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Seismic network design to detect felt ground motions from induced seismicity

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Abstract

Human activities, such as fluid injection as part of the stimulation of an enhanced geothermal system (EGS) for heat and power production, can cause damaging earthquake ground motions. A difficulty in quickly settling or rejecting insurance claims to the policy of the operator of the EGS is the lack of ground truth on the observed shaking at sites of reported damage. To overcome this problem a local seismic network could be installed prior to injection to constrain the ground-motion field at points of potential damage. Since the installation and maintenance of seismometers is costly there is an incentive to keep the number of instruments to a minimum. In this short communication, ground-motion fields are simulated and receiver operating characteristic analysis conducted to guide decisions on the number of sensors required to obtain a certain confidence in the rate of false alarms and missed detections. For densities of 10–20 instruments per km² the ability to estimate potentially-damaging ground motions is reasonable but associated with a significant chance of missed detections and false alarms. If an EGS operator

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or regulatory authority does not want to accept such chances then network densities of 50–100 instruments per km² are required and even in this case the exceedance/non-exceedance of a certain ground-motion threshold cannot be completely constrained.

Keywords: seismic networks, geothermal power production, induced seismicity, spatial correlation, enhanced geothermal systems, earthquake ground motions, receiver operating characteristic

1. Introduction

Heat and power production via enhanced geothermal systems (EGS) is an attractive low-carbon renewable energy source and a number of tests of this technology are operating (e.g. Soultz-sous-Forêts, France) or are in the planning stage (e.g. Newberry, USA). In an EGS the permeability of a geothermal reservoir is enhanced using hydraulic stimulation, which purposely induces micro-earthquakes but because of existing (tectonic) may also trigger larger shocks [1]. As discussed by Gardini [2], during the Deep Heat Mining (Basel, Switzerland) project a mainshock of magnitude $M_L 3.4$ was triggered along with thousands of smaller earthquakes. The shaking from these tremors were cause for concern to the local population and led to the shutdown of this project and insurance claims amounting to more than \$9 million for minor building damage (e.g. non-structural cracking). A difficulty in resolving these insurance claims is knowing whether the observed building damage was actually due to shaking caused by earthquakes induced or triggered by the EGS or were actually pre-existing and only noticed after the tremors. Resolution of this question requires information on two aspects: the earth-

18 quake shaking that the local building stock was subjected to due to the EGS
19 project, and the vulnerability of the buildings to this shaking, which could
20 be modelled using appropriate fragility curves. The second of these topics is
21 not discussed here, although fragility curves to predict cracking from high-
22 frequency ground motions from shallow induced seismicity is a topic that
23 has not be widely researched and hence is ripe for investigation. This short
24 communication concerns the ability to recover the true earthquake shaking,
25 characterized by a scalar intensity measure (e.g. peak ground velocity, PGV)
26 that is useful for the prediction of building damage, based on measurements
27 from a local seismic network.

28 The advantage of having a local seismic network in a population cen-
29 tre close to an area of geothermal power production is shown by a recent
30 study concerning the Icelandic village of Hvergerdi, which is monitored by
31 the dense network known as ICEARRAY [3]. These instruments were used to
32 demonstrate that the pseudo-spectra accelerations in the village due to some
33 recent induced seismicity (including an $M_L3.8$ earthquake) from a nearby
34 (at 11 km) geothermal power plant, Hellisheidi, were close to and sometimes
35 surpassed the codified design spectral accelerations for the majority of the
36 building stock.

37 The aim of this study is to provide guidance on the number of instruments
38 required to obtain a certain detection rate of an intensity measure surpassing
39 a given threshold. It is based on the simulation of local ground-motion fields
40 consistent with those observed from induced seismicity. These simulations
41 are discussed in the following section. The subsequent section presents the
42 method (kriging) used to recover this ground-motion field based on obser-

43 vations at a limited number of (simulated) instruments. The penultimate
44 section analyzes the results of thousands of such simulations using the ap-
45 proach known as receiver operating characteristic (ROC) analysis to draw
46 graphs allowing the number of required instrument density to obtain certain
47 true and false positive rates to be estimated. This short communication ends
48 with some brief conclusions and suggestions for future research.

49 **2. Simulated ground-motion fields**

50 The procedure presented by Strasser and Bommer [4, pp. 2625–2626] is
51 used to simulated the spatially-correlated ground-motion fields taking into
52 account the within(intra)-event variability. Between(inter)-event variability
53 is considered in the ground-motion fields by the inclusion of event terms
54 within the PGV computation computed using the between-event standard
55 deviation (τ) and the normal distribution. Similar approaches have been
56 used in previous studies [e.g. 5]. Since the aleatory variabilities associated
57 with the GMPE used here are very large the ground-motion fields show great
58 differences and hence many runs are required to obtain stable results from
59 this analysis.

60 The empirical ground-motion prediction equation (GMPE) derived by
61 Douglas et al. [6] for PGV based on thousands of records from microseis-
62 micity in geothermal zones is used here to obtain the deterministic ground-
63 motion field assuming a point source, which is a common assumption for
64 small earthquakes even though the causative rupture will have length of a
65 few hundreds of metres. This equation, for a rock site based on a generic
66 velocity profile, is (in terms of cm/s and hypocentral distance, r_{hyp}):

$$\log_{10} y = -2.3426 + 0.8526M_w - 1.4048 \log_{10}(\sqrt{r_{hyp}^2 + 2.9330^2}) - 0.013r_{hyp} \quad (1)$$

67 with a between-event standard deviation of $\tau = 0.6746$ and a within-event
68 standard deviation of $\phi = 0.4467$. The impact of the high value of ϕ on the
69 results was tested and within a reasonable range for this component of the
70 aleatory variability it does not have a significant influence on the detection
71 rates so it is not considered further.

72 This deterministic ground-motion field is perturbed by the addition of
73 random field derived from a multivariate normal distribution based on an ex-
74 ponential correlation function with a correlation length h_0 (i.e. $\exp(-h/h_0)$,
75 where h is the separation distance between points of interest) and a stan-
76 dard deviation equal to the within-event variability of the selected GMPE.
77 The exponential correlation function has been found to fit the observed spa-
78 tial correlation of earthquake ground motions but h_0 appears to vary with
79 the structural period, geographical region and earthquake [e.g. 5, 7]. To
80 consider the observed range of h_0 two values are considered here: 5 and
81 20 km. In addition, two end-members: $h_0 = 0.001$ (no correlation between
82 sites) and $h_0 = 10000$ km (complete correlation between sites) are simulated
83 to understand the role of this key parameter, which is poorly known par-
84 ticularly for induced seismicity. The spatial correlation of ground motions
85 from small earthquakes could be higher than for larger earthquakes since
86 the point source assumption is more appropriate but on the other hand the
87 short seismic wavelengths from small earthquakes could mean that the spatial
88 variability is large because of scattering due to a heterogeneous crust.

89 A moment magnitude (M_w) of 3.5 and a focal depth of 3 km are assumed
90 for the scenario earthquake because EGS operators would hope to contain
91 the seismicity to smaller events and hence such a scenario could be considered
92 a worst case for most projects. An area of 1 km \times 1 km above the injection
93 well is considered for these calculations with a resolution of 20 m (i.e. a grid
94 of $50 \times 50 = 2500$ points) and the earthquake epicentre in the centre of
95 this zone. A building density of 1 000 houses per km², corresponding to a
96 European suburban area, is assumed. The number of instruments co-located
97 with the houses is varied between 10, roughly corresponding to the density
98 of the ICEARRAY [8], and 100, which is much higher than any existing
99 strong-motion array [9] and corresponds to an instrument every 100 m. A
100 PGV threshold of 7.4 mm/s is considered because this corresponds to the
101 2nd-percentile (median minus two standard deviation) PGV for an Modified
102 Mercalli intensity of V (slight cracking of plaster possible) according to the
103 ground-motion intensity conversion equations (GMICEs) of Worden et al.
104 [10]. These GMICEs are used because they are the most recent ones available
105 and they are based on a large database of observations (roughly 200 000
106 intensity-PGV pairs).

107 An example simulated ground-motion field with the associated houses
108 and sensors is presented in Figure 1 for $h_0 = 5$ km, showing the considerable
109 spatial variation to be expected in earthquake ground motions that is not
110 explained by the distance from the source. It is this spatial variation in
111 shaking that makes the estimation of ground motions at the location of a
112 house based on measurements at surrounding instruments prone to large
113 uncertainties.

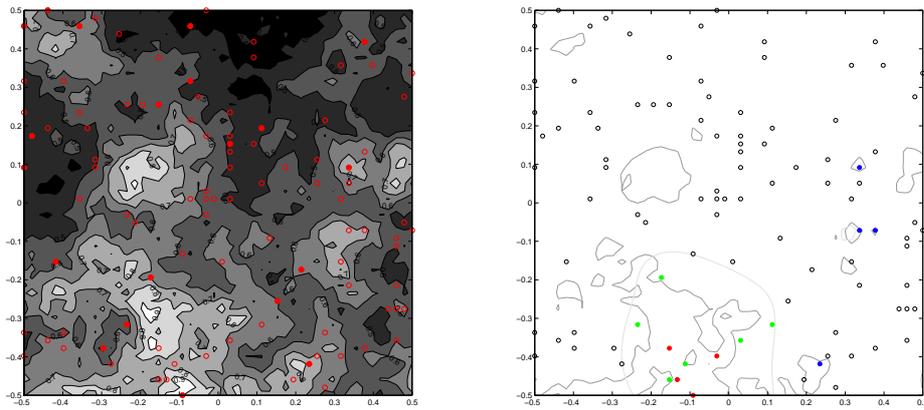


Figure 1: Left: Example ground-motion field simulated for this study, with the simulated locations of 100 houses (unfilled circles) and 20 instruments (filled circles). Right: Simulated (dark grey) and recovered (light grey) contour of PGV threshold using the measurements at the 20 instruments and the relations between these thresholds at the 100 considered houses colour-coded thus: red, true positive; blue, false negative; green, false positive; and black (unfilled), true negative. Note that 100 rather than 1000 houses are assumed to more clearly show the results.

114 **3. Recovery of observed ground motion at sites of interest**

115 In this section it is assumed that all that is available to estimate the
116 ground-motion field are the PGV observations at the simulated sensors. From
117 these measurements the PGVs estimated at the considered houses will be
118 computed and checked against the considered threshold. The geostatistical
119 technique known as kriging with a trend is used for this purpose. Krig-
120 ing is a commonly-used technique for the interpolation of measurements at
121 geographically-distributed locations and it has been used in ground-motion
122 estimation in a number of studies [e.g. 11, 12, 13]. The trend model used
123 as part of this procedure accounts for the overall distance decay that on av-
124 erage is present in earthquake ground motions — it is assumed here that
125 the earthquake location is precisely known (this is reasonable given that the
126 earthquakes are assumed to be induced in an EGS reservoir that is moni-
127 tored by a local seismic network). This technique roughly corresponds to
128 the inverse of the method used to simulate the ground-motion field because
129 kriging makes use of a spatial correlation model, for which here an exponen-
130 tial model is assumed for consistency with the simulations. A comparison
131 between the simulated and recovered ground-motion thresholds at the con-
132 sidered houses is shown in Figure 1. It should be noted that the same value
133 of h_0 is assumed as for the simulations — the impact of this assumption
134 is investigated below. In general this procedure leads to a high correlation
135 between the simulated and recovered PGVs at all grid points, particularly
136 when the density of instruments is large (Figure 2).

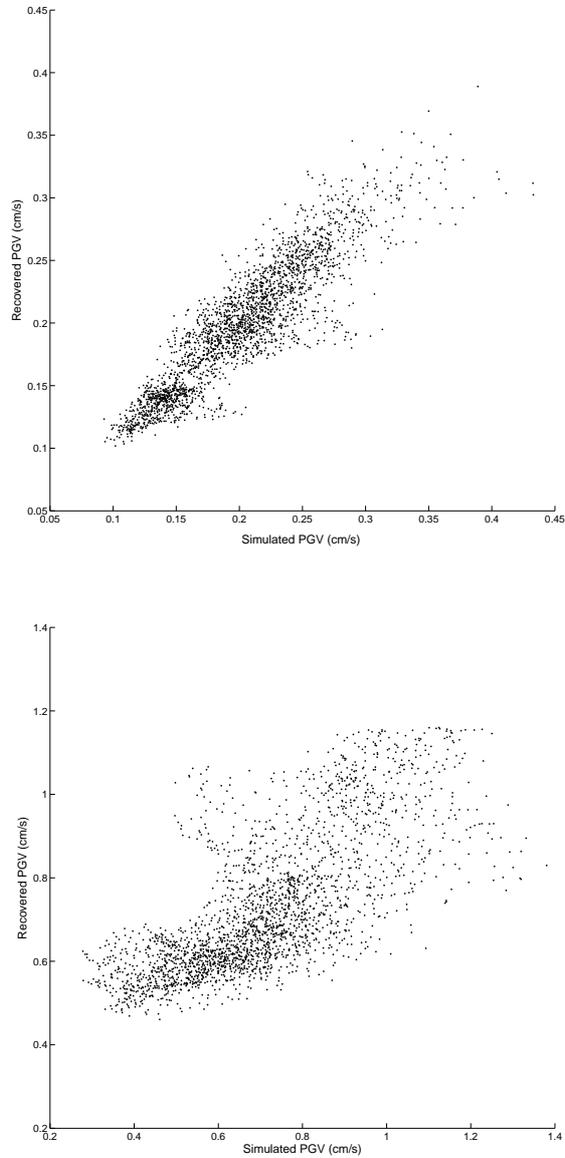


Figure 2: Top: Simulated versus recovered PGVs at the 2 500 grid points for an example ground-motion field assuming 200 instruments. Bottom: Simulated versus recovered PGVs at the 2 500 grid points for an example ground-motion field assuming only 20 instruments.

137 4. Receiver operating characteristic

138 In this study, the interest is in the ability to predict the surpassing or not
139 of a ground-motion threshold indicating a possibly damaging level of shak-
140 ing at houses within the epicentral zone. A useful tool in such a situation is
141 ROC analysis in which the rates of the four possible outcomes of a predic-
142 tion are considered. These four outcomes are: true positive (observed and
143 predicted PGV both above threshold), false positive (false alarm, i.e. pre-
144 dicted PGV above threshold but observed PGV actually below threshold),
145 true negative (observed and predicted PGV both below threshold) and false
146 negative (missed detection, i.e. observed PGV above threshold but predicted
147 PGV below threshold). A good local network would be one where the true
148 positive and negative rates were maximized with respect to the false positives
149 and negatives because this would allow, for example, the insurance claims
150 for building damage to be quickly resolved.

151 To construct a ROC curve the true positive rate is plotted against the false
152 positive rate. The better the prediction method the closer the ROC curve is
153 to the upper left hand corner of the graph $(0, 1)$, i.e.: a true positive rate of
154 100% and a false positive rate of 0% (no false alarms or missed detections).
155 The closer the ROC curve is to the 45 degree line the worse the detection
156 technique. These curves, therefore, provide a useful way of comparing the
157 ability of different densities of sensors to assess the PGVs at sites of interest.
158 The impact of increasing the density of instruments is shown in Figure 3,
159 where it can be seen that increasing the number of sensors moves the results
160 of the ROC analyses away from the 45 degree line and towards the top-
161 left corner. Because of the large variation in the ground-motion fields and

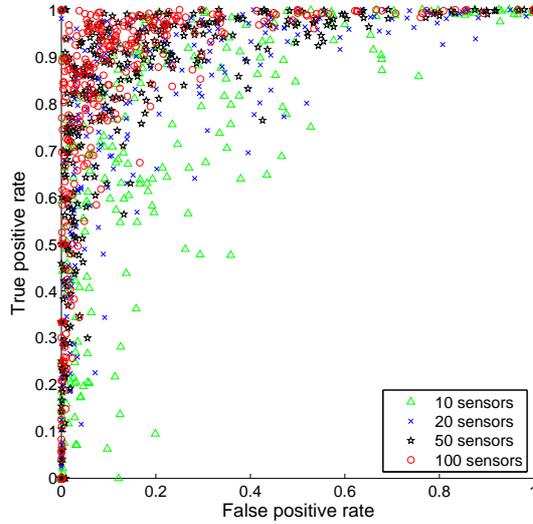


Figure 3: Results of ROC analyses for four different densities of instruments: 10, 20, 50 and 100 within a 1 km^2 zone assuming a spatial correlation length $h_0 = 5 \text{ km}$, $M_w 3.5$ and a PGV threshold of 7.4 mm/s .

162 the random distribution of houses and instruments the results of the ROC
 163 analysis do not form a curve but show considerable dispersion. In the extreme
 164 case of a seismometer in every house the ROC curve would correspond to a
 165 point at $(0, 1)$ indicating a perfect detection rate and no false alarms.

166 Modification of the size or depth of the scenario earthquake or the PGV
 167 threshold would increase or decrease the absolute number of samples above
 168 or below the considered limit without necessarily changing the ability of the
 169 network to discriminate between potential damaging amplitudes or not. For
 170 example, Figure 4 shows the results of a ROC analysis using the same proce-
 171 dure but assuming a smaller magnitude ($M_w 3$) and a lower PGV threshold,
 172 2.2 mm/s , corresponding to the 2nd-percentile (median minus two standard
 173 deviation) PGV for an Modified Mercalli intensity of IV (microcracks in

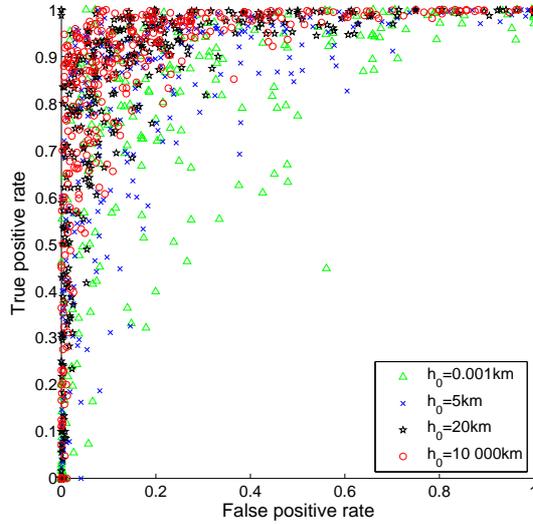


Figure 4: Results of ROC analyses for four different densities of instruments: 10, 20, 50 and 100 within a 1 km^2 zone assuming a spatial correlation length $h_0 = 5 \text{ km}$, $M_w 3$ and a PGV threshold of 2.2 mm/s .

174 plaster possible) again using the same GMICEs as above [10]. By comparing
 175 Figures 3 and 4 it can be seen that the rates of true and false positives are
 176 almost unchanged by the modification of the scenario and the threshold.

177 Apart from the instrument density, a key parameter affecting the ROC
 178 results is the correlation length h_0 . In Figure 5 the impact of varying this
 179 parameter is shown assuming 20 instruments. As expected, as the value
 180 of h_0 increases (PGVs at neighbouring points are increasing correlated) the
 181 ROC results tend to the top left corner, i.e. better detection rate with fewer
 182 false alarms. When there is no correlation between neighbouring points (h_0
 183 very small) the ground-motion field cannot be recovered from the available
 184 measurements and the question of whether PGV surpassed the considered
 185 threshold becomes a matter of complete chance. This is indicated by the ROC

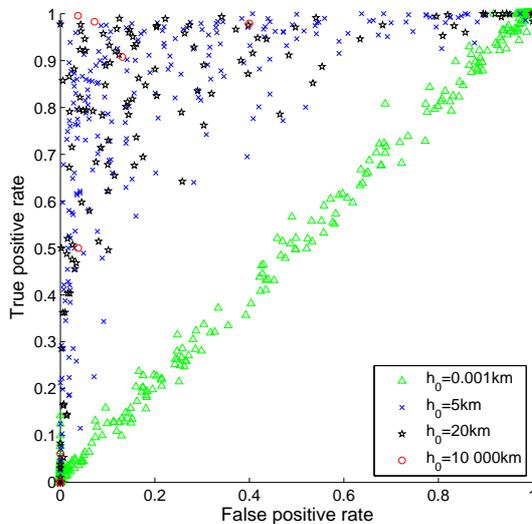


Figure 5: Results of ROC analyses for four different values of h_0 : 0 (no spatial correlation), 5, 20 and 10000 km (all points perfectly correlated) assuming 20 instruments.

186 curve falling along the 45 degree line in Figure 5. When ground motions are
 187 perfectly correlated spatially (h_0 is very large) the ground-motion field can
 188 be recovered at all points based on only a few measurements that enable the
 189 decay with distance to be estimated. This leads to a ROC curve that falls
 190 in the top left hand corner of the graph (Figure 5). The reason why there
 191 appears to be far fewer points for $h_0 = 10000$ km than for the other three
 192 cases is that almost all of the points overlap since the ground-motion fields
 193 only differ due to the between-event variability. There is generally a small
 194 difference in the results when $h_0 = 5$ or $h_0 = 20$ km.

195 One assumption made above is that the same h_0 is assumed to simulate
 196 the ground-motion field and to reconstruct the field based on PGVs at the
 197 hypothetical instruments. In reality, however, h_0 is uncertain. To investigate
 198 the impact of not knowing h_0 an additional test is conducted. ROC analyses

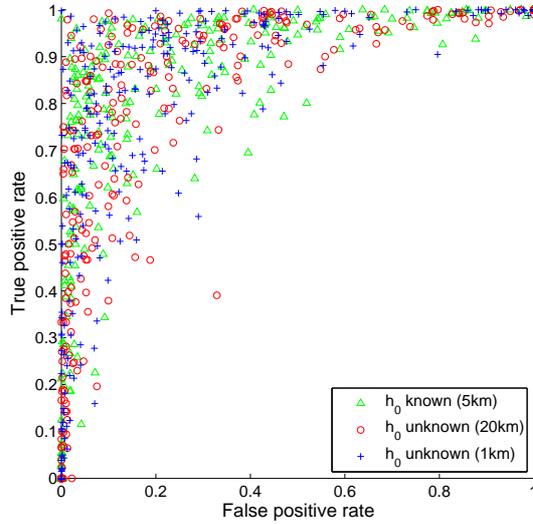


Figure 6: Results of ROC analyses for assuming 20 instruments and using $h_0 = 5$ km for the simulations and the same value for the inversion or $h_0 = 20$ km or $h_0 = 1$ km for the inversion.

199 are conducted assuming 20 instruments and $h_0 = 5$ km for the simulations but
 200 inversion assuming $h_0 = 20$ km or $h_0 = 1$ km, which can then be compared to
 201 the results when h_0 is assumed to equal 5 km (Figure 6). This graph supports
 202 the observation made previously that for h_0 within the range 5 (or even 1)
 203 to 20 km, which corresponds to the values observed for moderate to large
 204 earthquakes in active regions, the exact value used for this parameter is not
 205 critical.

206 5. Conclusions

207 In this brief article, the benefits of installing a (very) dense seismic net-
 208 work in the vicinity of a source of induced seismicity are assessed from the
 209 point of view of detecting potentially damaging motions at local buildings.

210 The considered scenarios are limited to those that are realistic from the point
211 of view of current monitoring technology, induced ground motions and the
212 latest research on spatial correlations. It is found that installing a local net-
213 work of a density similar to some recent arrays (e.g. ICEARRAY), i.e. 10 to
214 20 instruments per km² would lead to a reasonable detection rate but with
215 the risk of a considerable number of false alarms and missed detections. As
216 the number of sensors increases to densities not yet seen in engineering seis-
217 mology (50 to 100 instruments per km²) the number of missed detections and
218 false alarms decreases significantly. The density of instruments installed is a
219 decision for the EGS operator and the regulatory authority since it is related
220 to the chance of correctly recovering potentially-damaging ground motions
221 that is accepted by these organizations.

222 The type of study presented here could form part of a wider cost-benefit
223 analysis that seeks to find the optimum number of instruments to install in
224 the vicinity of a project that could induce earthquakes (e.g. an EGS) based
225 on the trade-off between the cost of the instruments and their installation and
226 maintenance and their benefit in terms of the ability to accurately estimate
227 the ground motions at points of interest and also, if the instruments could
228 also be used to locate earthquakes, the improvement in reservoir monitoring.
229 Such an analysis would require, however, estimates on the likely cost of re-
230 solving insurance claims, required length of monitoring and so forth, which
231 are difficult aspects to define *a priori*. For the location of a future project
232 where the locations of the buildings, their overall vulnerabilities to earth-
233 quakes and a local ground-motion model are known, a site-specific analysis
234 could be conducted following a similar approach to give more precise guid-

235 ance on the installation of a local monitoring network.

236 The results obtained here are dependent on the value assumed for the
237 spatial correlation length h_0 . As demonstrated by Jayaram and Baker [7]
238 and others h_0 appears to show a dependency on structural period, earthquake
239 magnitude and geographical region. All previous studies on this parameter
240 focus on its value for moderate and large tectonic earthquakes ($M_w > 5$)
241 in active regions with high instrument densities (predominantly California,
242 Taiwan and Japan) and, therefore, there is uncertainty on the values to
243 use for this key parameter for small induced earthquakes, particularly those
244 occurring in areas with low instrument densities. Therefore, there is a need
245 for additional research on spatial correlation of ground motions from small
246 (induced) earthquakes to better constrain spatial correlation models.

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