33 rigorous seismic design procedures need to be developed, verified and implemented. In this

34 context a range of different experimental researches have been carried out over recent years  
35 aiming at the investigation of the seismic response of underground structures and tunnels  
36 (Shabayama et al., 2010, Lanzano et al., 2012; Cilingir and Madabhushi, 2011a, 2011b,  
37 2011c; Chian and Madabhushi, 2011; Chen et al., 2013; Chen and Shen, 2014; Tsinidis et al.,  
38 2015a; Ulgen et al., 2015; Abuhajar et al., 2015). Experimental studies have been also  
39 conducted for the evaluation of the seismic behavior of actual case studies during retrofitting  
40 projects (Adalier et al., 2003; Chou et al., 2010). Although there are some published  
41 experimental programs investigating the behaviour of rectangular embedded structures, where  
42 strain gauges were employed to record the lining forces (e.g. Chen and Shen, 2014), no clear  
43 reference is given for the calibration of these crucial instruments.

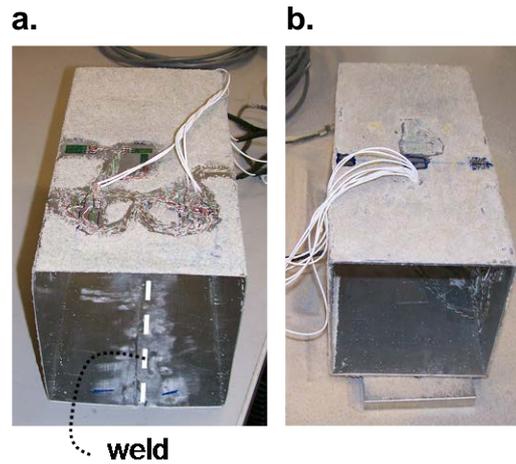
44 This lack of reference, along with the need for more artificial ‘case studies’, motivated the  
45 realisation of the collaborative experimental project TUNNELSEIS, through the EU funded  
46 research project SERIES. Within the framework of this research project, the seismic response  
47 of shallow square tunnels embedded in dry sand was investigated by means of dynamic  
48 centrifuge tests. The tests were carried out at the geotechnical centrifuge facility of the  
49 Schofield Centre, University of Cambridge. This technical note summarizes the calibration  
50 procedure followed for the resistance strain gauges, which were used to record the lining  
51 forces and highlighting the significance of advanced numerical simulation in the calibration  
52 procedure of complex construction models.

53

## 54 **2. Description of centrifuge tests undertaken**

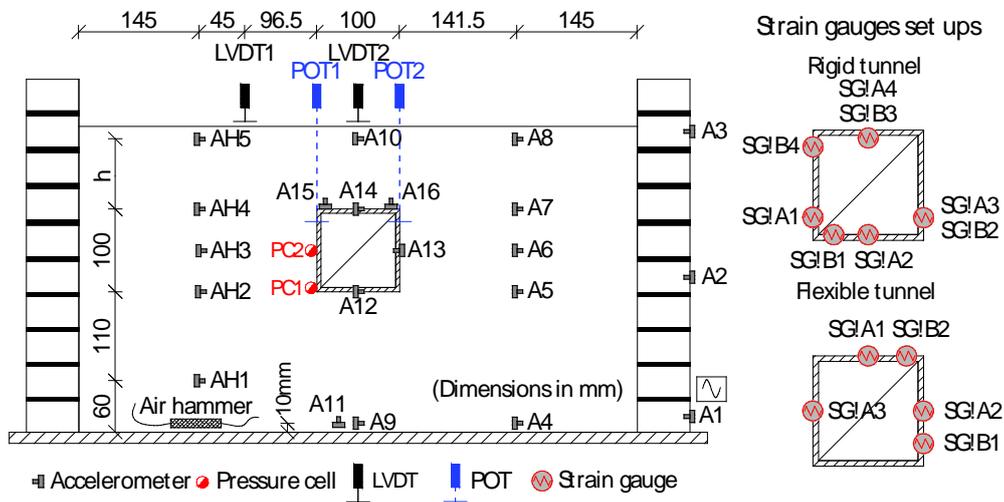
55 Three dynamic centrifuge tests were performed on square tunnel models embedded in dry  
56 Hostun HN31 sand, reconstituted at two different relative densities of about 50 % and 90 %.

57 Two square tunnel models were manufactured and tested, namely: a relative rigid one  
58 having a thickness of 2 mm and a more flexible one having a thickness of 0.5 mm (Fig. 1).  
59 The rigid model was made of an extruded section of 6063A aluminum alloy, while the  
60 flexible model was manufactured by folding a 33swg soft aluminum foil to form the square  
61 section and joined by means of a weld at the centre of the invert slab of the tunnel. Both the  
62 models were 100 mm wide, while the length was 220 mm for the rigid model and 210 mm for  
63 the flexible one. The thickness of the linings was selected so as to study the effects of tunnel  
64 flexibility at extreme ends. To simulate more realistically the soil-structure interface, Hostun  
65 sand was stuck to the external face of the tunnel-models, creating a rough surface.



66  
67 **Fig. 1.** (a) Flexible tunnel, (b) Rigid tunnel

68  
69 A typical model layout is presented in **Fig. 2**. A dense instrumentation scheme was  
70 implemented to record the soil-tunnel systems response, comprising of miniature  
71 accelerometers, linear variable differential transformers (LVDTs), draw wire potentionmeters  
72 (POTs), miniature total earth pressure cells (PCs) and resistance strain gauges to measure the  
73 internal forces of the lining at several locations (axial and bending moment strains). Details  
74 about the model preparation, setups, and representative experimental data may be found in  
75 [Tsinidis et al. \(2014; 2015b; 2015c\)](#).



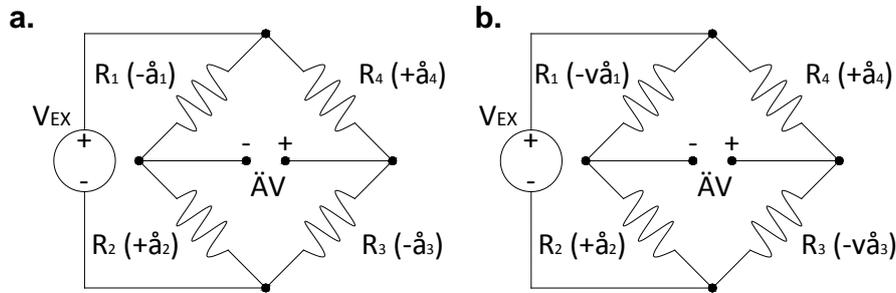
76  
77 **Fig. 2.** Typical models layout (h = 60 mm for flexible tunnel, 100 mm for rigid tunnel)

78  
79 **3. Strain gauging regime**

80 Resistance strain gauges (TML FLA-6-350-23) were attached to the inner and outer face of  
81 the tunnels to measure the bending moment and the axial force (bending and axial strains) at  
82 several locations around the tunnel lining (**Fig. 2**). Eight sets of gauges were used for the rigid

83 tunnel, with four of them recording the bending moments near the tunnel corners and at the  
 84 middle of the roof slab (SG-B1, SG-B2, SG-B3 and SG-B4 in Fig. 2) and four of them  
 85 recording the axial forces in the walls and the slabs of the model tunnel (SG-A1, SG-A2, SG-  
 86 A3, SG-A4 in Fig. 2). Similarly, five sets of strains gauges were used for the flexible tunnel,  
 87 namely; two sets were recording the bending moments near the tunnel corners (SG-B1, SG-  
 88 B2 in Fig. 2) and three sets were recording the axial forces in the walls and the roof slab (SG-  
 89 A1, SG-A2, SG-A3 in Fig. 2).

90 To achieve the greatest possible accuracy full Wheatstone bridges were used with two  
 91 gauges on the inside of the tunnel and two on the outside (Fig. 3). A full bridge allows for  
 92 strains which arise from alternative sources to be removed, for example the effect of  
 93 temperature changes, axial forces (in the case of the bending gauges) and bending moments  
 94 (in the case of the axial gauges).



95  
 96 **Fig. 3.** Typical circuit layouts for (a) bending moment strain gauges, (b) axial force strain gauges  
 97

98 The normal procedures with regard to adhering the gauges to the tunnel were followed. In  
 99 particular, to record the lining bending moments, the gauges were arranged by attaching a pair  
 100 of arms on the external face of the lining (e.g. \$R\_1\$ and \$R\_3\$ in Fig. 3a) and a second pair on the  
 101 internal face (e.g. \$R\_2\$ and \$R\_4\$ in Fig. 3a). An application of an excitation Voltage \$V\_{ex}\$ at the  
 102 extremities of the circuit causes a Voltage variation \$\Delta V\$ that can be measured with a  
 103 galvanometer, as illustrated in Fig. 3. According to the wiring pattern, the Voltage ratio is  
 104 proportional to the average deformation \$\epsilon\$ of the gauges:

$$105 \quad \frac{\Delta V}{V_{ex}} = \frac{K_{gf}}{4} \epsilon = \frac{K_{gf}}{4} (-\epsilon_1 + \epsilon_2 - \epsilon_3 + \epsilon_4) \quad (1)$$

106 where: \$K\_{gf}\$ is the gauge factor and \$\epsilon\_i\$ is the deformation of the \$i^{th}\$ arm of the bridge.  
 107 Assuming a linear elastic response for the lining, the deformations of the arms may be  
 108 computed, as follows:

$$109 \quad \epsilon_1 = \epsilon_3 = \frac{N}{EA} + \frac{M}{EI} \times \frac{t}{2}, \quad \epsilon_2 = \epsilon_4 = \frac{N}{EA} - \frac{M}{EI} \times \frac{t}{2} \quad (2)$$

110 where:  $t$  is the thickness of the lining,  $EI$  is the flexural stiffness of the lining,  $EA$  is the axial  
 111 stiffness of the lining,  $M$  is the bending moment at the specific location of the lining and  $N$  is  
 112 the axial load at the specific location of the lining. By substituting the arm deformations in  
 113 Eq. 1, the following expression is obtained for the Voltage change:

$$114 \quad \left\{ \frac{\Delta V}{V_{ex}} \right\}_M = -K_{gf} \times \frac{M}{EI} \times \frac{t}{2} = K_m \times M \quad (3)$$

115 Eq. 3 implies that the measured Voltage  $\Delta V$  is directly proportional to the bending moment  
 116 at the specific section, through the calibration factor  $K_m$  and the input Voltage  $V$ . In this  
 117 regard, it is related to known geometrical and mechanical parameters of the model.

118 Another bridge arrangement was implemented for the axial force strain gauges (Fig. 3b). A  
 119 pair of gauges ( $R_2$  and  $R_4$ ) was attached in the circumferential direction, while a second pair  
 120 of gauges ( $R_1$  and  $R_3$ ) was aligned perpendicularly, in order to form a couple of Poisson's  
 121 gauges. Following the elastic theory, the arm deformations are now given by the following  
 122 expressions:

$$123 \quad \begin{aligned} \varepsilon_1 &= -\nu \left( \frac{N}{EA} + \frac{M}{EI} \times \frac{t}{2} \right), & \varepsilon_2 &= \frac{N}{EA} + \frac{M}{EI} \times \frac{t}{2}, \\ \varepsilon_3 &= -\nu \left( \frac{N}{EA} - \frac{M}{EI} \times \frac{t}{2} \right), & \varepsilon_4 &= \frac{N}{EA} - \frac{M}{EI} \times \frac{t}{2} \end{aligned} \quad (4)$$

124 where:  $\nu$  the Poison ratio of the aluminium model. By substituting again the arm deformations  
 125 in Eq. 1, the following expression is obtained for the Voltage change:

$$126 \quad \left\{ \frac{\Delta V}{V_{ex}} \right\}_N = (1 + \nu) \times \frac{K_{gf}}{2} \times \frac{N}{EA} = K_n \times N \quad (5)$$

127 Similar to the bending moment gauges, the measured  $\Delta V$  is directly proportional to the axial  
 128 force at the specific section through the calibration factor  $K_n$  and the input Voltage  $V$ .

129

#### 130 **4. Calibration procedure**

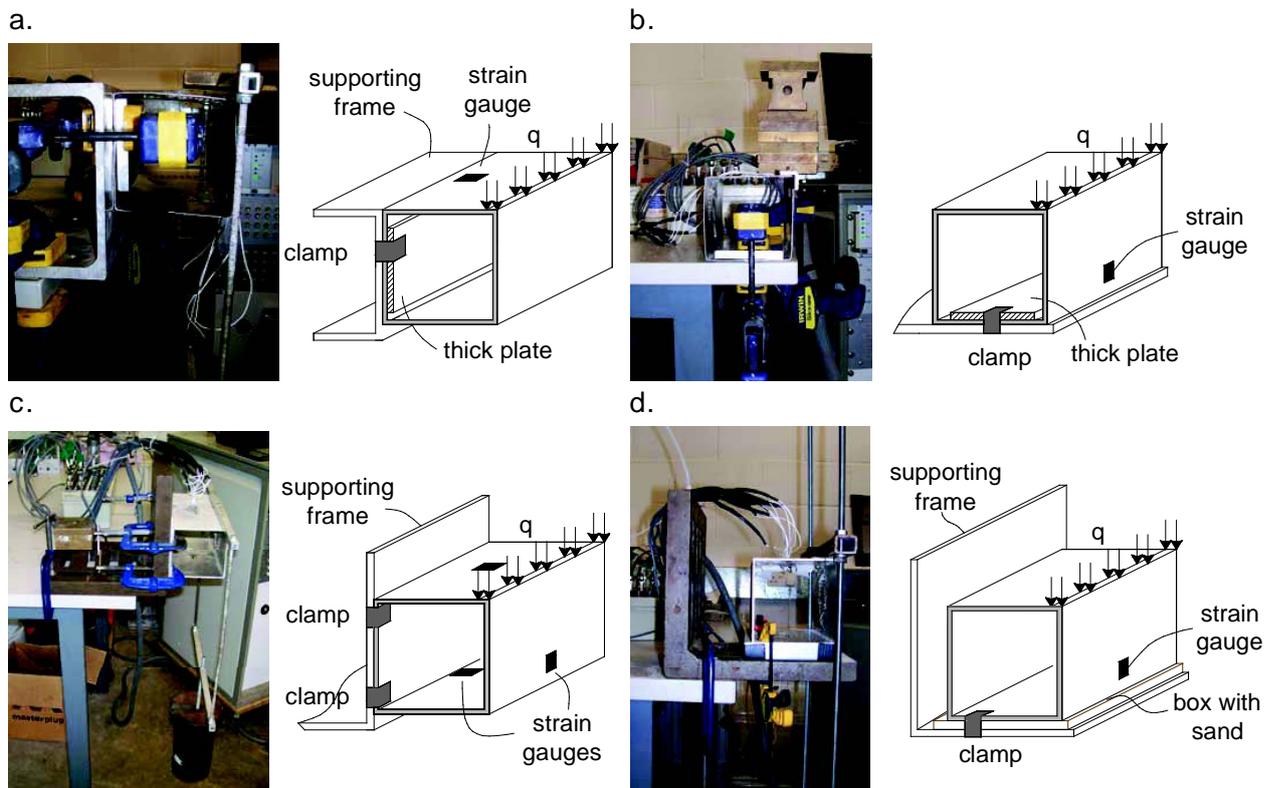
131 The calibration factors for both the axial and the bending moment strain gauges were derived  
 132 for simple static loading patterns. For each loading case, the model was incrementally loaded  
 133 and unloaded by adding and removing weights, while the output Voltage from each strain  
 134 gauge bridge was recorded for each loading step. The loading systems (e.g. loading locations,  
 135 fixities) were selected to ensure the elastic response of the model tunnels and therefore they  
 136 were slightly different between the flexible and the rigid tunnel, as described in the following  
 137 sections. Through these procedures, Voltage-mass calibration curves were derived. To come

138 out with the final internal force-Voltage calibration curves and thus with the final calibration  
 139 factors, the static configurations were properly simulated and analyzed, by means of 3D static  
 140 analyses, using the general purpose finite element code ABAQUS (ABAQUS, 2012). This  
 141 numerical approach was selected due to the complicated nature of the calibration system that  
 142 could not be described by available closed form solutions.

143

#### 144 4.1 Flexible tunnel loading regime

145 **Figures 4a** and **4b** present the loading set ups used for the calibration of the bending moment  
 146 and axial force strain gauges of the flexible tunnel, respectively.



147

148 **Fig. 4.** Static configurations for the calibration of (a) the bending moment gauges of the flexible  
 149 tunnel, (b) the axial force gauges of the flexible tunnel, (c) the bending moment gauges of the stiff  
 150 tunnel, (d) the axial force gauges of the stiff tunnel

151

152 To calibrate the bending moment strain gauges, one tunnel wall was clamped to a rigid  
 153 frame. The loading was introduced on the free side of the tunnel using a frame (to distribute  
 154 the load along the length of the tunnel), consequently forming a ‘cantilever static system’ for  
 155 the wall containing the strain gauge being calibrated (**Fig. 4a**). A thick aluminum plate was  
 156 introduced between the clamps and the tunnel to avoid stress concentrations in the tunnel

157 lining near the connections that could cause local yielding. This configuration resulted in a  
158 fixed connection for almost the entirety of the tunnel wall.

159 A similar configuration was used for the calibration of the axial force strain gauges (Fig.  
160 4b). The tunnel base slab was fixed using clamps, while a thick aluminum plate was  
161 introduced between the clamps and the tunnel to avoid stress concentrations near the fixities,  
162 similar to the bending moment case. The loading was introduced along the upper edge of the  
163 wall containing the strain gauge under calibration.

164 Each loading-unloading procedure was performed twice, so as to check the repeatability of  
165 the gauges response, while to calibrate all the strain gauges, the tunnel was appropriately  
166 rotated and clamped for each case. The calibration procedure was performed before the main  
167 centrifuge test, while no post test calibration was performed, as the tunnel collapsed during  
168 the actual test (Tsinidis et al., 2015b).

169

#### 170 **4.2 Rigid tunnel loading regime**

171 Figures 4c and 4d present the loading set ups used for the calibration of the bending moment  
172 and axial force strain gauges of the rigid tunnel. To calibrate the bending moment strain  
173 gauges, one tunnel wall was clamped using four points (upper and lower corner at each end)  
174 to a rigid frame (Fig. 4c). The loading was introduced on the free side of the tunnel using a  
175 frame. This configuration allowed the calibration of all the bending moment strain gauges  
176 simultaneously. The loading-unloading procedure was performed twice to check the  
177 repeatability of the gauges response, while the model was re-clamped and loaded several  
178 times, changing each time the “fixed side wall”. This procedure allowed multiple records for  
179 different loading patterns for each strain gauge to be collated.

180 A set-up similar to the flexible tunnel configuration was used for the calibration of the  
181 axial force strain gauges (Fig. 4d). The tunnel was seated on a small box containing  
182 compacted sand, while the base slab was held down (in case of uplifting during loading) with  
183 clamps at both ends of the tunnel. The solution involving the sand box at the base of the  
184 tunnel was implemented due to the sand that had been stuck along the external face of the  
185 tunnel, which in addition to the relatively high rigidity of the tunnel lining would have  
186 resulted to stress concentrations (e.g. ‘stress bridging’) affecting the strain gauge recording  
187 response, if a rigid flat surface (as in the case of the flexible tunnel) had been used under the  
188 tunnel instead. Indeed, testing the gauges without the sand box at the base did result in a much  
189 more scattered response. The loading was introduced upon the wall containing the under  
190 calibration strain gauge.

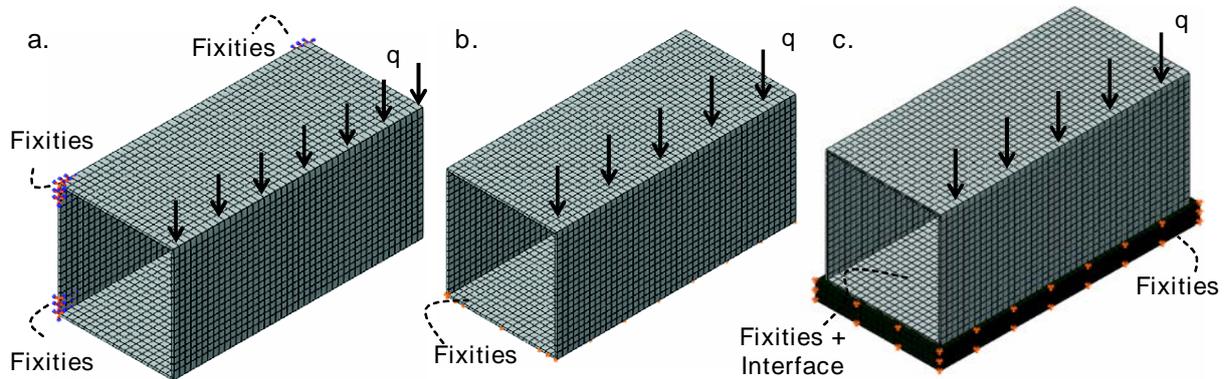
191 Similar to the other cases, each loading-unloading procedure was performed twice, so as to  
192 check the repeatability of the gauges response, while to calibrate all the strain gauges, the  
193 tunnel was properly rotated and clamped for each case. Both pre- and post-test calibration was  
194 performed to check the repeatability of the gauges response. Care was taken during the  
195 calibration procedure to ensure the loading magnitude was sufficient to obtain clear  
196 measurements of the strains without causing any yielding of the model-tunnel.

197

### 198 4.3 Numerical analysis

199 The internal forces at each gauge position were computed through numerical static analyses of  
200 the structural models. The results were plotted against the measured voltage change in order  
201 to evaluate each gauge calibration factor. The structural models were simulated in ABAQUS  
202 (ABAQUS, 2012) with elastic shell elements, taking into account the exact supports and  
203 loading positions of each test case (Fig. 5). The static load caused by the weight was  
204 introduced on the loaded area of the tunnel lining as an equivalent pressure,  $q$ , thus  
205 resembling the actual loading configuration imposed during the calibration procedure.

206



207

208 **Fig. 5.** (a) Numerical model of the rigid tunnel bending moment strain gauges calibration  
209 configuration, (b) simplified numerical model of the rigid tunnel axial strain gauges calibration  
210 configuration, (c) rigorous numerical model of the rigid tunnel axial strain gauges calibration  
211 configuration

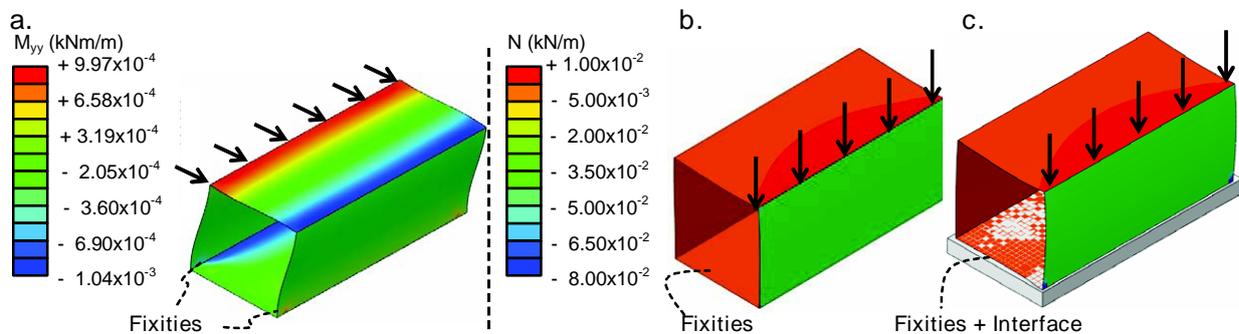
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213 The precise simulation of the actual support system by the numerical analyses is the key in  
214 order to determine the most accurate value for the internal force at the strain gauge locations.  
215 To replicate the static system used during the calibration procedure of the flexible tunnel  
216 bending moment strain gauges, the translational and rotational degrees of freedom of the  
217 tunnel along the clamped area (restrained with the thick aluminum plate as discussed) were  
218 fixed, while a similar procedure was also used for the axial force strain gauges.

219 For the simulation of the bending moment strain gauges calibration procedure of the stiff  
 220 tunnel, both the transnational and rotational degrees of freedom of the clamped areas were  
 221 fixed (Fig 5a). To examine the effect of the sand box at the base of the tunnel (used during the  
 222 calibration of the axial force strain gauges) two cases were investigated; during the first case,  
 223 the base slab of the tunnel was simply fixed in terms of vertical displacement (Fig. 5b), while  
 224 in the second case the sand layer under the tunnel was also simulated with solid elements  
 225 (Fig. 5c). The sand-tunnel interface was adequately modelled using a finite-sliding hard  
 226 conduct formulation embedded in ABAQUS (ABAQUS, 2012). The model precludes  
 227 penetration between the interacting surfaces, while it allows for separation. The tangential  
 228 behaviour was simulated implementing the classical isotropic Coulomb friction model. The  
 229 friction coefficient  $\mu$  was set equal to 0.62, based on the friction angle of the specific sand  
 230 fraction. The restraints that were induced by the clamps (e.g. end sides) were simulated with  
 231 proper kinematic constrains between the model tunnel nodes and the base of the sand layer  
 232 model. The sand elastic properties were parametrically checked, ranging between values  
 233 corresponding to either loose or dense sand.

234 Fig. 6 portrays typical deformed shapes of the stiff model tunnel, along with the  
 235 distributions of the internal forces for pressure loadings corresponding to a 1 kilogram of  
 236 weight. The effect of the static model configuration on the axial force of the stiff tunnel is  
 237 highlighted by comparing the numerical predictions between the simplified model and the  
 238 detailed model (Figs. 6b and c). The presented results refer to a relatively loose sand bed.  
 239 Generally, the difference on the computed axial force between the more accurate and the  
 240 simple model was less than 5 %, indicating that the presence of the sand bed did not had a  
 241 significant impact on the simulation.

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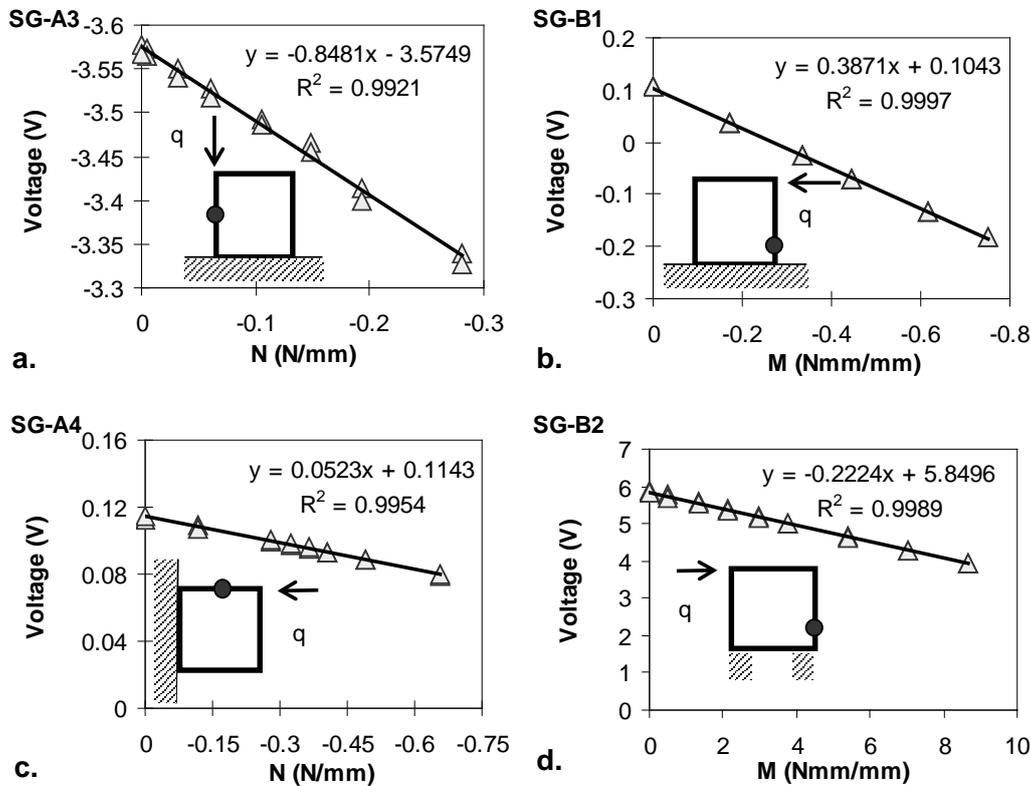


243

244 **Fig. 6.** Representative deformed shapes of the stiff tunnel for different loading configurations, (a)  
 245 contour diagram tunnel bending moment  $M_{yy}$ , (b) contour diagram of the axial force computed by the  
 246 simplified model, (c) contour diagram of the axial force computed by the detailed model

247 **4.4 Calibration factors**

248 **Fig. 7** presents representative examples of Voltage-internal force calibration curves, for axial  
 249 force and bending moment strain gauges attached to both the flexible and the rigid tunnel.

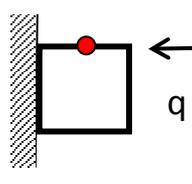
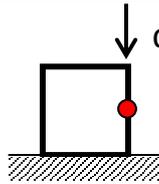
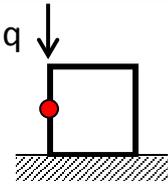


250  
 251 **Fig. 7.** Voltage-internal force calibration curves for the flexible tunnel strain gauges (a, b) and the  
 252 rigid tunnel strain gauges (c, d)

253  
 254 **Tables 1 and 2** summarize the calibration factors estimated for the flexible tunnel, while in  
 255 **Tables 3 and 4** the calibration factors of the rigid tunnel strain gauges are presented. With  
 256 regard to the flexible tunnel, the comparisons between the different loading repetitions  
 257 reveal differences up to 4-5 % for the bending moment strain gauges and up to 30 % for the  
 258 axial force strain gauges. Similar observations are made regarding the differences between the  
 259 recorded responses of the rigid tunnel strain gauges.

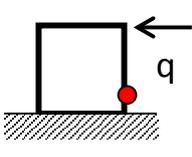
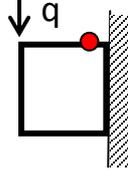
260 Generally, the calibration factors of the axial strain gauges were found to be more scattered  
 261 compared to the bending moment strain gauges. This is attributed to difficulties regarding the  
 262 axial loading of the tunnel-models. As already stated, the loading should be ‘strong’ enough  
 263 to obtain clear measurements of the axial strains, without however, jeopardizing the elastic  
 264 response of the model (e.g. yielding). In addition, problems related to the support systems  
 265 used during the calibration procedure or stress concentrations caused by the sand stuck around  
 266 the tunnel could affect the estimated factors.

267 **Table 1.** Axial force strain gauge calibration factors for the flexible tunnel

Loading case							Final calibration factor N/mm
	1	2	1	2	1	2	
Repetition #	1	1	2	1	2	-	
SG-A1	-1.5	-	-	-	-	-1.5	
SG-A2*	-	9.7	3.2	-	-	3.2	
SG-A3	-	-	-	-1.2	-1.7	-1.4	

268 \* probably malfunctioned

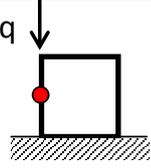
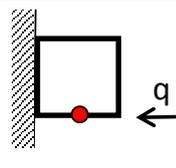
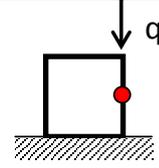
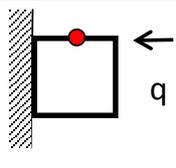
269 **Table 2.** Bending moment strain gauge calibration factors for the flexible tunnel

Loading case					Final calibration factor Nmm/mm
	1	2	1	2	
Repetition #	1	2	1	2	-
SG-B1	2.50	2.58	-	-	2.54
SG-B2	-	-	2.69	2.70	2.70

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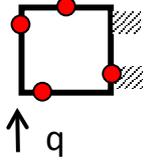
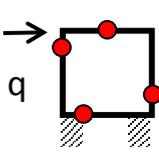
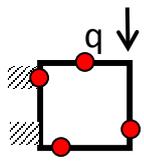
271 **Table 3.** Axial force strain gauge calibration factors estimated before and after test for the rigid tunnel

272 (factor for pre test calibration procedure / factor for post test calibration procedure)

Loading case										Final calibration Factors (N/mm)	
	1	2	1	2	1	2	1	2	3	Pre test	Post test
SG-A1	24.8/ 19.6	24.0/ 22.0	-	-	-	-	-	-	-	24.4	20.8
SG-A2	-	-	15.8/ 17.1	18.6/ 26.0	-	-	-	-	-	17.2	21.6
SG-A3	-	-	-	-	14.6/ 18.5	16.1/ 14.3	-	-	-	15.3	16.4
SG-A4	-	-	-	-	-	-	17.0/ 24	19.1/ 25	15.9/ -	17.3	25

273

274 **Table 4** Bending moment gauges calibration factors estimated before and after test for the rigid tunnel  
 275 (factor for pre test calibration procedure / factor for post test calibration procedure)

Calibration factors							Final calibration factors (Nmm/mm)	
	1	2	1	2	1	2	Pre test	Post test
SG-B1	4.50/ 4.50	4.60/ 4.00	4.90/ 4.90	5.10/ 5.20	4.70/ 5.40	4.70/ 5.40	4.74	4.90
SG-B2	-4.90/ -5.20	-5.00/ -5.00	-4.50/ -4.80	-4.60/ -4.90	-4.50/ -4.90	-4.50/ -4.90	-4.66	-4.94
SG-B3*	0.10/ 3.20	0.10/ 3.20	0.10/ 9.00	0.10/ 10.30	-1.40/ -26.00	-1.10/ -23.00	-	-
SG-B4	4.30/ 4.60	4.30/ 4.60	4.70/ 4.50	4.70/ 4.90	5.00/ 5.40	5.20/ 5.40	4.71	4.92

276 \*broken

277

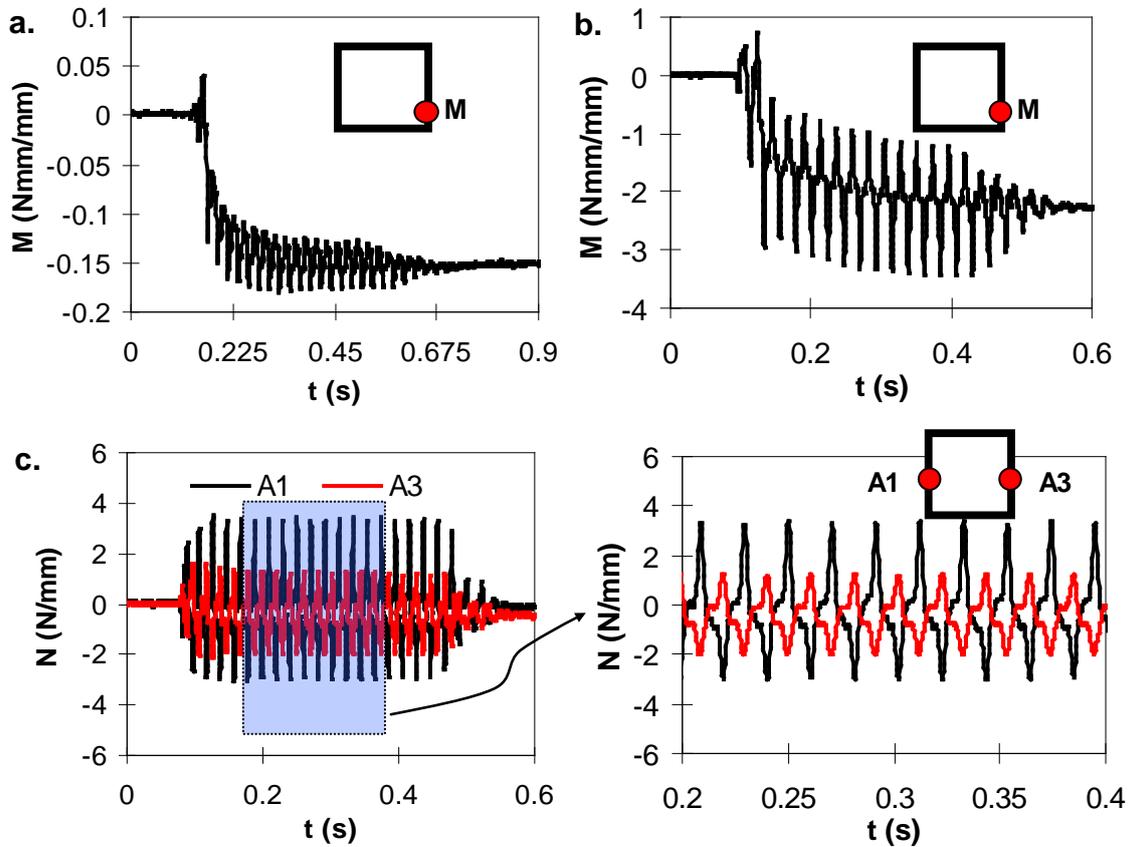
278 The calibration factors derived after the main centrifuge tests (for the rigid tunnel) were  
 279 slightly higher compared to the pre-test values, with the deviations being larger for the axial  
 280 force gauges. This could be attributed to a permanent lining response as a consequence of  
 281 severe loading during the earthquake loading. Therefore, the pre-test calibration factors were  
 282 adopted for the final interpretation of the lining recorded response data. In particular, a mean  
 283 value was adopted for each gauge factor, accounting for all the estimated factors of each  
 284 strain gauge and assuming the same level of uncertainty for each loading procedure.

285

## 286 5. Representative records

287 **Figures 7a and 7b** illustrate representative time histories of the dynamic bending moments,  
 288 recorded near the right side-wall bottom corner of both the flexible and the rigid tunnels.  
 289 Positive values represent bending moment with tensile stress increments for the internal lining  
 290 face. Records indicate significant locked-in bending induced strain after shaking finished, due  
 291 to the soil densification and yielding around the tunnel. Representative dynamic axial force  
 292 time histories recorded at the side-walls of the rigid tunnel are presented in **Fig. 7c**. In this  
 293 case, positive values represent tensile axial force. The records are out of phase, indicating a  
 294 rocking mode of vibration for the tunnel in addition to the pure racking distortion. A thorough

295 discussion of the recorded response may be found in relevant publications (e.g. Tsinidis et al.,  
 296 2014, 2015b; 2015c).



297  
 298 **Fig. 8.** Dynamic bending moment time histories recorded near the right side-wall bottom corner of the  
 299 (a) flexible and the (b) rigid tunnel, (c) dynamic axial force time histories recorded on the side-walls of  
 300 the rigid tunnel

301

## 302 6. Conclusions

303 A series of dynamic centrifuge tests were performed on square model tunnels embedded in  
 304 dry sand. This technical note presented the calibration procedure followed for the resistance  
 305 strain gauges, which were attached to the model tunnels to record the lining internal forces at  
 306 several crucial locations during the tests. Strain gauge calibration factors were derived for  
 307 simple static loading patterns. A crucial step within this calibration procedure was the rational  
 308 evaluation of the model response due to these simplified loading patterns (e.g. computation of  
 309 internal forces at strain gauges locations). This evaluation was performed by means of 3D  
 310 numerical analysis of the static configurations, simulating as accurately as possible the  
 311 supports and loading regimes. Accounting for the complicated nature of the calibration  
 312 system and the inexistence of plausible analytical closed form solutions, numerical analysis

313 was mandatory. The combination of experimental testing and numerical analysis was found to  
314 be quite satisfactorily in calibration of this model, as the recorded lining forces were found to  
315 be in good agreement with the theoretically expected behaviour. The main conclusion of this  
316 work is that combined experimental testing and numerical analysis can be used quite  
317 efficiently for the calibration of complex structural models, as well as for cases where no  
318 analytical closed form solutions are available. A crucial point for the efficiency of this  
319 approach is the proper simulation of the static configurations (e.g. supports, loading regimes  
320 etc).

321

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328

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