ASSESSMENT OF THE PERFORMANCE OF A NOVEL REGIONAL
LOW-MAGNITUDE GMPE FOR SOUTHERN ITALY

Francesca BOZZONI1, Elisa ZUCCOLO2, Carlo G. LAI3

ABSTRACT

Performance of a novel low-magnitude regional ground-motion prediction equation (GMPE) is assessed in the
paper by comparing GMPE predictions with independent ground-motion data and other regional, European, and
global GMPEs through the log-likelihood method. The novel GMPE was developed using 2270 waveforms
coming from 319 earthquakes occurred in Southern Italy till the end of year 2014, with local magnitudes ranging
between 1.5 and 4.2, recorded at 60 stations with hypocentral distances varying from 3 km to about 100 km. This
GMPE is able to predict peak ground acceleration and 5% damped spectral acceleration at 11 oscillator periods
ranging from 0.1 to 3 s with reference to stiff ground conditions (i.e. ground category B according to the Italian
Building Code and Eurocode 8). The GMPE coefficients were computed through a nonlinear weighted damped
least-squares algorithm, attributing a higher weight to accelerometric data recorded at stations whose soil
category was defined using purposely-assembled geotechnical and geophysical measurements. Predictions of the
GMPE are compared herein against an independent accelerometric dataset built out of 326 waveforms from 55
low-magnitude earthquakes occurred in Southern Italy in 2015, 2016, and 2017. The comparison shows that the
novel GMPE performs better than any other GMPE considered in this study (overall five attenuation models).
Applications of the proposed GMPE are also illustrated in the paper with reference to low-magnitude
earthquakes recorded by the regional seismic network operating in Southern Italy.

Keywords: GMPE, low-magnitude earthquakes, Southern Italy, performance, log-likelihood method

1. INTRODUCTION

Ground-motion prediction equations (synonyms of ground-motion models and attenuation
relationships) are empirical models which allow to estimate the earthquake ground motion expected at
a given site, starting from a varying number of seismological variables like the magnitude and the
hypocentral distance. Generally, the coefficients of these equations are defined by a curve fitting
procedure using recorded ground motion data. The GMPEs represent the simplest and most easy-to-
use tool to estimate one or more ground motion parameters or intensity measures (e.g. peak ground
acceleration, PGA, peak ground velocity, PGV, or other intensity measures), since they only require
knowledge of few seismological parameters such as the magnitude of the event and the location of the
epicenter/hypocentre. For these reasons GMPEs are widely used in a variety of applications from
seismic hazard assessment to earthquake early warning (EEW) systems.
Historically, GMPEs have been derived by using data coming from large earthquakes (moment
magnitude $M_W$ greater than 5), as recognized by Douglas (2016) in his most recent comprehensive
summary of attenuation relationships developed worldwide over the past 50 years. It has been well
established that empirical strong-motion GMPEs generally do not extrapolate reliably to smaller

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magnitudes (e.g., Bommer et al. 2007). Therefore, in the last few years, the development of GMPEs for low-magnitude earthquakes has grown rapidly. Several small-magnitude GMPEs have been published, for example Bommer et al. (2007), Massa et al. (2007), and Chiou et al. (2010). It is also important to point out that regional differences in ground-motion characteristics become more apparent at small magnitudes (e.g., Chiou et al. 2010).

We developed a novel low-magnitude ground-motion prediction equation (GMPE) for PGA and 5%-damped spectral acceleration at 11 oscillator periods from 0.1 to 3 s, based on a regional dataset of digital accelerometric signals recorded mainly in the Campania and Basilicata regions, in Southern Italy, by stations located on stiff ground conditions (i.e. ground category B according to the Italian Building Code, NTC 2008, and Eurocode 8, 2003; hereinafter, EC8).

After a brief presentation of the GMPE, which is fully described by Zuccolo et al. (2017), this paper focuses on the assessment of its performance. Predictions of the GMPE are tested against independent ground-motion data and compared with other GMPEs from the literature by means of the log-likelihood (LLH) method proposed by Scherbaum et al. (2009). The LLH method allows assessing the relative performance of various GMPEs against a ground-motion dataset. The importance of adopting an independent dataset in measuring the performance of ground-motion models is highlighted in the literature (e.g., Mak et al. 2017b). Thus, an independent accelerometric dataset built out of 326 waveforms from 55 earthquakes occurred in Southern Italy from 2015 to 2017, with local magnitude (M_L) ranging from 1.5 to 3.2, recorded at stations located on ground category B with hypocentral distances ranging from 3 to about 70 km, has been adopted in this study.

Moreover, applications of the novel GMPE are illustrated in the paper with reference to two low-magnitude earthquakes recorded by the local seismic network, named Irpinia Seismic Network (ISNet), showing the comparison between recordings and GMPE predictions.

2. BRIEF PRESENTATION OF THE GMPE

At EUCENTRE, a novel regional low-magnitude GMPE was developed in the framework of the “Tools and Technologies for Risk Management of Transportation Infrastructures (STRIT)” project, within a specific work package devoted to the development of tools to be used in the EEW system operating in Southern Italy. The GMPE, based on a regional dataset of digital accelerometric signals mainly recorded in the Campania and Basilicata regions, is able to predict PGA and 5%-damped spectral acceleration at 11 oscillator periods from 0.1 to 3 s.

An effort was made to reliably classify the majority of the seismic stations of the accelerometric database according to the soil categories specified by the Italian building code (NTC 2008). Geotechnical, geophysical and geological data were collected for the area under investigation, including 103 direct measurements of the shear wave velocity (V_S). A GIS (Geographic Information System) database was constructed as a basis for determining the ground conditions at the recording sites. For more than 30% out of 87 station sites, the soil category was defined based on the measured V_S profiles. For the remaining stations the classification was made using available geological information. Almost all seismic stations turned out to be located on ground category B (NTC 2008; EC8). As such, it was assumed statistically meaningful to generate a GMPE considering stiff ground conditions (soil B) only.

The dataset was built out of 2270 waveforms from 319 earthquakes, with local magnitude ranging from 1.5 to 4.2, recorded at 60 stations belonging to the regional ISNet network and to the Italian strong-motion network (RAN) with hypocentral distances ranging from 3 to about 100 km.

The GMPE has the following functional form:

\[ \log(Y) = a + bM_L + c \log(R) \pm \sigma_{log Y} \]

in which Y (the logarithm is in base 10) is the intensity measure to be predicted (in m/s², geometric mean of horizontal components), M_L is the local magnitude, and R is the hypocentral distance (in km). Regression coefficients and associated standard errors of the novel GMPE are shown in Table 1 for each intensity measure. The GMPE coefficients were computed through a weighted nonlinear damped
least squares algorithm, attributing an higher weight to accelerometric data recorded at the sites whose soil category was defined on the basis of the collected geotechnical and geophysical measurements. Further details on our GMPE can be found in Zuccolo et al. (2017).

Table 1. Regression coefficients (a, b, c) and associated standard errors (σ_{log Y}) for our GMPE (Zuccolo et al. 2017) for the prediction of peak ground acceleration (PGA) and spectral accelerations (SA).

<table>
<thead>
<tr>
<th>Y (m/s)</th>
<th>a (-)</th>
<th>b (-)</th>
<th>c (-)</th>
<th>σ_{log Y} (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGA</td>
<td>-2.1575</td>
<td>0.8359</td>
<td>-1.9690</td>
<td>0.3542</td>
</tr>
<tr>
<td>SA (T=0.1s)</td>
<td>-1.5885</td>
<td>0.7897</td>
<td>-1.9857</td>
<td>0.3898</td>
</tr>
<tr>
<td>SA (T=0.2s)</td>
<td>-2.1557</td>
<td>0.9031</td>
<td>-1.8537</td>
<td>0.3129</td>
</tr>
<tr>
<td>SA (T=0.3s)</td>
<td>-2.6067</td>
<td>0.9617</td>
<td>-1.8030</td>
<td>0.2805</td>
</tr>
<tr>
<td>SA (T=0.4s)</td>
<td>-2.9809</td>
<td>1.0189</td>
<td>-1.7945</td>
<td>0.2652</td>
</tr>
<tr>
<td>SA (T=0.6s)</td>
<td>-3.4484</td>
<td>1.0444</td>
<td>-1.7633</td>
<td>0.2609</td>
</tr>
<tr>
<td>SA (T=0.8s)</td>
<td>-3.7459</td>
<td>1.0314</td>
<td>-1.7163</td>
<td>0.2584</td>
</tr>
<tr>
<td>SA (T=1.0s)</td>
<td>-3.9527</td>
<td>0.9947</td>
<td>-1.6368</td>
<td>0.2607</td>
</tr>
<tr>
<td>SA (T=1.5s)</td>
<td>-4.2905</td>
<td>0.8673</td>
<td>-1.3798</td>
<td>0.2655</td>
</tr>
<tr>
<td>SA (T=2.0s)</td>
<td>-4.4619</td>
<td>0.7412</td>
<td>-1.1520</td>
<td>0.2666</td>
</tr>
<tr>
<td>SA (T=2.5s)</td>
<td>-4.5438</td>
<td>0.6423</td>
<td>-0.9925</td>
<td>0.2617</td>
</tr>
<tr>
<td>SA (T=3.0s)</td>
<td>-4.5811</td>
<td>0.5596</td>
<td>-0.8700</td>
<td>0.2573</td>
</tr>
</tbody>
</table>

3. DATA-DRIVEN ASSESSMENT OF THE PERFORMANCE OF GMPE

Assessment of the performance of GMPEs has been attracting increasing attention (e.g., Mak et al. 2017a). Such an evaluation is aimed at assessing the relative performance among alternative models by comparing model predictions with the corresponding observations. This is necessary for properly selecting the suitable GMPEs to be included in a seismic-hazard assessment, for demonstrating the superiority of a newly proposed model, or, ideally, for investigating how a model can be improved. Among proposed assessing methods, those using a score to quantify the model performance have the advantage of simplifying the comparison among the models. In a series of papers, Scherbaum and coauthors (e.g., Scherbaum et al. 2009) proposed scores based on likelihoods.

Performance of our GMPE (Zuccolo et al. 2017) is assessed herein by means of the LLH method proposed by Scherbaum et al. (2009). According to Scherbaum et al. (2009), the LLH values should be computed using a dataset different from the one used to develop the GMPE. Therefore, an independent dataset was built by collecting ground-motion data recorded by ISNet network in 2015, 2016, and 2017, as illustrated in Section 2.1. Predictions of the novel GMPE are tested against independent ground-motion data and compared with other GMPEs from the literature (Section 2.2).

2.1 Independent ground-motion dataset

The independent accelerometric dataset is composed of 326 accelerograms from 55 earthquakes with depth smaller than 30 km occurred in Southern Italy from 2015 to 2017, with local magnitude ranging from 1.5 to 3.2, recorded at stations located on ground category B with hypocentral distances ranging from 3 to about 70 km. Figure 1 shows the 55 earthquakes (red circles) used in this study to assess the performance of GMPE. The 319 earthquakes (grey circles) included in the dataset used to develop our regional GMPE are also overlapped in Figure 1.
Figure 1. GIS map showing the 319 earthquakes (grey circles), recorded by 60 stations (black squares), included in the dataset used to develop our regional GMPE (Zuccolo et al. 2017). The red circles indicate the 55 independent earthquakes used in this study to assess the performance of GMPE. The size and color of the circles is proportional to the event local magnitude. The Individual Seismogenic Sources (ISS) from DISS Working Group (2015) are also overlapped.

The independent dataset built by Zuccolo et al. (2017) using data recorded by ISNet in 2015 has been purposely-integrated in this study by using ground-motion data recorded in 2016 and 2017. Accelerometric data were downloaded from the SeismNet Manager (http://seismnet.fisica.unina.it/, last accessed October 2017), a web-based application that allows handling of ground-motion data acquired by ISNet. The available data were processed by using the same procedure adopted in the development of the GMPE. Indeed, following Emolo et al. (2011), uncorrected recordings were preliminarily processed for a linear detrending and to remove the mean acceleration. Subsequently, a band-pass filter (a four-pole Butterworth filter in the range 0.075-20 Hz) and a 2% cosine taper window were applied to the signals. For each seismogram the signal-to-noise ratio (SNR) was then computed to exclude records having a dominant noise contamination. The SNR was computed according to the procedure proposed by Vassallo and Cantore (2010), which is based on comparing the pre-event noise amplitude with respect to a portion of the signal centered at the time of occurrence of maximum amplitude. Only records with SNR greater than or equal to 10 in both the horizontal components of ground motion were selected. The independent dataset is composed of 326 good-to-high-quality accelerograms. Magnitude-distance distribution is shown in Figure 2, both in terms of $M_L$ and $M_W$ ($M_W$ values were retrieved from the ISNet Bulletin http://isnet-bulletin.fisica.unina.it/cgi-bin/isnet-events/isnet.cgi, last accessed October 2017) to allow a comparison with global GMPEs, which typically are based on $M_W$. Magnitude-distance distribution of the independent dataset adopted in this study (Figure 2b) is compared to the same plot provided in Zuccolo et al. (2017), shown in Figure 2a. It is important to highlight that the set of independent data adopted in this study cover an evident gap (between $M_L$ 2.5 and 2.8) in the magnitude-hypocentral distance distribution of the dataset used in Zuccolo et al. (2017).
2.2 Testing the relative performance of the novel GMPE among alternative models

Predictions of our GMPE are tested against independent ground-motion data (described in Section 2.1) and compared with other GMPEs from the literature. The adopted algorithm is based on the probability that an observed ground motion is actually realized under the hypothesis that a model is true (Beauval et al. 2012). In this study, the negative average LLH (Delavaud et al. 2009) was adopted. It measures the distance between a model and the data-generating distribution as:

\[ \text{LLH} = -\frac{1}{N} \sum_{i=1}^{N} \log_2(g(x_i)) \]  

(2)

where \( N \) is the number of observations \( x_i \), and \( g \) is the probability density function (assumed to have a normal distribution) predicted by the GMPE. The smaller the value, the closer is the candidate GMPE to the model that has generated the data.

Predictions of our GMPE (hereafter, ZUC17) were compared with those of other regional GMPEs (Frisenda et al. 2005, hereafter, FRI05; Massa et al. 2007, hereafter, MAS07; Emolo et al. 2011, hereafter, EMO11), an European model (Bindi et al. 2014a,b, hereafter, BIN14), and a global GMPE (Cauzzi et al. 2015, hereafter, CAU15). It is important to note that CAU15 was developed using the rupture distance (\( R_{\text{RUP}} \)) as distance metrics. However, \( R_{\text{RUP}} \) can be approximated to \( R_{\text{hyp}} \) for \( M_w \) smaller than 5.7 (Cauzzi et al. 2015), that is, in the magnitude range of our study. EMO11 proposed a regional GMPE developed for Southern Italy (i.e. the same area of our study) with a station-dependent functional form, thus ground motion was predicted herein only at the 21 stations considered in that study. Except EMO11 and FRI05, the remaining GMPEs were extrapolated below their magnitude range of validity.

The performance assessment of the aforementioned GMPEs against independent data is shown in Figure 3, in which the LLH value is plotted as a function of the structural period. ZUC17 provides the lowest LLH values (smaller than 1.0) for the entire period range, which means that it performs better than any other considered GMPE. Low values are also obtained for PGA for the remaining regional GMPEs. Among them, only MAS07 predicts spectral accelerations for periods different from zero (i.e., PGA). Despite the fact that LLH values for PGA are close to those computed for our GMPE, a
significant deviation can be observed for $T$ greater than 0.5 s. The two global GMPEs show the highest LLH values. LLH smaller than 1.0 are found only in two different limited period ranges: $0.2 < T \leq 1.0$ s for BIN14 and $1.25 < T \leq 2.0$ s for CAU15. This supports the idea that GMPE models based on moderate-to-large magnitudes are not able to correctly predict the ground motion for low-magnitude earthquakes.

![Figure 3. Log-likelihood (LLH) values versus structural period computed using the independent dataset for different GMPEs including our model (ZUC17)](image)

### 4. APPLICATIONS OF THE NOVEL GMPE

Applications of the novel GMPE are herein illustrated. Low-magnitude earthquakes recorded by the regional ISNet network (Table 2), not included in the database used to develop the GMPE, were selected for the comparison with ZUC17 predictions. The recorded signals were preliminarily processed by using the procedure illustrated in Section 3.1.

<table>
<thead>
<tr>
<th>Date</th>
<th>$M_L$</th>
<th>Lat. (°)</th>
<th>Long. (°)</th>
<th>Depth (km)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015-07-01</td>
<td>1.8</td>
<td>40.688</td>
<td>15.442</td>
<td>13.7</td>
<td>Sant’Angelo Le Fratte (Potenza)</td>
</tr>
<tr>
<td>2016-05-16</td>
<td>2.7</td>
<td>40.535</td>
<td>15.571</td>
<td>16.0</td>
<td>Ricigliano (Salerno)</td>
</tr>
</tbody>
</table>

Shake maps provide a first estimate of the spatial distribution of ground motion after an earthquake occurrence. Figure 4 shows the shake map computed by interpolating the 5% damped spectral acceleration computed at 0.1s oscillator period with reference to the $M_L1.8$ earthquake occurred in the Campania region (Southern Italy) on July 1, 2015 (red star) recorded by the ISNet stations. The *kriging algorithm* was adopted (e.g. Isaaks and Srivastava 1989) to obtain the shake map. The maximum value of 0.1s SA (computed as the geometric mean of the horizontal components) reached about 0.013 m/s² at SCL3, the recording station closest to the epicenter (at about 5.9 km). Figure 4 shows also the 0.1s SA mean values predicted by ZUC17 at the sites of recording stations (located on ground category B), represented by circles colored on the basis of the predicted SA. Concerning the stations near the epicenter, the predicted accelerations are in good agreement with the recordings: at SCL3 station the value predicted by the GMPE is equal to about 0.019 m/s². At COL3 station (located at 9.3 km from the epicenter), recorded and predicted values of SA are equal to 0.006 m/s² and to 0.008 m/s², respectively. With reference to the remaining stations, the GMPE predictions are generally lower than the observed values. However, the comparison is overall satisfactory.
Figure 4. Shake map obtained from the interpolation of 0.1s SA (geometric mean of the horizontal components in m/s²) recorded by the ISNet seismic stations (black squares) for the M_l 1.8 earthquake (red star) occurred in Southern Italy on July 1, 2015. Circles are colored on the basis of 0.1s SA predicted (mean values) at the stations sites by ZUC17 according to color scale adopted for the shake map.

With reference to the selected M_l 2.7 earthquake occurred on May 16, 2016, Figure 5 shows the observed PGA values (black circles) as a function of hypocentral distance, compared with our GMPE (mean values plus/minus one standard deviation represented by continuous and dashed red lines, respectively). From this first analysis, it turns out that predicted PGAs are in good agreement with the recordings.

Figure 5. Observed PGAs for the selected M_l 2.7 earthquake (black circles) as a function of hypocentral distance, compared with our GMPE (mean values plus/minus one standard deviation represented by continuous and dashed red lines, respectively)
Time histories recorded at the ISNet seismic stations for the selected $M_L$ 2.7 earthquake were processed to obtain acceleration response spectra (computed as the geometric mean of the horizontal components). Figure 6 shows the acceleration response spectra from the recordings compared to the predictions of our GMPE (ZUC17) and other models (i.e. MAS07, BIN14, CAU15) at two stations located at 17.3 km (a) and 54.4 km (b) from the epicenter, respectively. Regional models (i.e. ZUC17 and MAS07) capture the recorded response spectra better than other attenuation models. This agrees with the outcome obtained from the LLH values (Section 3).

Figure 6. Comparisons among predicted acceleration response spectra (average values, solid lines; average values plus/minus one standard deviation, dashed lines) and acceleration response spectrum of recordings at STN3 (a) and LIO3 (b) stations for the $M_L$ 2.7 earthquake occurred in 2016.
4. CONCLUSIONS

This paper illustrated a data-driven assessment of the performance of a recently developed low-magnitude GMPE proposed for Southern Italy (ZUC17). The GMPE, which is able to predict PGA and 5% damped SA up to 3s, was developed starting from waveforms coming from 319 earthquakes occurred till the end of year 2014, with local magnitude ranging from 1.5 to 4.2, recorded from 60 stations located on stiff soil (i.e. ground category B according to NTC 2008 and EC8), with hypocentral distances ranging from 3 to about 100 km.

The relative performance of the proposed GMPE against alternative models was assessed by comparing the model predictions with the corresponding observations by means of the LLH method. Five GMPEs were selected for the comparison: three regional models, i.e. FRI05, MAS07, and EMO11, one European GMPE, i.e. BIN14, and one global model, i.e. CAU15. An independent dataset was built by collecting ground-motion data recorded in Southern Italy by the regional network. Indeed, 326 waveforms from 55 earthquakes occurred from 2015 to 2017, with local magnitude ranging from 1.5 to 3.2, recorded at stations located on ground category B with hypocentral distances ranging from 3 to about 70 km, were used.

Our GMPE exhibited the best performance when compared with others GMPE models. As argued by Mak et al. (2017b), a data-driven GMPE evaluation purely based on empirical evidence is seldom sufficient to select attenuation models because the available data seldom cover all situations of practical interest. Nevertheless, a data-driven evaluation helps to clearly separate the portion of the decision made based on empirical evidence from that based on expert judgment, enhancing the transparency of the decision-making process.

Finally, some applications of our GMPE are provided in the paper with reference to two recent earthquakes of local magnitude 1.8 and 2.7 occurred in Southern Italy in 2015 and 2016, respectively. These events were recorded by a large number of seismic stations belonging to ISNet network. The GMPE estimates are in good agreement with the corresponding ground motion parameters from the recordings, represented in terms of shake map, attenuation plot (i.e. ground motion parameter as a function of hypocentral distance), and acceleration response spectra. In particular, the comparison between the acceleration response spectra predicted by the selected GMPEs and the response spectra of the recordings for two hypocentral distances of the $M_L$ 2.7 earthquake confirm the outcome obtained from the LLH values. Indeed, the proposed GMPE performs better than the other attenuation models considered in this study.

5. ACKNOWLEDGMENTS

The current research work has been carried out within the “Tools and Technologies for Risk Management of Transportation Infrastructures” (STRIT) project (Code PON01_02366), in the framework of the National Operational Programme for Research and Competitiveness 2007-2013 (NOP for R&C), cofounded with the European Regional Development Fund and national resources. We would like to express our gratitude to the governmental institutions involved within the NOP for R&C, in particular the European Commission, the Italian Ministry of Education, University and Research, and the Italian Ministry of Economic Development, for their support.

6. REFERENCES


