Prediction Models for Vertical Ground Motion for Italy and France

Ramadan Fadel– National Institute of Geophysics and Volcanology, Milan, Italy, e-mail: fadel.ramadan@ingv.it

Lanzano Giovanni– National Institute of Geophysics and Volcanology, Milan, Italy, e-mail: giovanni.lanzano@ingv.it

Smerzini Chiara–Politecnico di Milano, Milan, Italy, e-mail: chiara.smerzini@polimi.it

Pacor Francesca– National Institute of Geophysics and Volcanology, Milan, Italy, e-mail: francesca.pacor@ingv.it

Traversa Paola–Electricity of France, Aix-en-Provence, France, e-mail : paola.traversa@edf.fr

Felicetta Chiara– National Institute of Geophysics and Volcanology, Milan, Italy, e-mail: felicetta.chiara@ingv.it

Abstract: This work presents a novel Vertical-to-Horizontal (VH) empirical Ground Motion Model (GMM) for peak ground acceleration, spectral accelerations up to 10s and peak ground velocity. Being calibrated on the most up-to-date dataset for Italian crustal earthquakes (ITA18), the model is consistent with the ITA18 GMM for the horizontal ground motion. To account for the increase of VH ratios in the proximity of the seismic source, an adjustment term is introduced to improve the prediction capability of the model in near-source conditions, relying on the worldwide NEar-Source Strong motion dataset (NESS). The proposed model uses a simple functional form restricted to a limited number of predictor variables, namely, magnitude, source-to-site distance, focal mechanism, and site effects, and the variability associated with both VH and V models is provided. The model predictions are compared to a French dataset, FR21 and a correction coefficient is calibrated, to be used in the epicentral area.

Keywords: ground motion model, Italian crustal earthquake, vertical-to-horizontal spectral ratios.

1. Introduction

For ordinary structures, seismic actions for design are typically prescribed only in terms of horizontal ground motion components, represented by a design response spectrum. According to the Italian Building Code NTC (2018) and Eurocode 8 - EC8 CEN (2004), the vertical component of the seismic action shall be taken into account in a very limited number of cases, typically, for base-isolated structures and for selected building components (e.g. horizontal structural members with large spans). Nonetheless, it has been recognized that the vertical ground motion may be significantly larger than its horizontal counterpart in the near-source region of earthquakes, especially at periods less than about 0.3s, with potential impact for short-period structures (Ramadan et al. 2021).

In general, two main approaches can be used to develop vertical design seismic spectra in the framework of a Probabilistic Seismic Hazard Assessment (Ramadan et al. 2021): (1) perform hazard integrations using Ground Motion Models (GMM) specifically developed for the vertical response spectral ordinates, (Chiou and Youngs, 2013); Çağnanet al., 2017) separately from those for the horizontal components; (2) use a GMM for the vertical to horizontal (VH) response spectral acceleration ratios to scale the horizontal Uniform Hazard Spectrum (UHS). The main limitation of the first approach is that disaggregation of hazard may lead to different earthquake scenarios controlling the horizontal and vertical spectral accelerations. Such inconsistency may pose obstacles to site specific engineering studies, such as in the selection of hazard-consistent three-component ground motions to be used in dynamic time history analyses of structures. For these reasons, the most commonly used approach is to generate the vertical spectrum by making use of empirical models for VH ratios (Bozorgnia and Campbell, 2016); Poggi et al., 2019). This approach, although simplified, is effective for seismic design purposes because it avoids performing vector-valued PSHA (Bazzurro and Cornell, 2002), including both horizontal and vertical components and the full treatment of their correlation.

Those models are regional dependent and calibrated for active shallow crustal regions. In some regions (i.e. France) the distance and magnitude ground motion scaling is hard to assess, given the scarcity of seismic records. In this case and instead of calibrating an ad-hoc model for vertical ground motion, correction factors could be computed for an existing model.

We present a complete study on empirical GMM for VH ratios of Spectral Acceleration (SA), Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) using Italian earthquakes and extending its applicability to near source region of active and continental shallow regions. The regression is calibrated using the same dataset adopted by Lanzano et al. (2019) for horizontal GMM, which ensures consistency between the two models, both in terms of validity range and functional form. To account for the effect of near-source conditions on the VH ground motion, a near-source adjustment term is proposed, following the Referenced Empirical Approach (Atkinson 2008; 2010). In this approach, for a given GMM, a corrective term is computed based on the residuals between the additional observations and the prediction, allowing to model specific effects on the ground motion (Figure 1). In our case, the corrective term for the reference ITA18 GMM is calibrated based on the analysis of residuals with respect to a worldwide dataset of near-source recordings, namely, NESS1.0 (Pacor et al. 2018). Then, we build a dataset of French records to extend the VH model to low-seismicity areas. To highlight the ground motion features in epicentral areas, the same approach of the near-source adjustment (Figure 1) is adopted, considering a French sub-dataset composed of records within 15km.

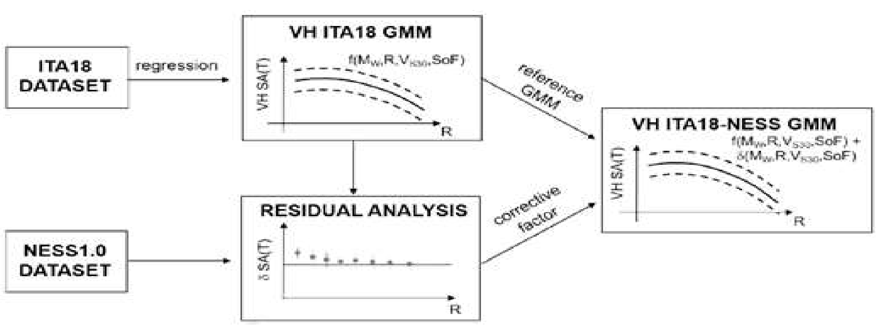

Fig. 1 Conceptual framework at the basis of the methodology proposed to develop the Italian VH GMM accounting for near-source effects, After Ramadan et al. (2021).

2. VH ITA18 model

2.1. ITA18 Dataset

The VH GMM model calibrated in this study is based on the ITA18 dataset, built to develop the horizontal GMM by Lanzano et al. (2019) for shallow active crustal regions in Italy. This dataset is composed of about 6000 seismic data for 156 events in the magnitude Mw range between 3.5 and 8 and recorded by 1684 stations within a RJB up to 200 km. Besides, the events are classified with normal (NF, 47% of total events), reverse (TF, 28%) and strike-slip (SS, 25%) focal mechanisms. We refer the reader to Lanzano et al. (2019) for detailed information regarding the dataset processing.

2.2. Functional Form

The functional form for the VH ITA18 median model is defined as follows (Ramadan et al., 2021):

$$log_{10} Y = a + F_M(M_W, SoF) + F_D(M_W, R) + F_S(V_{S30}) \quad (1)$$

where Y is the VH ratios for PGA, PGV and 36 ordinates of 5% damped SA in the range 0.01-10 s, a is the offset, $F_M(M_W, SOF)$ is the source function, $F_D(M_W, R)$ is the distance function and $F_S(V_{S3}\ )$ is the site term. The functional form is consistent with the one adopted for the horizontal GMM of Lanzano et al. (2019), apart from a minor modification regarding the source term owing to the more limited dependence of VH on M_w.

The source term consists of two terms:

$$F_M(M_W, SoF) = bM_W + \ f_j SoF_j \quad (2)$$

where coefficient b controls the source scaling and the coefficients f_j provide the correction for the Style of Faulting (SoF) of the event. SoF_js are dummy variables, introduced to specify SS (j=1), reverse TF (j=2), and normal NF (j=3) focal mechanism types. The regression is performed constraining to zero the coefficient for normal faulting ($f_3 = 0$). The path term is defined as:

$$F_D(M_W, R) = \left[c_1\left(M - M_{ref}\right) + c_2\right] log_{10} R \quad (3)$$

where the first term is the magnitude-dependent geometrical spreading and the second is the distance attenuation, M_{ref} is the reference magnitude assumed to be constant for all periods with a value of 6.0, while c_1 and c_2 are the path coefficients. The distance is computed as

$R = \sqrt{R_{JB}^2 + h^2}$, in which R_{JB} is substituted by R_{rup} when using the model coefficients related to R_{rup}, and h is the pseudo-depth, assumed to be constant for all periods with a value of 5 km. The values of M_{ref}=6 and h=5 km were calibrated from a first stage non-linear regression.

Finally, the site term is defined as a function of the time-averaged shear wave velocity in the top 30 meters (V_{S30}):

$$F_S(V_{S30}) = k\, log_{10}\left(\frac{V_0}{800}\right) \tag{4}$$

in which $V_0 = V_{S30}$ when $V_{S30} \leq 1500\, m/s$ and V_0=1500 m/s otherwise. Because the record sampling of very hard-rock sites is poor, the upper bound of the V_{S30} scaling, corresponding to 1500 m/s, above which the amplification is independent on V_{S30} according to Kamai et al. (2014). The function is linearly dependent on V_{S3} , consistently with the ITA18 horizontal model.

The uncertainty associated with the vertical ground motion is computed from the error propagation between the horizontal and VH models.

3. Near-Source Adjustment

The ITA18 dataset is governed by far-field records, and this may create biases in ground motion prediction in the proximity of the source. In this section a residual analysis is done with respect to a NEear-Source strong ground motion dataset, NESS1.0 see http://ness.mi.ingv.it/. An adjustment coefficient Fns is calibrated to account for near source effects.

In order to determine the proper functional form for the modeling of the adjustment factor, the residuals of ITA18 with respect to NESS1.0 data have been computed as follows:

$$\delta_C = log10(VH_{OBS,NESS}) - log10(VH_{ITA18}) \tag{5}$$

where $VH_{OBS,NESS}$ represents the observed VH from NESS1.0 dataset and VH_{ITA18} represents the predicted ratios from the ITA18 model as in Eq. (1).

As the residuals analysis shows a variation with respect to the different explanatory variables, the functional form for the correction term is defined as follows:

$$\delta_R = a_R + F_{MR}(M_W, SoF) + F_{DR}(R) + F_{SR}(V_{S30}) \tag{6}$$

where δ_R is the residual as in Eq. (5), a_R is the offset, $F_{MR}(M_W, SoF)$ is the source function, $F_{DR}(R)$ is the distance function, and $F_S(V_{S30})$ is the site term.

$$F_{MR}(M_W, SOF) = b_R M_W + f_{jR} SoF_j \tag{7}$$

$$F_{DR}(R) = c_R \, log_{10} R \tag{8}$$

$$F_S(V_{S30}) = k_R \, log_{10}\left(\frac{V_0}{800}\right) \tag{9}$$

The coefficients, b_R, f_{jR}, c_R, and k_R, and variables R, Mw and V_0 are defined as in the VH ITA18 model. However, the pseudo depth used herein is h_R=1 km, obtained from some trial regressions (Ramadan et al. 2021).

An improved VH model, referred to as VH ITA18-NESS hereafter, is then proposed as follows:

$$log_{10} VH_{ITA18-NESS} = log_{10}(VH_{ITA18}) + max(\delta_R, 0) \tag{10}$$

Figure 2 shows the median VH spectra of the proposed ITA18 and ITA18-NESS models for different scenario earthquakes, obtained by varying the explanatory variables one at a time (Figure 2A: R_{JB}; Figure 3B: Mw; Figure 2C: SoF; Figure 2D: V_{S30}). At short periods (less than 0.1 s), as expected, the VH ratios show a strong dependence on distance (Figure 2A), with higher values, up to nearly 1.5, for near-source sites (< 15 km).

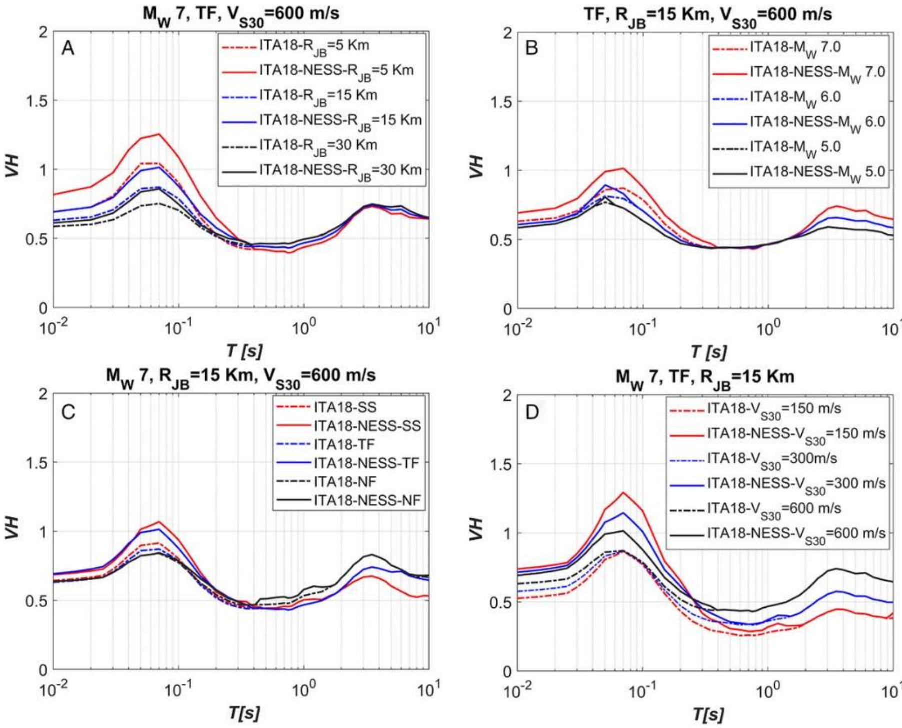

Fig. 2 Dependence of ITA18 and ITA18-NESS VH median spectra on (A) RJB, (B) Mw, (C) SoF and (D) VS30, After Ramadan et al. (2021).

4. Model correction for the French Context

4.1. Dataset

We selected events from the seismic dataset prepared by Traversa et. Al. (2020), with moment magnitude (Mw) greater than or equal to 3.0 and epicentral distance (Repi) less than 200 Km (see figure 3); we selected 119 stations installed in free-field or free-field-like conditions. The final dataset, named FR21, includes 2505 records of 297 earthquakes recorded by 119 stations in the period interval 1996-2019. Figure 3 the Mw-Rjb distribution of the ITA18 and FR21 datasets. It is rather clear that most records in both cases are from a distance > 10 Km and that a relatively high number of records in the French dataset are with a Mw <4. In fact, the ITA18 VH model shows a comparable result with respect to the FR21 dataset expect for ner source conditions. In which the NESS adjustment coefficient could not be applied as the Mw range of the FR21 is relatively small with respect to the NESS Mw.

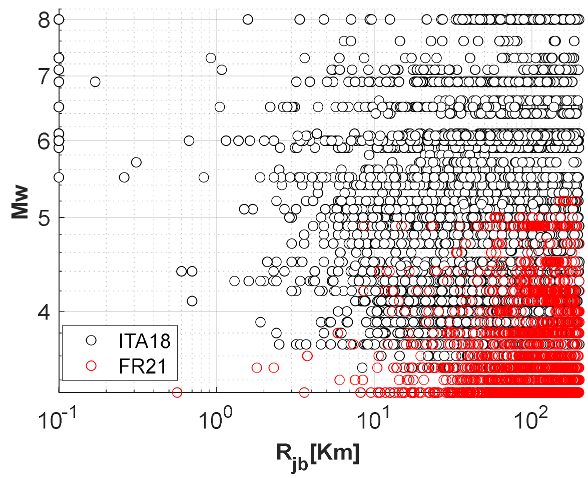

Fig. 3 Mw-Rjb distribution of the ITA18 and FR21 datasets

4.2. Correction Coefficient

Figure 4 shows the VH event- and site- correction residuals (δWes) are plotted as a function of Repi for distances <15 Km: the mean value of δWes is represented by a dotted red line and is remarkably positive at short periods (i.e. around 0.1 at SA(0.1s)), while it is almost zero at long periods.

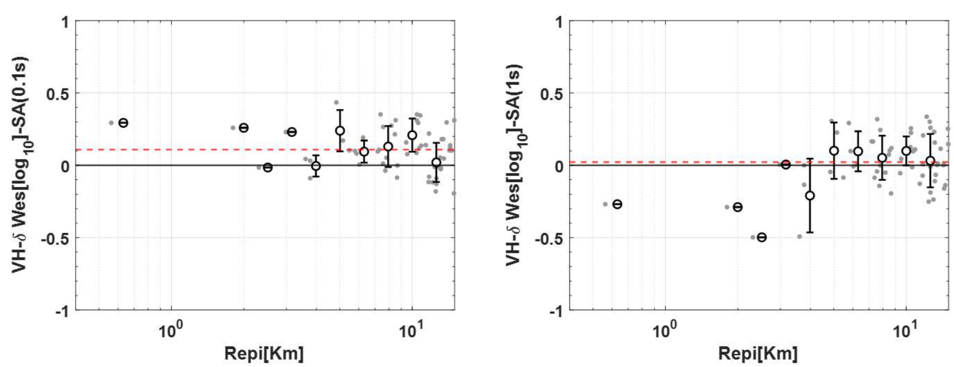

Fig. 4 ITA18 VH event- and site- corrected residuals (δWes) as a function of Repi for records with Repi<15km: a) SA-T=0.1s; b) SA-T=1s. Red dotted line represents the mean of δWes in this distance interval.

The average bias shows a positive peak at T=0.1s, corresponding to about 0.11 log10 units, i.e., an amplification of the VH ITA18 predictions of about 1.3 times. The minimum value is about zero (no amplifications) and is reached at about T=0.75s; while at longer periods it increases 17 again up to about 0.08 log10 units (amplification is about 1.2 times) at T=10s. No remarkable differences are observed between the ITA18 residuals in Rjb and Rrup.

This trend is confirmed in Figure 5, which shows the trend of the δWes mean with period for Rjb and Rupt ITA18 models: the average bias shows a positive peak at T=0.1s, corresponding to about 0.11 log10 units, i.e., an amplification of the VH ITA18 predictions of about 1.3 times. The minimum value is about zero (no amplifications) and is reached at about T=0.75s; while at longer periods it increases 17 again up to about 0.08 log10 units (amplification is about 1.2 times) at T=10s

Since the δWes mean value for the near-source region is calculated on a limited number of recordings (61), the bias trend does not change smoothly with period but presents many jumps. For this reason, rather than using the averaged value of δWes as model correction, we prefer to linearize the empirical curve of Figure 5, according to the following equation**:**

$$\delta_c(T) = \begin{cases} 0.6 \quad for \quad T \leq 0.07s \\ \frac{5}{3}T - 0.056 \; for \; 0.07s < T \leq 0.1s \\ -\frac{11}{90} \times T + \frac{11}{90} \; for \; 0.1s < T \leq 1s \\ 0 \; for \; T > 1s \end{cases}$$

(11)

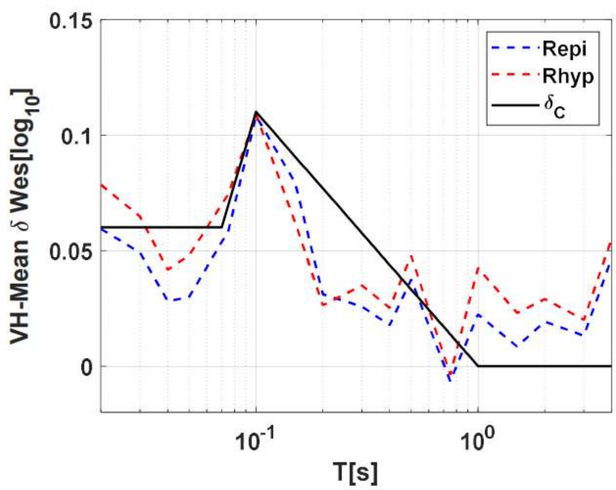

Figure 5 Mean value of the ITA18 VH event- and site- corrected residuals (δWes) of the spectral ordinates for the records within 15km as a function of period and δc(T) model to correct ITA18 VH in near-source condition (Repi<15 Km) for French events. Given the small magnitude of the events in the FR21 dataset, Repi and Rrup are used instead of Rjb and Rrup.

The expression of δc in Eq. [11] follows the shape of the mean residual δWes for the first peak at 0.1s and resets to zero at 1s; at longer periods we ignore the increasing trend as the long periods of small earthquakes are poorly sampled.

The correction term δc can be used to predict the VH spectrum in France in near-source conditions (Repi<15Km 3.0<MwM5.5), according to the following expression:

$$\boldsymbol{log_{10} Y_{ITA18-FR}(T) = log_{10} Y_{ITA18}(T) + \delta_c(T)} \qquad (12)$$

where ITA18 is the VH model for Italy by Ramadan et al. (2021) and ITA18-FR is the abbreviation for the ITA18 model corrected for France.

5. Conclusion

This study proposes a novel empirical GMM for VH response spectral accelerations (up to 10 s), PGA and PGV for shallow crustal earthquakes in Italy. The model is calibrated using the most up-to-date Italian seismic dataset, ITA18, hence consistent with the horizontal GMM Lanzano et. al. (2019). The model is a function of predictor variables, namely, magnitude, source-to-site distance, site condition and focal mechanism. An adjustment coefficient is suggested for near-source conditions. The latter coefficient is calibrated after evaluating the residuals of the model with Near-Source strong ground motion dataset, NESS1.0. A French subset, FR21 is prepared with Mw range between 3.2 and 5.2. The model is tested against the latter French dataset and tends to represent the French context, however, an offset bias is observed at short periods and distances Repi<15 Km. For this reason, a correction coefficient is suggested to improve the capability of the model to predict VH ratios not only within Italian context but within the French one as well.

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