Ground motion prediction maps including site effects for Near-Real-Time Assessment of Seismically Induced Landslide.

Acunzo G., Falcone G., Mendicelli A., Mori F., Moscatelli M., Naso G.

05 November 2021
Summary

• Introduction: ground shaking, from source to local site effects

• Key dynamic properties and seismic effects national maps: $V_{S30}$, Amplification Factors

• Ground motion prediction maps

• Conclusions

• What's next?
• Introduction: ground shaking, from source to local site effects

• Key dynamic properties and seismic effects national maps: $V_{S30}$, Amplification Factors

• Ground motion prediction maps

• Conclusions

• What's next?
**Introduction:**
ground shaking, from source to local site effects

**Ground motion:** ground motion recorded at a reference site (outcropping stiff rock characterised by a flat ground surface), in general, differs from the ground motion recorded at a site of interest due to local stratigraphic condition, buried morphology, and topography.

**Seismic induced phenomena:** ground motion variation over small areas, subsidence, liquefaction, and landslides.

(from Kramer S.L., 1996)
**Ground motion prediction over small areas** is based on a detailed subsoil model and a proper characterization of mechanical soil response. In addition, the topography should be considered in the model. Moreover, an input motion should be retrieved from a proper hazard analysis considering the seismic source of interest (*Kramer, 1996*). Hence, numerical simulation of seismic site response is performed providing detailed output (e.g., acceleration time history, pseudo-acceleration response spectra, and so on).

On the other hand, **Ground motion prediction over large areas**, is based on key parameters which provide the mechanical response of soil, the subsoil setting, and the topography of the area of interest in a synthetic way. A reliable list of synthetic parameters is (*Zhou et al., 2020; Mori et al., 2021*):

- mean shear wave velocity in the upper 30 m of the soil deposit ($V_{S30}$);
- fundamental frequency ($f_0$) and thickness ($H_{cover}$) of the cover deposit;
- elevation ($H$);
- slope ($s$);
- topographic gradients ($h_x$ and $h_y$, where $x$ and $y$ are two orthogonal directions);
- second-order topographic gradients ($h_{xx}$ and $h_{yy}$).

Finally, the seismic source condition can be considered in terms of magnitude (M) and epicentral distance (R).
Ground motion prediction over small areas is based on a detailed subsoil model and a proper characterization of mechanical soil response. In addition, the topography should be considered in the model. Moreover, an input motion should be retrieved from a proper hazard analysis considering the seismic source of interest (Kramer, 1996). Hence, numerical simulation of seismic site response is performed providing detailed output (e.g., acceleration time history, pseudo-acceleration response spectra, and so on).

On the other hand, Ground motion prediction over large areas, is based on key parameters which provide the mechanical response of soil, the subsoil setting, and the topography of the area of interest in a synthetic way. A reliable list of synthetic parameters is (Zhou et al., 2020; Mori et al., 2021):

- mean shear wave velocity in the upper 30 m of the soil deposit ($V_{s30}$);
- fundamental frequency ($f_0$) and thickness ($H_{cover}$) of the cover deposit;
- elevation ($H$);
- slope ($s$);
- topographic gradients ($h_x$ and $h_y$, where $x$ and $y$ are two orthogonal directions);
- second-order topographic gradients ($h_{xx}$ and $h_{yy}$).

Finally, the seismic source condition can be considered in terms of magnitude ($M$) and epicentral distance ($R$).

Maps of synthetic parameters are required to predict ground motion over large areas.
• Introduction: ground shaking, from source to local site effects

• Key dynamic properties and seismic effects national maps: $V_{S30}$, Amplification Factors

• Ground motion prediction maps

• Conclusions

• What's next?
1) \(V_S\) and lithological data were retrieved from about 11'000 *in situ* investigations (DH, MASW, and continuous boreholes from Italian Seismic Microzonation Studies available at https://www.webms.it/);

2) \(V_S\) and lithological data were grouped according to 40 morpho-geological (Iwahashi et al., 2018) and 2 lithological clusters;

3) A multilinear regression model was performed for each cluster:

\[
\ln(V_{S30}) = c_0 + c_1 \cdot \ln(s) + c_2 \cdot \ln(H)
\]

where \(s\) and \(H\) are slope and elevation, respectively.

(from Mori et al., 2020a)
1) $V_S$ and lithological data were retrieved from about 16'000 and 44'000, respectively, in situ investigations (DH, MASW, and continuous boreholes from Italian Seismic Microzonation Studies available at https://www.webms.it);

2) About 2 millions of $V_S$ profiles were provided basing on a stochastic procedure and grouped according to 40 morpho-geological (Iwahashi et al., 2018) and 2 lithological clusters;

3) Reference motions were selected according with the Italian Seismic Hazard (http://esse1.mi.ingv.it/d2.html) with reference to 475 years as return period;

4) About 30 million of numerical simulations of seismic site response were performed;

5) A regression model was suggested for each cluster depending on the intensity of the reference motion:

$$\ln(\text{AF}) = c_0 + c_1 \cdot \ln^2(V_{S30}) + c_2 \cdot \ln(V_{S30})$$

where AF is the amplification factor.

(from Falcone et al., 2021)
Maps of key parameters (e.g., $V_{S30}$) and amplification factors can be considered to outweigh permanent ground deformation phenomena (e.g., liquefaction and slope movements). For instance, logistic regression models were considered. Machine learning procedure will be provided in the future.

The probability of landslide occurrence is given by:

$$P(X) = 1/(1 + e^{-t})$$

$$t = k_0 + k_1 \cdot \ln(PGV) + k_2 \cdot \text{slope} + k_3 \cdot \text{lithology} + k_4 \cdot \text{landcover} + k_5 \cdot \text{CTI} + k_6 \cdot \ln(PGV) \cdot \text{slope}$$

(Nowicki et al., 2018)

The probability of liquefaction occurrence is given by:

$$P(X) = 1/(1 + e^{-t}) = k_0 + k_1 \cdot \ln(PGV) + k_2 \cdot \ln(V_{S30}) + k_3 \cdot \text{precip} + k_4 \cdot \text{dw} + k_5 \cdot \text{wtd}$$

(Zhu et al., 2017)

where PGV was determined considering the local site effects (i.e., reference motion modified by the amplification factors).
Summary

• Introduction: ground shaking, from source to local site effects

• Key dynamic properties and seismic effects national maps: $V_{S30}$, Amplification Factors

• Ground motion prediction maps

• Conclusions

• What's next?
A ML procedure was selected to provide near-real-time ground motion prediction maps to support emergency management system. The paradigm was shifted from the evaluation of amplification factors to the evaluation of the ground motion variation over large areas directly including local site effects.

In detail, ML approach was adopted to:

i) implement source parameters (H, R, and M) available few minutes after a seismic event;

ii) include both lithostratigraphic ($V_{S30}$) and morphological ($h, h_x, h_y, h_{xx}, h_{yy}$) key parameters;

iii) provide maps of intensity measure (peak ground velocity, peak ground acceleration, and spectral acceleration at 0.3 s, 1.0 s and 3.0 s) over large areas few minute after an earthquake;

iv) capture the spatial variation at short distances (hundreds of meters) due to local site effects, which is essential for reliable hazard assessments.
<table>
<thead>
<tr>
<th>Type of data</th>
<th>Category</th>
<th>Control Factors</th>
<th>Database</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT</td>
<td>Seismological</td>
<td>H hypocentral depth</td>
<td>Seismological DB</td>
<td>Luzi et al., 2016 and 2020</td>
</tr>
<tr>
<td>INPUT</td>
<td>Seismological</td>
<td>M moment magnitude</td>
<td>Seismological DB</td>
<td></td>
</tr>
<tr>
<td>INPUT</td>
<td>Seismological</td>
<td>R epicentral distance</td>
<td>Seismological DB</td>
<td></td>
</tr>
<tr>
<td>INPUT</td>
<td>Geophysical</td>
<td>$V_{530}$ the time-averaged shear-wave velocity to 30 m depth</td>
<td>Seismological DB or $V_{530}$ map</td>
<td>Luzi et al., 2016 and 2020 DPC, 2018 Mori et al., 2020b</td>
</tr>
<tr>
<td>INPUT</td>
<td>Morphological</td>
<td>$h_x$ first order partial derivative $dx$ (E-W slope)</td>
<td>ALOS World 3D-30m DEM</td>
<td></td>
</tr>
<tr>
<td>INPUT</td>
<td>Morphological</td>
<td>$h_y$ first order partial derivative $dy$ (N-S slope)</td>
<td>ALOS World 3D-30m DEM</td>
<td></td>
</tr>
<tr>
<td>INPUT</td>
<td>Morphological</td>
<td>$h_{xx}$ second order partial derivative $dyy$</td>
<td>ALOS World 3D-30m DEM</td>
<td></td>
</tr>
<tr>
<td>INPUT</td>
<td>Morphological</td>
<td>$h_{yy}$ second order partial derivative $dxx$</td>
<td>ALOS World 3D-30m DEM</td>
<td></td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Seismological</td>
<td>PGA Peak Ground Acceleration</td>
<td>Seismological DB</td>
<td>Luzi et al., 2016 and 2020</td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Seismological</td>
<td>PGV Peak Ground Velocity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Seismological</td>
<td>$Sa_{0.3}$ Spectral acceleration at 0.3 s</td>
<td>Seismological DB</td>
<td></td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Seismological</td>
<td>$Sa_{1.0}$ Spectral acceleration at 1 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Seismological</td>
<td>$Sa_{3.0}$ Spectral acceleration at 3 s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The “Matlab Regression Learner App” tool (https://it.mathworks.com/help/stats/regression-learner-app.html) was employed to produce ground motion prediction maps using a supervised ML approach. The desired model among many different methods was chosen as characterized by the best performance in terms of RMSE.

<table>
<thead>
<tr>
<th>ML Prediction Model</th>
<th>Performance in term of RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PGA</td>
</tr>
<tr>
<td>Linear Regression (Linear)</td>
<td>0.53</td>
</tr>
<tr>
<td>Linear Regression (Interactions Linear)</td>
<td>0.48</td>
</tr>
<tr>
<td>Linear Regression (Robust Linear)</td>
<td>0.53</td>
</tr>
<tr>
<td>Stepwise Linear Regression (Stepwise Linear)</td>
<td>0.48</td>
</tr>
<tr>
<td>Tree (Fine Tree)</td>
<td>0.42</td>
</tr>
<tr>
<td>Tree (Medium Tree)</td>
<td>0.40</td>
</tr>
<tr>
<td>Tree (Coarse Tree)</td>
<td>0.40</td>
</tr>
<tr>
<td>Support Vector Machine (Linear)</td>
<td>0.53</td>
</tr>
<tr>
<td>Support Vector Machine (Quadratic)</td>
<td>0.43</td>
</tr>
<tr>
<td>Support Vector Machine (Cubic)</td>
<td>0.40</td>
</tr>
<tr>
<td>Support Vector Machine (Fine Gaussian)</td>
<td>0.48</td>
</tr>
<tr>
<td>Support Vector Machine (Medium Gaussian)</td>
<td>0.37</td>
</tr>
<tr>
<td>Support Vector Machine (Coarse Gaussian)</td>
<td>0.43</td>
</tr>
<tr>
<td>Ensemble (Boosted Trees)</td>
<td>0.40</td>
</tr>
<tr>
<td>Ensemble (Bagged Trees)</td>
<td>0.33</td>
</tr>
<tr>
<td>Gaussian Process Regression (Squared Exponential)</td>
<td>0.38</td>
</tr>
<tr>
<td>Gaussian Process Regression (Matern 5/2)</td>
<td>0.37</td>
</tr>
<tr>
<td>Gaussian Process Regression (Exponential)</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The Gaussian Process Regression (GPR) was selected to produce ground motion prediction maps.
The mean and standard deviation (std) values of the residuals’ distribution was quantified and compared with available literature data.

It is worth noting that the suggested ML approach provides the best performance with respect to the approaches proposed by the other studies in terms of both accuracy (mean value) and precision (standard deviation). In detail, the standard deviation values are reduced by the 45-60%.

\[
\text{residual} = \log_{10} \left( \frac{\text{IM}_{\text{observed}}}{\text{IM}_{\text{predicted}}} \right)
\]

<table>
<thead>
<tr>
<th>IM (geoH)</th>
<th>This study (ML)</th>
<th>ShakeMap*</th>
<th>GMPE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>std</td>
<td>mean</td>
</tr>
<tr>
<td>PGA</td>
<td>-0.000033</td>
<td>0.161</td>
<td>0.038</td>
</tr>
<tr>
<td>PGV</td>
<td>-0.000015</td>
<td>0.156</td>
<td>0.041</td>
</tr>
<tr>
<td>Sa0.3</td>
<td>0.000024</td>
<td>0.192</td>
<td>0.046</td>
</tr>
<tr>
<td>Sa1.0</td>
<td>0.000028</td>
<td>0.160</td>
<td>0.017</td>
</tr>
<tr>
<td>Sa3.0</td>
<td>-0.000072</td>
<td>0.159</td>
<td>-0.012</td>
</tr>
</tbody>
</table>

* Mean and standard deviation of the residuals’ distributions referred to ShakeMap and GMPE were retrieved from the work of Jozinović et al. (2021).
The adopted GPR model was used to produce ground motion prediction maps referring to the Central Italy earthquake occurred on August 24, 2016.

The maps show an output that is in good agreement with the geological and geomorphological characteristics of the territory and, therefore, highlights local site effects. In fact, it can be noted that the highest $S_{a0.3}$ values well describe the valleys’ trend (i.e., the largest and continuous Tronto River valley) and the two extended areas in the southern part of the map (i.e., near Petrana and Torrita villages), which are characterized by lowest values of $V_{S30}$ (Mori et al., 2020a).
With reference to AA', BB', and CC' tracks, the $S_{a0.3}$ values from ML procedure were compared to results from site-specific numerical simulations (Gaudiosi et al., 2021; Giallini et al., 2020; Grelle et al., 2020) and the constant value from ShakeMap (http://shakemap.rm.ingv.it/shake4/), which fails to grasp the local site effects at this scale.
Summary

• Introduction: ground shaking, from source to local site effects

• Key dynamic properties and seismic effects national maps: $V_{S30}$, Amplification Factors

• Ground motion prediction maps

• Conclusions

• What's next?
Conclusions

- Italian maps of mean shear wave velocity in the upper 30 m of the deposit ($V_{S30}$) and of amplification factors (AF) were produced considering morpho-geological clustering and site data (about 11'000 geophysical surveys and 44'000 continuous boreholes) from the Italian database of seismic microzonation studies.

- $V_{S30}$ and AF maps were considered to provide probability of landslide triggered by earthquake and of liquefaction based on regression logistic models over large areas.

- Ground motion prediction maps (peak ground acceleration, peak ground velocity, and spectral acceleration at 0.3 s, 1.0 s, and 3.0 s) were provided using a supervised Machine Learning approach (Gaussian Process Regression).
What’s next?

- Produce maps of other key soil parameters (fundamental frequency and thickness of the cover deposit).
- Improve ground motion prediction maps including new key soil parameters to describe site conditions.
- Provide a Machine Learning procedure to predict earthquake triggered phenomena (e.g., co-seismic slope failure) including site conditions and ground motion retrieved from previous maps.
The Working Group

Acunzo G.

Mendicelli A.

Moscatelli M.

Falcone G.

Mori F.

Naso G.
References


References


Thank you for your attention