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# A DATABASE OF DAMAGE-CONSISTENT (INTENSITY-BASED) NATURAL AND SYNTHETIC ACCELEROGRAMS FOR SEISMIC RISK

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## ABSTRACT

The actual practice of seismic-risk assessment for critical infrastructures is based on Uniform Hazard Spectra (UHS) derived from Probabilistic Seismic Hazard Assessment (PSHA) in the format of (pseudo) spectral accelerations. The spectral (force-based) method is still widely applied in earthquake engineering, especially in the design of systems. It is also applied in fragility analysis. The UHS and subsequently the time-history derived based on it has the problem that in reality it does not represent a uniform hazard but the weighted contribution of earthquakes leading to very different intensities at the plant site.

In this work the outline of a methodology proposed to develop a database of damage-consistent accelerograms is presented. Macroseismic intensity represents a measure of the strength of an earthquake record inferred from observed damage. According to the European Macroseismic Scale (EMS), different earthquakes characterized by the same macroseismic intensity should lead to the same mean observed damage on buildings with homogenous characteristics (vulnerability classes). At the same time, macroseismic intensity allows to consider the variability on the ground motion parameters associated with the same level of damage. Therefore, to perform non-linear time-history analyses with intensity-consistent sets of accelerograms, means to subject the structures to the same damaging potential and to catch the variability on ground motion parameters. In order to do this, a database of intensity (EMS) consistent natural accelerograms is developed starting from existing catalogues of records and observed intensity. In order to extend the availability of intensity-consistent accelerograms, a methodology is then proposed to assign the macroseismic intensity to physics-based simulated accelerograms. This methodology is based on correlations between intensity and ground motion parameters and tested using non-linear SDOF systems representative of the non-linear behavior of different buildings vulnerability classes.

## INTRODUCTION

Classical Performance Based Seismic Design (PBSD) and seismic-risk assessment is based on Probabilistic Seismic Hazard Assessment (PSHA) (Cornell, 1968) using as representative ground motion intensity measure the spectral acceleration. This procedure leads to the definition of the Uniform Hazard Spectrum (UHS), that is, a response spectrum that shows at each vibrational period the spectral acceleration having a predefined probability of exceedance in a fixed period of time. UHS represents a weighted value due to the contribution of different earthquakes having different damaging potential (Klügel and Stäuble-Akcay, 2018), this is illustrated in a qualitative manner in Figure 1. Therefore, if a UHS is used as target spectrum, even when selecting spectrum compatible accelerograms the final structural demands will be affected by the different damaging potential of each selected accelerogram, hence the structures under analysis are not subject to a uniform hazard. Moreover, even if spectral acceleration represents an efficient intensity measure, it still represents a peak value and cannot capture the damaging features of the earthquake that depends on the time evolution (incl. duration) of the accelerations.

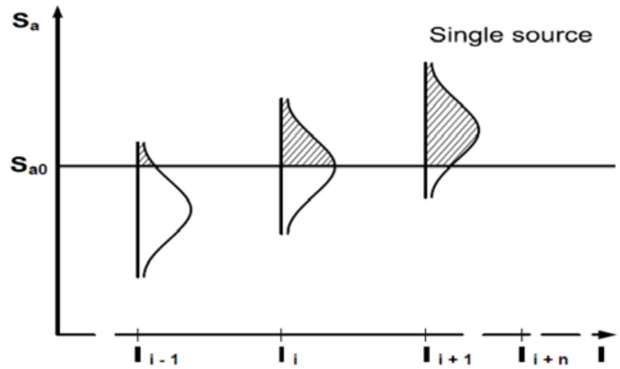


Figure 1. Illustration of the calculation concept of PSHA (example for a single source that with different frequency can cause earthquakes of different strength leading to different site intensities).

Seismic Hazard Assessment (either probabilistic or deterministic) can be done also using macroseismic intensity as intensity measure. Differently from spectral acceleration, macroseismic intensity represents a measure of the strength of the ground shaking inferred from the mean damage observed in a homogeneous area. In other words, buildings are used as sensors and the extent of damage is used as a measure of the strength of the signal. In particular, the European Macroseismic Scale EMS (Grünthal, 1998) should lead to consistent measures of the strength of the signal even if the built environment where the macroseismic intensity is assessed is very different. In other words, if the same earthquake (the same recorded signal) happens in two different cities with two different built environments, the evaluation of the intensity using the EMS should lead to the same value. This is assured subdividing buildings in different vulnerability classes and observed damage in different damage grades.

Since macroseismic intensity is directly based on observed damage, it follows that accelerograms having the same macroseismic intensity show the same damaging potential. Based on this consideration, non-linear time history analysis performed with accelerograms having the same macroseismic intensity should lead to a damage consistent evaluation of the performance of a building (or a stock of buildings), therefore to a damage-consistent risk analysis.

In this paper the outline of a methodology to assign the EMS macroseismic intensity ($I_{EMS}$) to accelerograms is presented along with some preliminary results. The methodology, is developed and proposed in the framework of the European project SeIsmic Ground Motion Assessment 2 (SIGMA-2, http://www.sigma-2.net/).

The final purpose is to create a database of damage-consistent natural and synthetic accelerograms to be used to perform intensity-based fragility assessment and subsequently, seismic risk analysis, to be compared with the risk results based on the classical PSHA with magnitudes and spectral accelerations.

## PROPOSED METHODOLOGY

The procedure consists mainly in three fundamental steps:

- developing a database of intensity (EMS) consistent natural accelerograms starting from existing catalogues of records and observed intensities;

- develop regressions between macroseismic intensity and ground motion parameters or structural demands on simplified SDOF systems;
- using the developed regressions, extend the database assigning a macroseismic intensity to physics-based synthetic accelerograms.

***Database Assembly***

The procedure proposed to assemble the Combined Database of Records and Observed Macroseismic Intensity (hereafter CROMI) consists in downloading the macrodata points (MDP) and the natural records from available databases and linking them using a minimum distance between the MDP and the record station. Similar procedures have been followed by many authors to in order to develop linear regressions between macroseismic intensity and ground motion parameters, see for example Bilal and Askan (2014), Faenza and Michelini (2010), Gomez Capera et al. (2007), Zanini et al. (2019). Up to now, only the regressions proposed by Zanini et al. (2019) are available in EMS intensity.

At this stage of the project data has been collected only for the Italian territory. The recorded accelerograms have been downloaded from the European Strong Motion Database (ESM) (Luzi et al., 2018). ESM database allows to download records of events having magnitude $M \geq 4$, mainly recorded in the European-Mediterranean and the middle-East regions. The MDPs have been downloaded mainly from the 2015 version of the Italian Macroseismic Database (DBMI) (Locati et al., 2016).

DBMI is updated to 2015 and assembled mainly in MCS scale (Mercalli-Cancani-Sieberg), however for many events the EMS intensity is also available. For the purpose of this study only $I_{EMS}$ MDPs have been retained. Data have also been integrated with publications available in literature in order to account for events happened after 2015 and for past events where the macroseismic intensity was revaluated using EMS scale. This has been done:

- replacing data of the 6 May 976 Friuli earthquake with those available in Tertulliani et al. (2018);
- replacing data of the 7 and 11 May 1984 central Italy earthquakes with those available in Graziani et al. (2017);
- replacing data of the 14 September 2003 Appennino Bolognese earthquake bases on information provided by the QUEST group (Quick Earthquake Survey Team);
- replacing data of the 6 April 2009 L'Aquila earthquake with those available in Azzaro et al. (2011);
- adding data of the 25 January 2012 Emilia earthquake available in Tertulliani et al. (2012);
- replacing data of the 21 June 2013 Lunigiana earthquake based on information provided by QUEST;
- adding data of the 2016 Central Italy earthquake sequence available in Rossi et al. (2019).

Initially a total number of 143 common events were found cross-matching DBMI with the ESM database. The time span is 1972 – 2016 (respectively the year of the first Italian accelerogram in ESM and the year of the last observed macroseismic data point in the gathered documents). These 143 events correspond to 2412 records in ESM and 32862 MDPs. The moment magnitude Mw ranges from the 3.9 of the 15/12/2005 Val Nerina earthquake to the 6.9 of the 23/11/1980 Irpinia earthquake whereas the macroseismic intensity ranges $II \leq I_{EMS} \leq XI$. In particular, 8563 MDPs are in EMS scale (corresponding to 37 events).

In DBMI and other references, MDPs are reported with non-conventional intensities when available data are not enough to assign a proper intensity. These MDPs have not been considered in data processing since they are not representative of a proper macroseismic intensity.

To link the MDPs with the records a criterion must be adopted. In literature the link is established based on the distance between da MDP and the record station. Usually a maximum distance ranging between 6 km to 3 km is used. This is justified since it could represent the average length of a village to which the intensity is assigned (since it is assigned to an area).

In this study the maximum distance is set equal to 3 km, however database with smaller distances have also been developed to assess the influence of this choice (due to different soil conditions).

Table 1: Characteristics of CROMI database

| ID | Date | Lat | Lon | Depth | $M_W$ | $M_L$ | N° I-MDP |
|---|---|---|---|---|---|---|---|
| IT-1976-0002 | 06/05/76 | 46.26 | 13.30 | 5.7 | 6.4 | 6.4 | 6 |
| IT-1983-0004 | 20/07/83 | 37.55 | 15.17 | 24.7 | 4.5 | 4.3 | 6 |
| IT-1984-0004 | 07/05/84 | 41.70 | 13.86 | 20.5 | 5.9 | 5.9 | 13 |
| IT-1984-0005 | 11/05/84 | 41.78 | 13.89 | 12.1 | 5.5 | 5.7 | 1 |
| IT-1999-0012 | 14/02/99 | 38.18 | 15.02 | 12 | 4.7 | 3.9 | 3 |
| IT-2001-0008 | 22/04/01 | 37.70 | 15.02 | 5 | 4.2 | 3.2 | 1 |
| IT-2002-0007 | 05/04/02 | 38.35 | 15.10 | 5 | 4.4 | 4.2 | 1 |
| IT-2002-0024 | 06/09/02 | 38.38 | 13.70 | 5 | 5.8 | 5.6 | 3 |
| IT-2002-0040 | 27/10/02 | 37.76 | 15.12 | 5 | 4.9 | 4.8 | 1 |
| IT-2003-0048 | 14/09/03 | 44.26 | 11.38 | 8.3 | 5.3 | 5.0 | 2 |
| IT-2006-0059 | 27/02/06 | 38.16 | 15.20 | 9.2 | 4.4 | 4.1 | 7 |
| IT-2006-0302 | 19/12/06 | 37.78 | 14.91 | 23.8 | 4.2 | 4.1 | 2 |
| IT-2009-0009 | 06/04/09 | 42.34 | 13.38 | 8.3 | 6.1 | 5.9 | 10 |
| IT-2009-0317 | 08/11/09 | 37.85 | 14.56 | 7.6 | 4.4 | 4.4 | 1 |
| IT-2009-0323 | 15/12/09 | 43.01 | 12.27 | 8.8 | 4.2 | 4.3 | 1 |
| IT-2009-0328 | 19/12/09 | 37.78 | 14.97 | 26.9 | / | 4.4 | 7 |
| ISIDe-2166809 | 02/04/10 | 37.80 | 15.08 | 0.3 | / | 4.3 | 1 |
| IT-2010-0032 | 16/08/10 | 38.35 | 14.89 | 13.5 | 4.7 | 4.8 | 2 |
| EMSC-20110506_0000042 | 06/05/11 | 37.80 | 14.94 | 20.4 | 4.3 | 4.0 | 1 |
| IT-2011-0110 | 23/06/11 | 38.06 | 14.78 | 7.3 | 4.5 | 4.4 | 7 |
| IT-2011-0020 | 17/07/11 | 45.01 | 11.37 | 2.4 | 4.8 | 4.8 | 3 |
| IT-2011-0022 | 25/07/11 | 45.02 | 7.37 | 11 | 4.3 | 4.3 | 4 |
| IT-2012-0002 | 25/01/12 | 44.87 | 10.51 | 29 | 5.0 | 5.0 | 3 |
| IT-2012-0008 | 20/05/12 | 44.90 | 11.26 | 9.5 | 6.1 | 5.9 | 1 |
| IT-2012-0011 | 29/05/12 | 44.84 | 11.07 | 8.1 | 6.0 | 5.8 | 26 |
| IT-2012-0061 | 25/10/12 | 39.87 | 16.02 | 9.7 | / | 5.0 | 14 |
| IT-2013-0001 | 04/01/13 | 37.88 | 14.72 | 9.6 | 4.3 | 4.4 | 2 |
| IT-2013-0005 | 21/06/13 | 44.13 | 10.14 | 7 | 5.1 | 5.2 | 6 |
| IT-2013-0013 | 15/08/13 | 38.11 | 14.91 | 19.4 | / | 4.5 | 6 |
| EMSC-20160824_0000006 | 24/08/16 | 42.70 | 13.23 | 8.1 | 6.0 | 6.0 | 33 |
| EMSC-20161026_0000095 | 26/10/16 | 42.91 | 13.13 | 7.5 | 5.9 | 5.9 | 18 |
| EMSC-20161030_0000029 | 30/10/16 | 42.83 | 13.11 | 9.2 | 6.5 | 6.1 | 105 |

After removing all non-conventional values and matching MDPs with records, CROMI contains 297 MDPs classified in EMS (202 records of 32 different events).

Table 1 shows the data of the events included in the prepared database. In particular it includes the event ID reported in the ESM database, along with event date, latitude, longitude, depth, moment magnitude ($M_W$) and local magnitude ($M_L$). The last column shows the number of couples MDP-record available from each event. Figure 1 shows the location of the events and of the couples MDP-record. Figure 2 (left) shows the distribution of couples for each intensity degree arranged in bins with half degree width. At this stage the choice of using half degrees has been done since macroseismic intensity is often reported using half degrees. However, EMS scale defines only twelve degrees therefore the arrangement in bins with one degree width has also been analysed but it is not reported here for the sake of brevity. Figure 2 (right) shows the distribution of the distances between the MDP and the station that recorded the associated accelerogram.

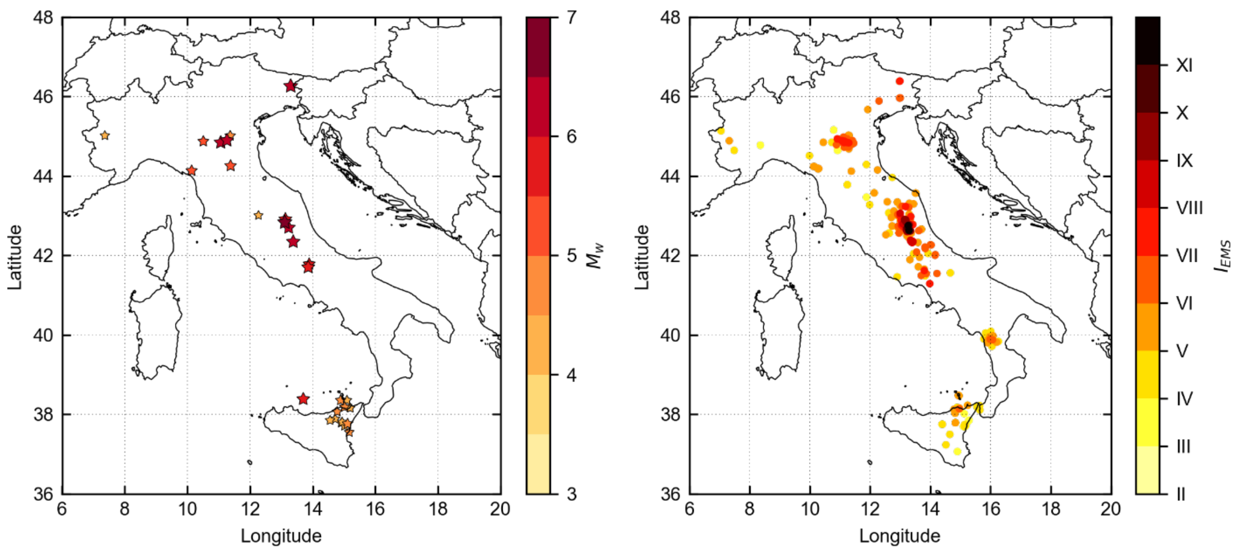


Figure 1. Location and magnitudes of the events included in CROMI (left) and location of the MDPs included along with macroseismic intensity (right)

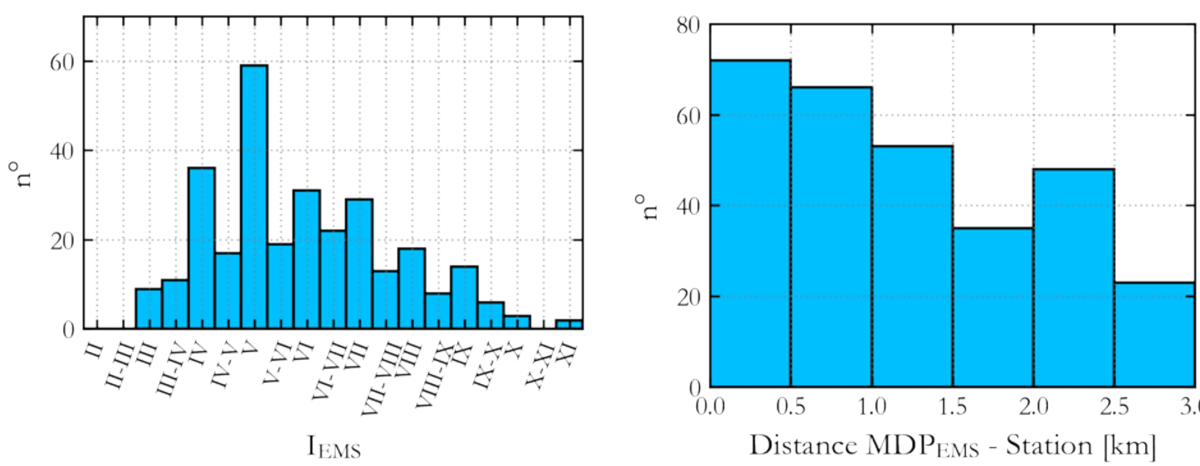


Figure 2. Distribution of couples MDP-record for each intensity degree (left) and for the distance MDP-station that recorded the accelerogram (right)

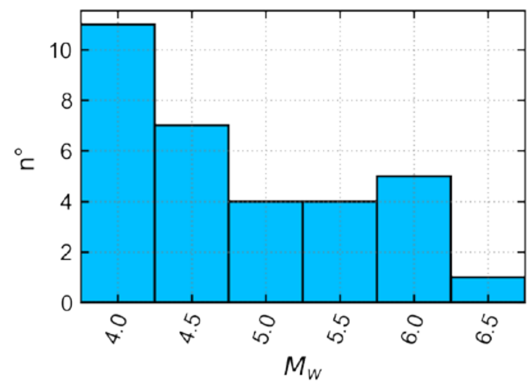


Figure 3. Distribution of couples MDP-record for different magnitude ranges

***Regressions Development***

The main scope is to find the best parameters (if they exist) that correlates with macroseismic intensity defined according to the EMS scale. Many papers proposed regressions mainly in MCS or Modified Mercalli Intensity (MMI) using Ordinary Least Square (OLS) or Orthogonal Distance Regression (ODR). At this stage ODR has been implemented since it allows to create invertible regressions that accounts for uncertainties in both variables. Up to now, the only regressions proposed in EMS intensity are published by Zanini et al. (2019), allowing to establish EMS intensity from Peak Ground Acceleration (PGA), Velocity (PGV), Displacement (PGD), Housner and Arias Intensity.

To the purpose of this study, more than sixty parameters have been derived from the analysis of the signal or from the response of linear and non-linear SDOF systems. Regressions are developed using different maximum distances between the MDP and the record station (3, 1.5 and 0.5 km), different binning size for the intensities in order to assess the influence of different choices, different intensities ranges (2-11, 5-11, 2-10, 5-10). Moreover, all the regressions have been developed using the maximum horizontal component (Max) or the resultant of the two (Res, also called $Max_{RotD100}$) and using mean values of the ground motion parameters for each intensity degree or using all data without binning.

As a rule, results show that commonly used ground motion parameters are not the ones that show the best correlation, however results change varying the input parameters. Overall, root mean square acceleration ($a_{RMS}$) root mean square velocity ($v_{RMS}$) and root mean square displacement ($d_{RMS}$) seems to be the signal parameters that gives the most stable results across the different cases. For these parameters regressions lines according to different hypothesis on the distance between the MDP and station where the signal is recorded are reported in Figure 4 to 6. For the sake of brevity only results for an intensity range from 2 to 11 and the maximum component (Max) are shown and since results are still preliminary, regressions equations have not been reported.

Regressions have also been done using parameters evaluated on the response of non-linear SDOF systems. Since the purpose is to assign a macroseismic intensity in order to separate accelerograms in damage consistent bins, regressions based on non-linear Engineering Demand Parameters (EDPs) should assure this consistency. EMS intensity represents an integral measure of the mean damage observed in a built environment. The EMS scale allows to assign intensity based on different grades of damage occurring in buildings of different vulnerability classes. The way EMS is assigned can be simulated using non-linear time-history analysis and modelling the behavior of buildings of different vulnerability classes. In this study different buildings typology and vulnerability classes have been modelled using 141 equivalent elasto-plastic non-linear SDOF systems. The characteristics of these SDOFs (yielding force $F_y$, displacement $\delta_y$ and ductility $\mu$) is extracted from the Lagomarsino and Giovinazzi (2006) who proposed these values to develop a mechanical damage model in the framework of the RISK-EU project (Mouroux and Brun, 2006).

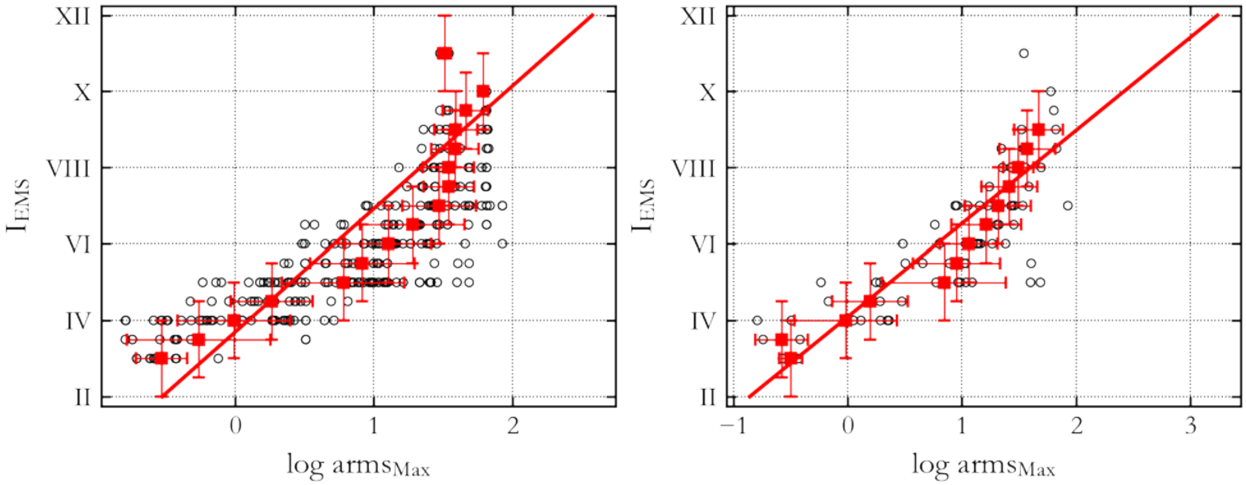


Figure 4. Regression between $I_{EMS}$ and $a_{RMS\text{-}Max}$: maximum MDP-record distance of 3 km (left) and 0.5 km (right)

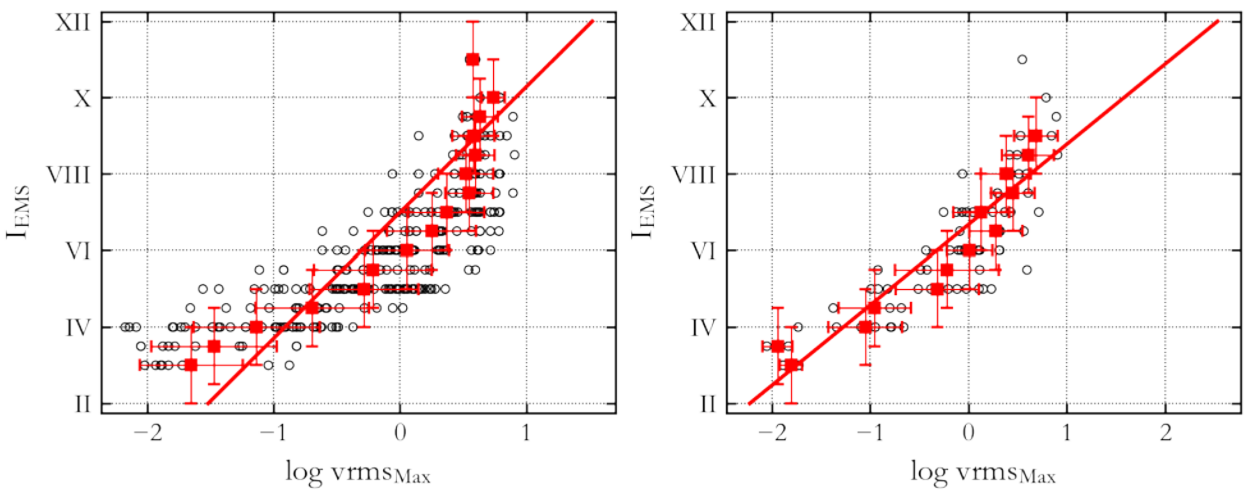


Figure 5. Regression between $I_{EMS}$ and $v_{RMS\text{-}Max}$: maximum MDP-record distance of 3 km (left) and 0.5 km (right)

The same cases performed for the linear parameters have also been performed for the non-linear cases. Overall, among the chosen EDPs, the Kinematic ductility is the parameter that seems to give more stable results across different cases. The kinematic ductility $\mu_{kin}$ is defined as follows

$$\mu_{kin} = \frac{\delta_{max}}{\delta_y} \tag{1}$$

Where $\delta_{max}$ is maximum absolute non-linear displacement reached in the analysis, $\delta_y$ the yielding displacement of the SDOF. Regressions are developed using, for each couple MDP-record, the mean value of the kinematic ductility from all the 141 different SDOF, hence accounting for the mean damage on a build environment characterized by buildings of different vulnerability classes. The regression lines for the kinematic ductility are reported in Figure 7 according to different hypothesis on the distance between the MDP and station where the signal is recorded. For the sake of brevity only results for an intensity range from 2 to 11 and the maximum component (Max) are shown and since results are still preliminary, regressions equations have not been reported.

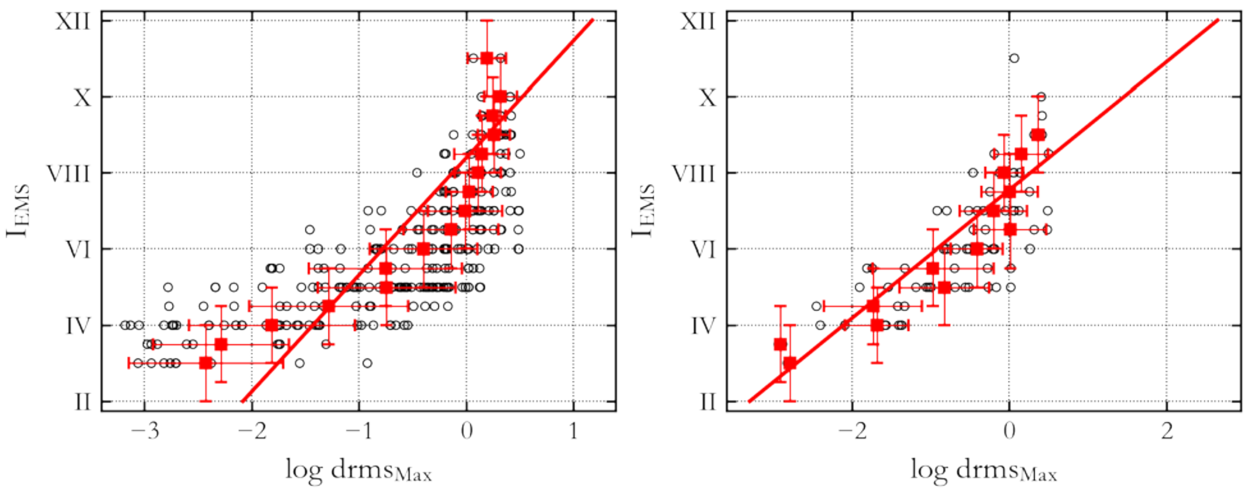


Figure 6. Regression between $I_{EMS}$ and $d_{RMS-Max}$: maximum MDP-record distance of 3 km (left) and 0.5 km (right)

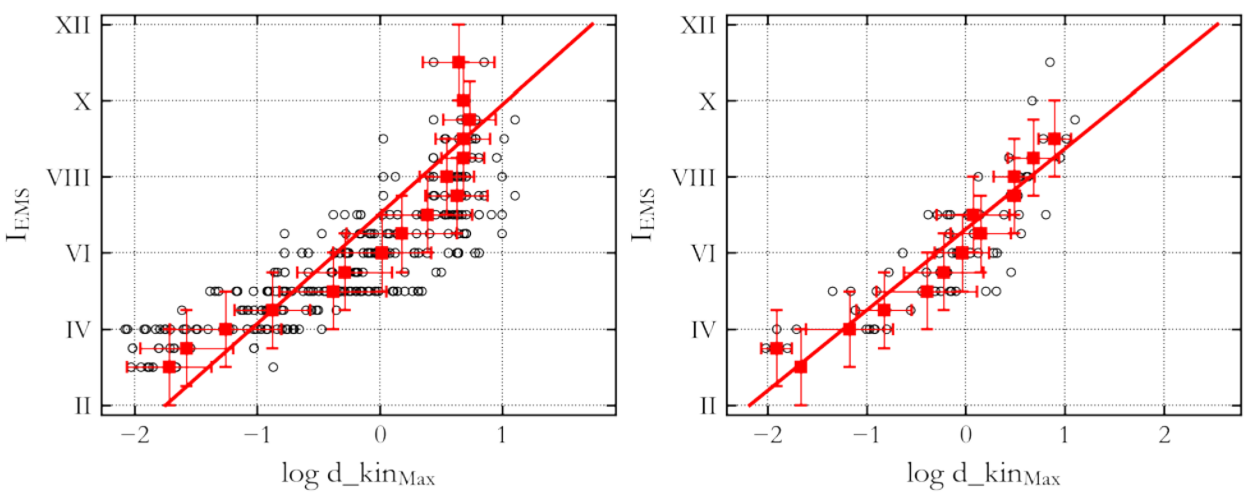


Figure 7. Regression between $I_{EMS}$ and $\mu_{kin}$: max MDP-record distance of 3 km (left) and 0.5 km (right)

From Figure 7 it is clear that the kinetic ductility is well correlated with $I_{EMS}$. This result allows to assign the macroseismic intensity to the simulated synthetic accelerograms and, at the same time, to assure a damage consistent feature across records classified with the same $I_{EMS}$.

***Physics-Based Synthetic Seismograms Modelling***

The last step consists in developing a database of three-component synthetic seismograms in order to extend the availability of accelerograms to be used in non-linear time history analysis. Macroseismic Intensity is assigned to the simulated accelerograms using the correlations developed at the previous steps. Using the correlations based on ductility demand on non-linear SDOF systems defined as shown in previous section means assuring that accelerograms classified with the same macroseismic intensity have a similar damaging potential.

At this stage simulations are not developed yet. The computations will be done with a frequency content up to 10 Hz using the Modal Summation (MS) technique (Panza et al., 2001; Panza et al., 2012) and the Discrete wavenumber (DWN) technique (Pavlov, 2009). For the purpose of this study, it is not necessary to The source is treated as Extended (ES) (Gusev, 2011; Magrin et al., 2016) in order to adequately account for the source-linked phenomena such as directivity or the slip distribution on the fault plane; Simulations based on this producers allows to produce accelerograms consistent with reals observations both in terms of ground motion parameters and engineering demand parameters on structures (Fasan et al., 2016).

In order to cover a wide range of possibilities, and therefore of accelerograms characteristics, a set of average structural models composed by flat, parallel anelastic layers is used as reference bedrock (Panza et al., 2001) and, on top of them, different local soil conditions are accounted for using average shear velocities $V_{S,30}$ according to the classes defined in EC8 (for soil type A, B and C). Magnitudes ranges from $M_w$=4.5 to $M_w$=8.0 with steps of 0.5. Epicentral distances ranges from 0 to 100 km. This range of possibilities is used to reproduce the variability presented in the database of natural accelerograms used to develop the regressions, where the binning is done exclusively in terms of macroseismic intensity.

## CONCLUSION

In this work an outline of a procedure to classify physics-based simulated accelerograms in damage consistent bins is proposed. For this purpose, a database of natural accelerograms linked with macroseismic intensities in EMS has been prepared. At this stage, the database includes events occurred in Italy from 1976 up to now. In the next project phase, it is planned to add also data from other neighbouring counties. Only events where a link based on a maximum distance between the record station and macroseismic data point could be established have been used. In order to assess the sensitivity to different parameters, such as the maximum distance or the intensity binning size, correlations between ground motion parameters and macroseismic intensity have been calculated with different hypothesis. The scope is finding the parameter (or parameters) that best correlates with the macroseismic intensity. Correlation have also been defined using non-linear SDOF systems representing different vulnerability classes according to EMS. This last type of correlations allows to check the "damage-consistent" status and therefore to assign a macroseismic intensity (that is a damage consistent measure by definition) to physics-based accelerograms based on their demand on the SDOF systems.

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