Earthquake Spectra

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National-scale Mapping of the Expected Earthquake Magnitude for Soil Liquefaction Triggering Analyses in Italy

Ali Güney Özcebe[1] | Francesca Bozzoni[1] | Carlo Giovanni Lai[2] | Elisa Zuccolo[3]

[1]European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy | [2]Department of Civil Engineering and Architecture, University of Pavia, Pavia, Italy | [3]National Institute of Oceanography and Applied Geophysics (OGS), Sgonico, Italy

Correspondence: Carlo Giovanni Lai (carlogiovanni.lai@unipv.it)

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ABSTRACT

This paper introduces a procedure to estimate moment magnitude (M_W) in earthquake-induced soil liquefaction probabilistic risk assessment. The method is based on using the historical seismicity modelled with a truncated Gutenberg-Richter (G-R) relation, jointly with an empirical model linking the M_W to the maximum source-to-site distance at which soil liquefaction was observed in past earthquakes. The proposed method predicts M_W as a function of the recurrence intervals, which are assimilated to return periods (RPs), and it may be used in probabilistic or semi-probabilistic seismic design as prescribed by modern building codes worldwide. Moreover, it is independent from any intensity measure (IM) of ground motion, and this is a desirable feature since the selection of the optimal IM for liquefaction risk assessment does not meet a general agreement among specialists. The novel procedure to estimate M_W has been applied at five Italian sites with different levels of seismicity. The results obtained with the proposed method to define M_W have been compared with other approaches from the current Italian engineering practice. Then, the application was extended to the whole Italian territory to compute maps of the expected M_W for liquefaction risk assessment for the RPs of 475, 975, and 2,475 years. Such maps represent useful tools for practitioners in Italy when performing liquefaction-triggering analyses. Although the proposed method to compute the expected M_W in soil liquefaction triggering studies has been developed with a specific focus on the Italian territory, the procedure may be applied elsewhere.

1 | Introduction

Assessment of the seismic triggering of soil liquefaction and its consequences are relevant topics of earthquake engineering attracting the interest of researchers and practitioners. The complex nature of the liquefaction phenomenon requires inter- and multidisciplinary expertise of geotechnical engineering for the definition of local site conditions (e.g., geotechnical characterisation and its modelling), engineering seismology for the definition of the seismic source-related characteristics (e.g., determination of moment magnitude - M_W, which hereinafter will be referred to magnitude), and structural engineering for the evaluation of the impact of the liquefied soil to the structural and infrastructural systems (e.g., response of buildings' foundations, buried structures, etc.).

Liquefaction triggering analysis is carried out following either a standard (i.e. uncoupled) or an advanced (i.e. coupled) approach, as described in the following

- Standard (uncoupled) approach: the soil strength against liquefaction triggering is defined by the Cyclic Resistance Ratio (CRR), which is estimated from the results of in situ geotechnical tests (e.g., cone penetration tests, CPT; standard penetration tests, SPT) taking into account the expected number of loading cycles calculated from the expected M_w, introduced via a magnitude scaling factor (MSF). The seismic demand is quantified through the Cyclic stress ratio (CSR) in which the expected (horizontal) peak ground acceleration (PGA) and its variation with depth are obtained either through an empirical approach or via an uncoupled (i.e. total stress-based) ground response analysis. Calculations of the CRR and CSR are dependent on M_w, which appears in the CRR via the MSF and in the CSR through depth-dependent reduction factor r_d (e.g., NASEM 2016; Boulanger and Idriss 2014; Kayen et al. 2013; Robertson 2009; Moss et al. 2006; Youd et al. 2001).
- Advanced (coupled) approach: in this approach, both the CRR and the CSR are computed using fully nonlinear, effective stress-dependent ground response analyses in which the adopted soil constitutive model which incorporates the solid-fluid phase coupling of the shear and volumetric deformations of the soil skeleton, which is the mechanism causing the increase of excess pore water pressure (e.g., PM4Sand model, Boulanger and Ziotopolou 2015; SD Model by Cubrinovski and Ishihara 1998a, 1998b; PDMY model by Yang et al. 2003, etc.). At a certain depth from the ground surface, the possible triggering of soil liquefaction is assessed as a direct output of a numerical wave propagation analysis. In these types of analysis, the dependence on the earthquake magnitude lies on the two main steps: (i) calibration of the parameters of the adopted constitutive model according to the expected number of cycles (a proxy for duration and thus of the earthquake magnitude) and (ii) selection and scaling of the earthquake ground motion suite to be used in the wave propagation analysis, which has to be compatible with the expected (probabilistic) seismic hazard at the site.

Building codes worldwide (e.g., in the United States of America, IBC 2021; in Europe, Eurocode 8, CEN 2004; in Italy, NTC 2018 and Circ. 2019) provide guidelines to assist practitioners in assessing both the liquefaction triggering and its consequences. Yet, they may still be insufficient to define all necessary inputs for design. The definition of the expected earthquake magnitude is one of these inputs, which is still controversial. Eurocode 8-Part 1 Clause 3.2.2.1 (4) (CEN 2004) requires that the expected magnitude be selected based on its relative magnitude-source distance contributions to the probabilistic seismic hazard (i.e. disaggregation analysis). This requirement is certainly well-aligned with the current state of practice in earthquake engineering, as it is by far the most used approach in setting up the dominant seismic scenario. As mentioned above, identifying the magnitude that contributes the most to the Probabilistic Seismic Hazard Assessment (PSHA) requires the implementation of a disaggregation procedure (e.g., Bazzurro and Cornell 1999), which is performed with respect to a preselected reference IM(s), IM(s), and return period (RP). Carrying out the seismic hazard disaggregation is not a straightforward operation, and it requires a certain level of expertise during the management of the outcomes. In fact, for the same RP, the resulting magnitude-distance-epsilon triplet (M_W, R, ε) and the marginal distribution of M_W would result in different M_W values.

Apart from the choice of the hazard disaggregation approach, the IM being disaggregated plays a critical role. There is currently no consensus in the scientific community on the IM which best correlates with liquefaction triggering. Moreover, performing disaggregation of PSHA with respect to different IMs (e.g. PGA, peak ground velocity-PGV) can lead to significantly different results. Although PGA is commonly used as reference IM (Seed and Idriss 1971; Kramer and Stewart 2024), it is of an instantaneous nature, capturing only the maximum acceleration during ground motion. In contrast, experimental laboratory cyclic tests (Ishihara 1996) have shown that liquefaction triggering is strongly influenced by the number of loading cycles (and thus by the duration of ground shaking), considering all the other parameters constant. Given these conditions, integral IMs, such as Arias intensity (IA) or cumulative absolute velocity would be more appropriate reference IMs for disaggregation, as they are better correlated with the number of cycles, hence liquefaction triggering. As explained before, the standard approach for performing liquefaction triggering analysis has been calibrated according to PGA, which is then corrected by MSF to take the M_W into consideration. Hence, the standard approach for liquefaction triggering analysis is based on a *PGA-adjusted for duration* intensity measure in a sort of hybrid, work-around solution to the problem. A fundamentally different approach to liquefaction triggering analysis based on selecting a set of IMs consistent with the physics of the problem would require recalibrating the whole procedure, which is not a trivial operation. Furthermore, PGA is commonly used in many countries worldwide to define the seismic hazard, making the standard approach highly practical for routine engineering applications.

In the update of Eurocode 8 Part 1 (CEN 2024), the reference IM is the spectral acceleration (S_A) at the oscillator period $T = 1$s which is then linked to M_W via a purposely developed empirical correlation based on European strong motion data.

However, the technical difficulties associated with the hazard disaggregation remain. These include the need of distinguishing between the modal and the mean M_W (Kramer and Mayfield 2005; Baker et al. 2021; Barani et al. 2023), the tendency of M_W to approach an asymptotic value as RP increases, particularly in certain seismogenic settings (Baker et al. 2021), and the choice of the spatial dimension of the disaggregation operation (i.e. 1D, 2D or 3D). Further discussion on the hazard disaggregation is beyond the scope of the current paper. Interested readers are referred to the work of Barani et al. (2023), where a set of good practice guidelines is presented.

To sum up, earthquake magnitude plays a fundamental role in liquefaction triggering analysis. However, its definition remains a challenging task. This applies not only to site-specific assessments but also when mapping the liquefaction potential in ever-extended territories (e.g., Zhu et al. 2015; Bozzoni, Bonì et al. 2021). To highlight this issue, Bozzoni et al. (2022) conducted a sensitivity analysis to quantify the influence M_W on national-scale liquefaction hazard maps for Italy. A probabilistic, machine-learning-based prediction algorithm was adopted using the following explanatory variables: the weighted-magnitude PGA (PGAm), the weighted-mean shear-wave velocity in the top 30 m, and the compound topographic index. The PGAm maps were generated by considering M_W values obtained from the Italian seismogenic model (ZS09 by Meletti et al. 2004) and, for comparison, by using M_W values obtained via disaggregation (Barani et al. 2009) and by the method proposed by Albarello (2012). It is worth noting that Bozzoni et al. (2022), the PGAm map based on M_W values from disaggregation, appears, overall, to be less conservative.

This paper presents a simple methodology for defining the earthquake magnitude in probabilistic liquefaction triggering assessments, which can be applied both at specific sites and in multiscale zoning (e.g. micro-, meso-, macro- and mega-zonation) of a territory. The proposed methodology allows the definition of a M_W value-based on return periods (RPs), and thus consistent to the semi-probabilistic framework at the limit states methodology referred to by most seismic buildings codes (e.g., CEN 2004; NTC 2018). Although it is applied to the Italian territory, the proposed methodology is of general (global) applicability. It is important to remark that the proposed method is not intended to replace any of the existing liquefaction triggering procedures which properly account for all the controlling factors (e.g., ground motion characteristics, soil mechanical properties, in situ stress conditions) either empirically (like CPT- or SPT-based liquefaction triggering analyses) or experimentally/numerically (like the use of numerical nonlinear modelling of the native soil profile subject to realistic input ground motions) rather to provide practitioners with an effective tool for defining the moment magnitude M_W expected at the site of interest to be used in liquefaction triggering analyses.

In the following sections, the methods currently adopted in the Italian practice to define the earthquake magnitude for liquefaction risk assessments are first briefly reviewed. This is followed by a detailed description of the proposed method. A comparison between the results obtained using the proposed method and those derived from existing Italian approaches is then presented for five selected case-study locations, accompanied by a sensitivity analysis with respect to the earthquake catalogue used. Finally, maps of the expected M_W for the Italian territory are presented for the recurrence intervals (which are assimilated to the RPs in this work) of 475, 975, and 2,475 years. These maps are practical tools for practitioners, who may adopt them in their liquefaction-triggering studies.

2 | State of the Art of the Current Italian Practice

A set of guidelines for seismic microzonation in areas prone to soil liquefaction was published in 2018 by the Italian Department of Civil Protection (ICMS-LIQ 2018). These guidelines provide a detailed overview for defining M_W to be used in liquefaction triggering analyses. These methods are

1. Disaggregation of the seismic hazard according to the current Italian seismic hazard model,
2. Maximum magnitude obtained from the current Italian catalogue of macroseismic intensities,
3. Maximum magnitude obtained from the current Italian earthquake catalogue and seismogenic zone model,
4. Magnitude assigned based on magnitude versus threshold source-to-site distance empirical correlations,
5. A probabilistic approach based on the Italian catalogue of macroseismic intensities.

In addition to the above methods, two further approaches are also described below

6. Magnitude as defined in the updated draft of Eurocode 8 (CEN 2024),
7. A recent seismic hazard-compatible approach to define M_W proposed by Barani et al. (2023).

The following sections provide a brief description and critical discussion of each method, followed by a summary evaluation of their compatibility with the Italian seismic hazard model.

2.1 | Method 1: Disaggregation of the Seismic Hazard According to the Current Italian Seismic Hazard Model

This method is based on identifying the seismic event characterised by the magnitude and distance that predominantly contribute to the desired hazard level at the site. This is achieved through a disaggregation analysis of PSHA performed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The seismic hazard model for the Italian territory is described by the MPS04 model, which includes the 475-year PGA map (MPS Working Group 2004; Stucchi et al. 2011; see Data Availability Statement) and the results from the Project S1 (DPC-INGV 2004-2006 Agreement). The MPS04 model, which is based on the ZS09 seismogenic model (Meletti et al. 2004) is also referenced in the current Italian Building Code (NTC 2018; hereinafter NTC18) and its Commentary (Circ. NTC18, 2019). The seismic hazard maps are accessible through the INGV WebGIS portal (see Data Availability Statement). This platform provides uniform hazard maps for a cluster of points, uniform hazard spectra, and annual probabilities of exceedance for spectral accelerations at any location within the Italian territory. Additionally, WebGIS allows users to retrieve the relative contributions of M_W and source-to-site distance pairs based on the results of the disaggregation analysis for the PGA associated with the 475-years RP (Barani et al. 2009). This method has the advantage of being fully compatible with the results of the PSHA study performed in Italy by INGV in 2004–2006, which continues to serve as the reference seismic hazard model for Italy[1].

2.2 | Method 2: Maximum Magnitude Obtained from the Current Italian Catalogue of Macroseismic Intensities

This method estimates the magnitude of interest based on the Italian Macroseismic Intensity Database (DBMI, Locati et al. 2022, Data Availability Statement) and its harmonised version combined with the Italian Earthquake Catalogue (CPTI v4.0; Rovida et al. 2020; Rovida et al. 2021). Both archives cover over 1,000 years of historical and instrumental seismic observations of the Italian territory. According to ICMS-LIQ (2018), the magnitude to be adopted for liquefaction triggering analyses should be defined based on the maximum magnitude observed in the DBMI database for the area under investigation. This approach, however, is subject to a certain degree of uncertainty. Specifically, the maximum magnitude can be interpreted in two ways: (a) considering any event felt at the site of interest (denoted by Method 2a in this work) or (b) filtering only those events with observed macroseismic intensity greater than VI, representing strong ground motions more likely to trigger liquefaction (denoted by Method 2b), which may potentially trigger liquefaction. Another limitation of this method is its incompatibility with a PSHA framework (hence the MPS04 model). The maximum magnitude derived from DBMI cannot be associated with a certain RP. Even if an RP is inferred, it remains unclear which set of M_W values should be used for different RPs given that the Italian building code NTC18 is based on a semi-probabilistic method limit states approach.

2.3 | Method 3: Maximum Magnitude Obtained from the Italian Earthquake Catalogue and Seismogenic Zones

The third approach proposed by ICMS-LIQ (2018) for estimating the earthquake magnitude to be used in liquefaction triggering analyses is based on the MPS04 model (Meletti et al. 2004, Stucchi et al. 2011). Specifically, it involves examining the seismogenic zones, according to the ZS09 model; each zone is associated with a corresponding maximum magnitude (M_{Wmax}). Table 1 presents the maximum magnitudes assigned to clusters of seismogenic zones (ZS) taken from the ZS09 model. Using this table, the magnitude to be adopted for liquefaction analyses can be selected, depending on the location of the site within one of these zones. For the sites located outside of the defined ZS boundaries, ICMS-LIQ (2018) suggests a simplified approach to estimate the reference magnitude. Like Methods 2a and 2b, the key weakness of Method 3 is that the obtained magnitude cannot be directly associated with a specific RP.

2.4 | Method 4: Magnitude Assigned Based on Magnitude versus Source-to-Site Distance Threshold Empirical Correlations

According to ICMS-LIQ (2018), the magnitude of interest can also be estimated using empirical correlations that relate this seismological parameter to the maximum source-to-site distance at which soil liquefaction was observed in historical earthquakes. These correlations are widely available in the literature, and they are typically developed on a regional basis using seismological data from earthquake catalogues documenting cases of seismic-induced soil liquefaction (e.g., De Marco et al. 2022). ICMS-LIQ (2018) proposes three different empirical threshold models: Seed et al. (1984)

[1] An update of the MPS04 hazard model in Italy is currently underway by INGV (Meletti et al. 2021).

TABLE 1 | Seismogenic zones (ZS) of ZS09 model (Meletti et al. 2004) grouped according to their corresponding maximum magnitudes (M_{Wmax}, from Stucchi et al. 2011).

ID (ZS09)	M_{Wmax}
922, 936	5.45
928	5.91
901–904, 907–909, 911–914, 916, 917, 920, 921, 926, 932–934	6.14
918, 919, 910	6.37
905, 906, 915, 930	6.60
924, 925, 931	6.83
923, 927	7.06
929, 935	7.29

(Equation (1)), Ambraseys (1988) (Equation (2)), and Galli (2000) (Equation (3)), corresponding to the sub-methods as Method 4a–c, respectively

$$M_{\mathrm{W,t}} = 2.46 + 2.16 \cdot \log R_{\mathrm{t}} \tag{1}$$

$$M_{\mathrm{W,t}} = 4.64 + 2.65 \cdot 10^{-3} \cdot R_{\mathrm{t}} + 0.99 \log R_{\mathrm{t}} \tag{2}$$

$$M_{\mathrm{W,t}} = 2.75 + 2.0 \cdot \log R_{\mathrm{t}} \tag{3}$$

where R_{t} is an estimate of the upper bound threshold (t) epicentral distance at which liquefaction phenomena were observed for an earthquake of magnitude $M_{\mathrm{W,t}}$. Similar to the previous approaches, the drawback of this approach is that the estimated magnitude cannot be directly linked to an RP.

2.5 | Method 5: A Probabilistic Approach Based on the Italian Catalogue of Macroseismic Intensities

The fifth method proposed by the ICMS-LIQ (2018) is based on a statistical analysis of local seismic history reconstructed from macroseismic information. Hazard computations were performed using the numerical code SASHA (D'Amico and Albarello 2008), which does not rely on any assumption regarding the geometry or distribution of seismogenic sources or the Poissonian nature of earthquake occurrence, unlike the traditional PSHA. On this basis, a sort of disaggregation analysis was conducted to identify past seismic events that mostly contributed to the resulting hazard estimate (Albarello 2012). As in classical disaggregation analysis, the results are characterised by magnitude and location; however, the outcomes of this approach are significantly different from those provided by the standard disaggregation analysis due to the different uses of the available information. For a complete discussion of the differences between these two methods, Albarello (2012) provides further details. The main results obtained through the application of this methodology are provided in the supplementary material attached to the ICMS-LIQ (2018), which were developed based on the most updated version of the DBMI archive at the time of publication (2011).

2.6 | Method 6: Magnitude as Defined in the Updated Draft of EC8 (2024)

Clause 5.2.2.5 of the latest draft of the updated EC8 (EN 1998-1, 2024), titled 'Conventional earthquake magnitude' states: '(*1*) A conventional value of earthquake magnitude (in terms of moment magnitude M_{W}), and of the corresponding duration D_{R} of the strong part of the ground motion, may be associated to the elastic response spectrum. (2) In the absence of specific evaluations, values given in Table 5.6 may be used.'

Table 2 reproduces the content of Table 5.6 of EN 1998-1 (2024).

The magnitude is defined based on the parameter $S_{\beta,\mathrm{RP}}$, which denotes the spectral acceleration on rock (for 5% damping) corresponding to a specific value of RP at the vibration period $T_{\beta} = 1$ s of the horizontal elastic response spectrum. The $S_{\beta,\mathrm{RP}}$ values are expressed as a fraction ($f_{\mathrm{h}} = 0.2$, 0.3, 0.4 for low/very low, moderate, and high seismicity regions,

TABLE 2 | Conventional values of earthquake magnitude and duration of the strong part of ground motion on rock for ranges of $S_{\beta,RP}$ (CEN 2024). Site A: rocky sites, Site B: stiff soil sites, Site C: medium-stiff soil sites.

Range of $S_{\beta,RP}$, m/s^2	M_W	D_R(s)		
		Site A	Sites B & C	Other Sites
$S_{\beta,RP} < 0.08$	4.5	0.5	0.6	0.75
$0.08 < S_{\beta,RP} < 0.20$	5.0	1.0	1.2	1.5
$0.20 < S_{\beta,RP} < 0.50$	5.5	2.0	2.4	3.0
$0.50 < S_{\beta,RP} < 1.20$	6.0	4.0	4.8	6.0
$1.20 < S_{\beta,RP} < 2.50$	6.5	8.0	9.6	12
$2.50 < S_{\beta,RP} < 4.00$	7.0	16	19	24
$4.00 < S_{\beta,RP}$	7.5	32	38	48

TABLE 3 | Range of $S_{\alpha,475}$ values to define seismicity levels according to the current update of EC8 Part 5 (EN 1998-1, 2024).

Seismicity level	$S_{\alpha,475}$, m/s^2
Very low	<1.0
Low	1.0–2.5
Moderate	2.5–5.0
High	>5.0

respectively) of $S_{\alpha,RP}$, which is the rock spectral acceleration (for 5% damping) for the RP corresponding to the constant acceleration range of the horizontal elastic response spectrum. If the reference RP is 475 years the values of $S_{\alpha,\ 475}$ are those reported in Table 3.

In the current work, the horizontal elastic response spectrum (for 5% damping) on the site category A (rock) required to recover the values of $S_{\alpha,475}$ and $S_{\alpha,RP}$ is adopted from the NTC18.

2.7 | Method 7: A Recent Seismic Hazard-Compatible Approach to Define M_W Proposed by Barani et al. (2023)

Barani et al. (2023) reanalysed the current Italian seismic hazard model (MPS04, Stucchi et al. 2011) and its disaggregation (Barani et al. 2009) by considering the liquefaction triggering criterion of $M_W > 5$ and $a_g > 0.1$ g for the entire Italian territory. Their work incorporates several key aspects of the problem: (i) stratigraphic amplification (Forte et al. 2019) and topographic amplification (Mascandola et al. 2021a) to scale the seismic hazard-dependent, horizontal PGA on bedrock outcrop, (ii) a distinction in the selection between the modal and mean M_W values, and (iii) an expert opinion-based selection of the oscillator period for site class-specific hazard disaggregation (PGA for type-A sites, $T = 0.2$ s for type-B sites, and $T = 1.0$ s for type C–E sites). The web-platform reported in Barani et al. (2023; see Data Availability Statement) was accessed to compute the output M_W.

2.8 | Summary Evaluation of the Available Methods in Italy

Considering the methods described between 2.1 and 2.7, two desirable criteria for selecting M_W ensuring the compatibility with the available MPS04 model, thus with the Italian Building Code (NTC 2018), are as follows

i. M_W should be a function of the RP of the seismic event, and
ii. M_W should increase with the RP of the seismic event

Methods 2–4 violate both criteria (i) and (ii), while criterion (ii) is not consistently satisfied in Methods 1 and 7, mainly due to the use of relatively coarse magnitude bins of 0.5 units (Barani et al. 2009; Barani et al. 2023). Although Method 6 fulfils both criteria (i) and (ii), it has never been systematically tested across the Italian territory.

Method 5 considers potential future events that may occur at the same geographic location and with the same magnitudes as past events. While this assumption contributes to the method's simplicity and straightforwardness, it also introduces a degree of inconsistency regarding the aleatory variability associated with the size and location of future earthquakes. Furthermore, the correlation between macroseismic intensity and magnitude exhibits significant dispersion (e.g., Pasolini et al. 2008).

3 | Proposed Methodology for Defining M_W in Soil Liquefaction Triggering Analyses

In this section, a simple procedure based on the Gutenberg-Richter (G-R) recurrence model is presented. The method relies on the following assumptions

1. The seismic zones representing the seismogenic sources are idealised as equivalent circular areas, in which the seismicity rates are calculated using the G-R model,
2. The maximum M_W within each circular area can be retrieved from the corresponding earthquake catalogue,
3. An empirical relationship exists between M_W and the maximum source-to-site distance (R) at which soil liquefaction has historically been observed within a given region (M_W-R relationship).

The steps for implementing the proposed method, concerning a site located in Italy, are as follows:

STEP 1. All events listed in an earthquake catalogue are evaluated using an M_W-R relationship for liquefaction triggering. In this study, the model proposed by De Marco et al. (2022) (Equation (4) and Figure 1a), which updates the equation proposed by Galli et al. (2000) (Equation (3) and Figure 1a), is adopted. An event *i* is classified as capable of having triggered liquefaction if its epicentral distance (R_i) is smaller than the threshold provided by Equation (4) for its corresponding magnitude (M_{Wi}). The maximum distance, R_{max}, is defined as the largest distance among the epicentral distances associated with the identified potentially triggering events. Then, maximum magnitude, M_{Wmax}, is the largest magnitude among the events located within the corresponding maximum distance circle (Figure 1b).

$$M_{W,t} = 0.921 + 2.596 \cdot \log(R_t) \tag{4}$$

STEP 2: The observed annual exceedance seismicity rates for each magnitude bin j ($\lambda_{obs,Mw,j}$) are computed considering the historical events located inside the circular area defined by R_{max} and centred at the site of interest (Figure 1b). During this operation, the information on the completeness of the earthquake catalogue is considered.

STEP 3: A continuous annual exceedance rate model (λ) is defined through a double-truncated G-R distribution. First, the G-R parameters (a_{GR} and b_{GR}) are calculated by a standard G-R distribution applied to the $\log_{10}$ of nonzero $\lambda_{obs,Mw,j}$

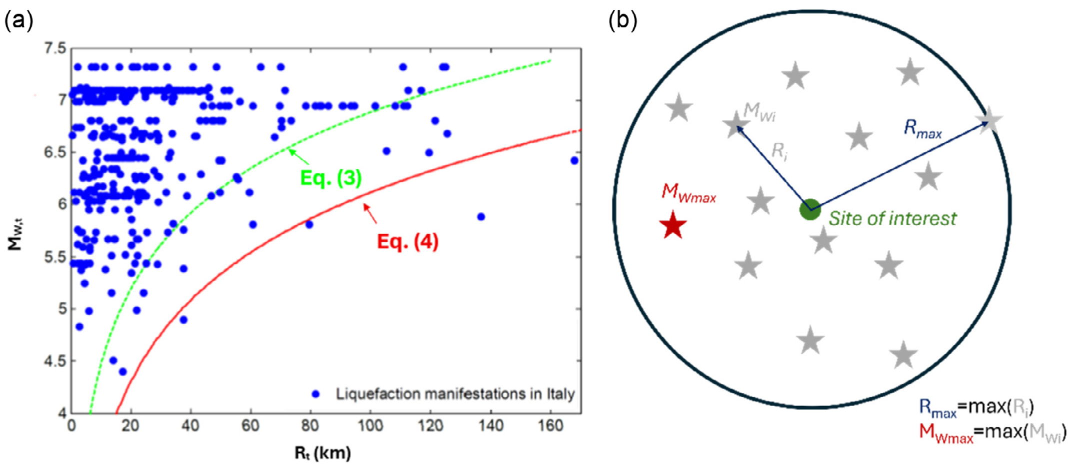

FIGURE 1 | (a) Empirical relationships linking $M_{W,t}$ to the maximum source-to-site epicentral threshold distance (R_t) at which soil liquefaction has been observed in Italy; the current Italian empirical model proposed by De Marco et al. (2022). Equation (4) is represented by the red line, while the previous model by Galli (2000). Equation (3) is indicated by the green dashed line. The blue dots indicate liquefaction manifestations in Italy according to the earthquake catalogue ECLiq (Bozzoni, Cantoni et al. 2021). (b) Definition of the seismic zone, along with the associated maximum magnitude (M_{Wmax}) and maximum epicentral distance R_{max} relevant to the site of interest.

values, through a least-squares line fit algorithm. Subsequently, a double lower and upper bound truncation to M_W is applied according to Equation (5a)–(5d), considering a prefixed minimum magnitude (M_{Wmin}) and the M_{Wmax} obtained from Step 1.

$$\lambda = \nu \cdot \frac{e^{-\beta(M_W - M_{Wmin})} - e^{-\beta(M_{Wmax} - M_{Wmin})}}{1 - e^{-\beta(M_W - M_{Wmin})}} \tag{5a}$$

$$\nu = e^{\alpha - \beta M_{Wmin}} \tag{5b}$$

$$\alpha = 2.303 a_{GR} \tag{5c}$$

$$\beta = 2.303 b_{GR} \tag{5d}$$

STEP 4: Although the seismicity is well represented by the circular seismic zone depicted in Figure 1b, not all the event magnitudes can potentially trigger soil liquefaction at the site of interest. To address this issue, the annual rates of occurrence are defined for finely spaced magnitude intervals ($\theta(M_{Wk})$), using the λ-model defined in Step 3. Then, $\theta(M_{Wk})$ values are corrected with a factor defined as the square of the ratio between the threshold distance $R(M_{Wk})$ calculated using Equation (4) for M_{Wk} and the maximum distance R_{max}, which results bounded by one. The result (Equation (6)) represents the annual seismicity occurrence rates of the truncated G-R relation in which the earthquakes are sufficiently severe to trigger soil liquefaction ($\vartheta_{liq}(M_{Wk})$).

$$\vartheta_{liq}(M_{Wk}) = \left(1, \frac{R^2(M_{Wk})}{R^2_{max}}\right) \vartheta(M_{Wk}) \tag{6}$$

Once the values of $\vartheta_{liq}(M_{Wk})$ are calculated for all of the finely spaced M_{Wk} bins, the annual seismicity exceedance rates compatible with the triggering of the soil liquefaction ($\lambda_{liq}(M_{Wk})$) are computed by summing the corresponding $\vartheta_{liq}(M_{Wk})$ values.

Finally, the magnitude corresponding to a given RP is obtained by identifying the M_W value corresponding to $\lambda_{liq} = 1/\text{RP}$. Figure 2 illustrates the results of Step 2–4 for the case study of Ravenna, which is going to be discussed in Section 4.

The procedure outlined up to STEP 4 can be applied when sufficient data is available to construct the G-R distribution. However, in cases where earthquake catalogues are limited in size or contain heterogeneous event sampling during the observation period, the corresponding G-R model is less rigorously constrained due to the limited size or heterogeneous sampling of events within the earthquake catalogues during the observation period. Thus, for low seismicity areas, the magnitudes corresponding to RP = 475, 975, and 2,475 years are defined in Equation (7a)–(7c).

$$M_W(\text{RP} = 475) = \max\left(4.5, \min(M_{Wi})\right) \tag{7a}$$

$$M_W(\text{RP} \geq 2,475) = \max\left(4.5, \max(M_{Wi})\right) \tag{7b}$$

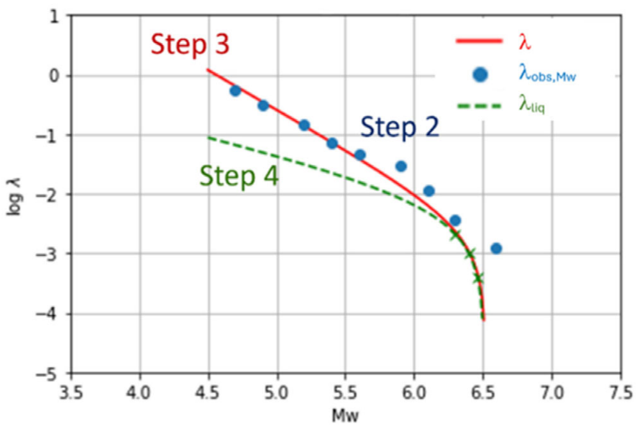

FIGURE 2 | Illustration of the proposed methodology. Red line: λ model; blue markers: $\lambda_{obs,Mw,j}$ values; green dashed line: λ_{liq} model. Markers x show the output M_W values for RP = 475, 975, and 2,475 years.

$$M_{\mathrm{W}}(\mathrm{RP}=975)=\mathrm{M}_{\mathrm{W}}(\mathrm{RP}=475)+\frac{\log(1/475)-\log(1/975)}{\log(1/475)-\log(1/2{,}475)}(M_{\mathrm{W}}(\mathrm{RP}=2,475)-M_{\mathrm{W}}(\mathrm{RP}=475)) \tag{7c}$$

where M_{Wi} is the vector of magnitudes is obtained at the end of Step 1 (see Figure 1).

4 | Application of the Existing Methods to Define M_{W} to Five Italian Sites: Comparison with the Proposed Procedure

A classical validation of the described methods using observed liquefaction datasets is not feasible without introducing subjective choices in the selection of simplified approaches, the assignment of surface PGA, and the determination of the RPs. Instead, the proposed method is applied to five Italian sites characterised by three different levels of seismicity (low seismicity: Ferno; moderate seismicity: Cavezzo and Ravenna; high seismicity: Amatrice and Gioia Tauro). The locations of the sites, along with the historical seismicity of the Italian territory, are shown in Figure 3a[2]. The resulting M_{W} values are then compared with those obtained using the alternative existing methods described in Section 2.

Let us first examine the representative case of Ravenna (44.474°N, 12.248°E), located along the north-eastern coast of Italy, approximately 80 km east of Bologna. The site falls within seismogenic zone ZS 912, as defined by the MPS04 hazard model (Figure 3b). The classical seismic hazard disaggregation with respect to PGA yields mean M_{W} values of 4.98, 5.02, and 5.06 for RP = 475, 975, and 2,475 years, respectively. These values refer specifically to the branch of the MPS04 logic tree denoted as Method 1 (Stucchi et al. 2011). Alternatively, when assigning $\mathrm{M_W}$ based on the data contained in the historical macroseismic intensity database DBMI, two different estimates are obtained depending on the application of a minimum felt intensity threshold: $M_{\mathrm{W}} = 7.1$ (Marsica 1041 event, felt intensity IV) without threshold (Method 2a) and $M_{\mathrm{W}} = 6.1$ (Faentino 1781, felt intensity VI) with threshold (Method 2b). The latter value aligns well with the maximum magnitude associated with the corresponding seismogenic zone, which is $M_{\mathrm{W}} = 6.12$ (Method 3). Using the earthquake catalogue CPTI (see Data Availability Statement), the maximum reported $\mathrm{M_W}$ is 6.12, with a source-to-site distance of 43 km. Potential liquefaction triggering is verified by using the Equations (1) and (3). In contrast, the Equation (2) proposed by Ambraseys (1988) does not predict liquefaction triggering for the magnitude-distance pair M_{W} 6.12 and R = 43 km. It should be noted that methods 2–4 (including their sub-variants) do not provide a direct association between M_{W} and RP, which represents a significant limitation. Tabulated values of macroseismic intensity-based M_{W} assessment (Method 5) provide $M_{\mathrm{W}} = 5.8$ for all three RPs of interest (475, 975, and 2,475 years). Applying Method 6, the obtained

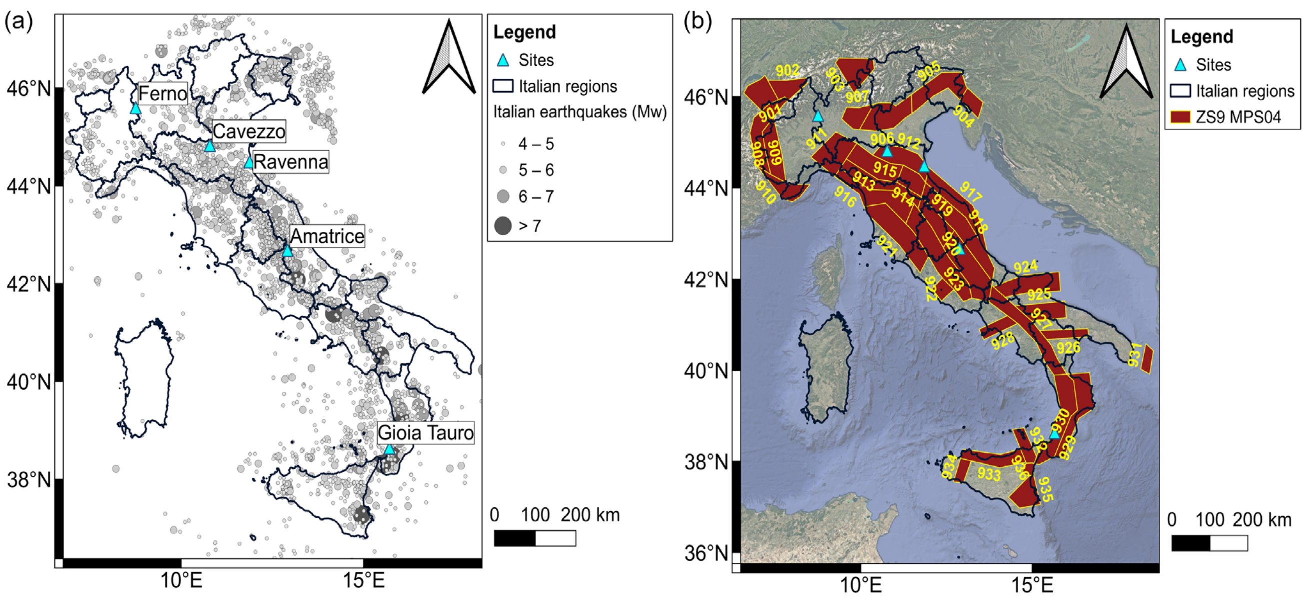

FIGURE 3 | (a) Geographic locations of the five selected Italian sites analysed in this study, overlapped to the map of historical and instrumental seismicity according to the CPTI (v4.0) earthquake catalogue (Rovida et al. 2020; Rovida et al. 2021). (b) Seismogenic zones according to the MPS04 hazard model, with the locations of the selected sites.

[2] Only for the plotting purposes, the most-recent version of the CPTI database (i.e., (v4.0) earthquake catalogue (Rovida et al. 2020, 2021) is adopted.

TABLE 4 | Comparison of M_W estimated for five Italian sites using the proposed methodology based on the CPTI (see Data Availability Statement), alongside estimates obtained from the other existing methods.

	RP	Existing methods							This work
Sites	Years	1[a]	2[b]	3	4	5	6	7	CPTI
Amatrice	475	5.7	7.1	7.1	7.1	6.7	6.5	5.8	7.0
	975	5.9	7.1	7.1	7.1	6.7	7.0	6.3	7.1
	2,475	6.1	7.1	7.1	7.1	6.7	7.5	6.8	7.1
Cavezzo	475	5.0	6.3	6.1	6.5	NA	6.0	5.8	6.3
	975	5.0	6.3	6.1	6.5	NA	6.5	5.8	6.4
	2,475	5.1	6.3	6.1	6.5	NA	6.5	5.8	6.5
Ferno	475	5.3	6.5[c]	5.3	NA	NA	5.0	5.3	5.8
	975	5.4	6.5[c]	5.4	NA	NA	5.5	5.8	6.0
	2,475	5.6	6.5[c]	5.6	NA	NA	5.5	5.8	6.1
Gioia Tauro	475	6.0	7.1	7.3	7.3	7.0	6.5	7.3	7.1
	975	6.1	7.1	7.3	7.3	7.0	7.0	7.3	7.2
	2,475	6.4	7.1	7.3	7.3	7.0	7.5	7.3	7.3
Ravenna	475	5.0	7.1	6.1	6.1	5.8	6.0	5.8	6.4
	975	5.0	7.1	6.1	6.1	5.8	6.5	5.8	6.4
	2,475	5.1	7.1	6.1	6.1	5.8	6.5	5.8	6.5

Abbreviation: NA, not available.
[a]mean M_W from classical disaggregation.
[b]estimate obtained without considering a minimum felt-intensity threshold.
[c]for Ferno, only one historical event with a felt. intensity of III is reported.

values of S_α are 0.41, 0.53, and 0.73 g, for RP = 475, 975, and 2,475 years, respectively. Given that $S_{\alpha,475} = 0.41$ g, Ravenna is classified as a site with moderate seismicity, corresponding to $f_h = 0.3$. This leads to $S_\beta = 0.12$ g, 0.15, and 0.21 g for the three RPs. Using Table 2, the corresponding M_W values are 6.0, 6.5, and 6.5, respectively. Method 7 (Barani et al. 2023), applied to the MPS04 hazard model, results in a constant M_W estimate optimate of 5.8 for all RPs. Finally, the M_W values derived using the proposed method (Section 3) are shown in Figure 2 (marker "x"), representing the actual results for the Ravenna case study.

By applying the same calculation procedure described for Ravenna to the remaining four sites, a set of predicted M_W is obtained for all the eight methods. Table 4 presents a comparison of the M_W values derived from the existing methods (1–7) with those estimated using the proposed methodology based on the CPTI (see Data Availability Statement).

Overall, the predictions obtained using the proposed method show good agreement with those derived from the existing alternative methods. However, certain weaknesses are observed in the existing approaches. In some cases, specific methods fail to yield results; for instance, Method 5 does not provide outputs for Cavezzo and Ferno. In other cases, the estimates exhibit considerable dispersion, such as in Amatrice, where M_w predictions range between 5.7 and 7.1, or in Ravenna, with values spanning from 5.0 to 6.5). By contrast, the proposed methodology demonstrates robustness, being independent of any IM, as well practicality and consistency across all case studies. Furthermore, the resulting M_W estimates generally align well with those obtained via Method 6, except for Ferno, where the proposed method yields slightly higher values. This specific case will be examined in greater detail in Section 5.

5 | Sensitivity of the Calculated M_W to the Selected Earthquake Catalogue

In this section, the dependency of the results on the selected earthquake catalogue is investigated using the same five sites discussed in Section 4. To assess the sensitivity of the results to the choice of the earthquake catalogues, two different sources are considered: (a) CPTI and (b) ESHM (for both, see Data Availability Statement). In addition, to the final outputs in terms of estimated M_w, intermediate results are also provided in the form of truncated G-R parameters (i.e., R_{max}, M_{Wmax} and a_{GR}, b_{GR}). Table 5 summarises both the intermediate and the final outputs of the proposed methodology.

TABLE 5 | Comparison between M_W values and G-R parameters computed using the method proposed in this study for the five selected sites shown in Figure 3, RP = 475, 975, and 2,475 years and the two earthquake catalogues CPTI and ESHM.

Seismic Hazard	Sites	Catalogue	a_{GR}	b_{GR}	R_{max}, km	M_{Wmax}	M_W RP = 475 years	M_W RP = 975 years	M_W RP = 2,475 years
Low	Ferno	CPTI	3.57	1.02	95	6.2	5.8	6.0	6.1
		ESHM	—	—	44	5.34	4.6	4.9	5.3
Moderate	Cavezzo	CPTI	4.73	1.10	104	6.53	6.3	6.4	6.5
		ESHM	4.49	1.06	104	6.57	6.4	6.5	6.5
	Ravenna	CPTI	4.65	1.07	131	6.52	6.4	6.4	6.5
		ESHM	4.41	1.03	131	6.57	6.4	6.5	6.5
High	Amatrice	CPTI	4.54	0.97	189	7.19	7.0	7.1	7.1
		ESHM	4.68	1.01	189	7.20	6.9	7.1	7.1
	Gioia Tauro	CPTI	4.42	0.93	211	7.32	7.1	7.2	7.3
		ESHM	4.27	0.93	211	7.34	7.1	7.2	7.3

From the comparison between the two earthquake catalogues provided in Table 5, the parameters a_{GR}, b_{GR}, R_{max}, and M_{Wmax} exhibit strong similarity for four out of the five sites. Consequently, the magnitudes corresponding to the RPs of interest turn out to be almost identical. The only site where differences arise between CPTI and ESHM is Ferno, where the equivalent circular zone is defined based on different interpretations of a historical event in Switzerland with $M_W > 6$ (the

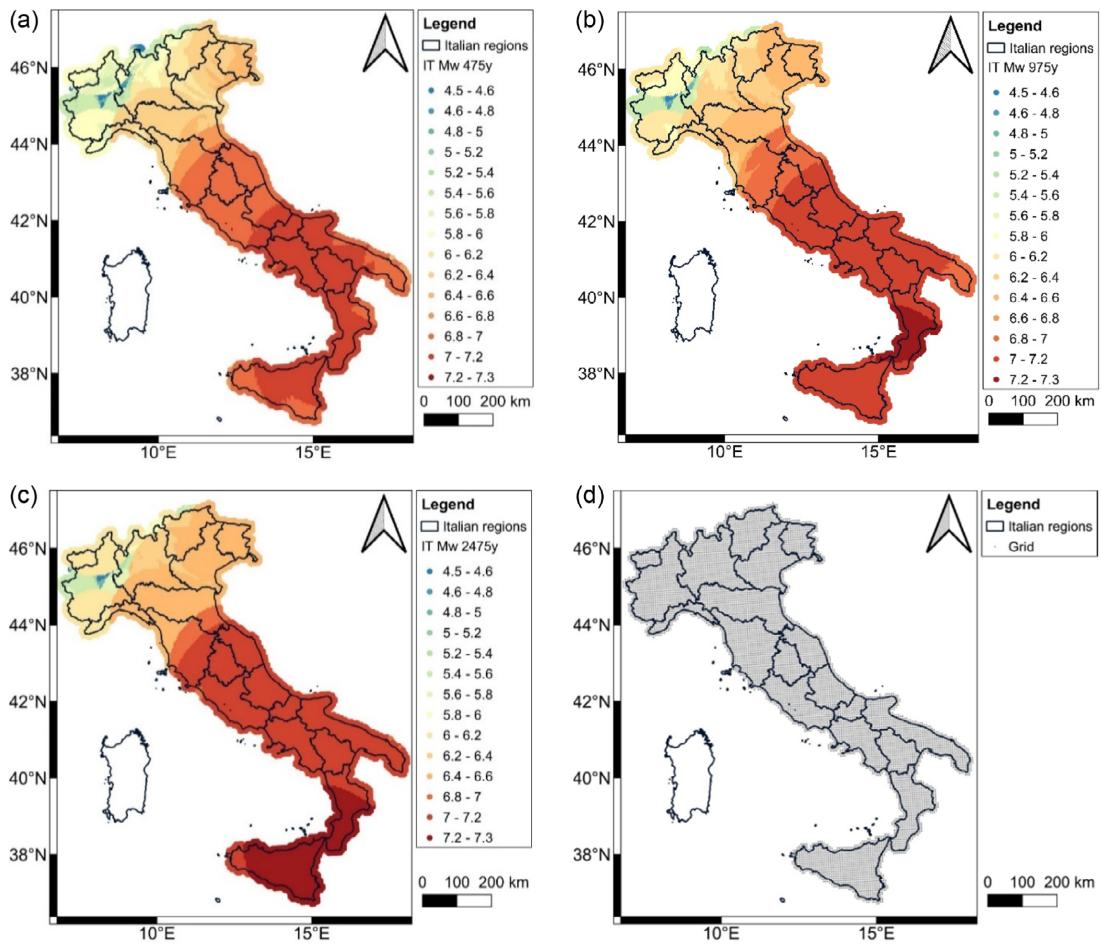

FIGURE 4 | Maps of expected M_W across Italy computed using the methodology proposed in Section 3 along with the CPTI earthquake catalogue for (a) RP = 475 years, (b) RP = 975 years, and (c) RP = 2,475 years. (d) Spatial grid adopted for the calculations.

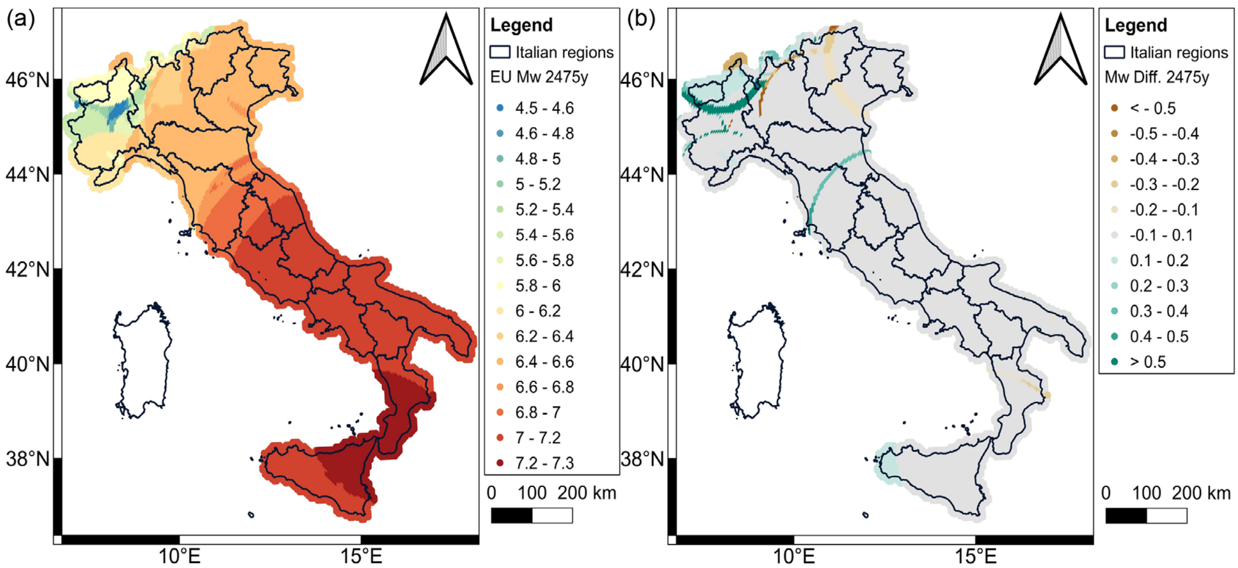

FIGURE 5 | (a) Map of expected M_W across Italy, calculated using the proposed methodology along with the ESHM earthquake catalogue for RP = 2,475 years. (b) Corresponding difference map showing the difference ΔM_W between the estimates obtained using ESHM and CPTI earthquake catalogues (i.e., CPTI-based values minus ESHM-based values).

25/07/1855 event). In CPTI, this event is characterised by $M_W = 6.2$ and an epicentral distance of 95.2 km from Ferno, which, according to Equation (4), could potentially have triggered liquefaction. Conversely, in ESHM catalogue, the same event is reported with $M_W = 6.06$ and epicentral distance of 99 km, making it not likely to have induced liquefaction. Due to this discrepancy, the equivalent seismic area is defined by a $R = 95$ km radius circle for CPTI, whereas for ESHM it is defined by a lower pair of M_{Wmax} and R_{max} values, insufficient to derive a_{GR} and b_{GR}. Therefore, Equation (7a)–(7c) are applied instead. Overall, for all five sites listed in Table 5, the proposed methodology meets the two criteria established in Section 2.8.

6 | Magnitude Computation over an Extended Area: Maps of the Italian Territory

The methodology used to compute M_W, as applied in the previous section to five sites, has been extended to the whole Italian territory for RP = 475, 975, and 2,475 years (Figure 4a–c). This was done after defining a homogeneously spaced grid composed of 10,751 nodes covering the entire country (Figure 4d), in line with the subdivision currently adopted by the Italian Building Code (NTC 2018) for defining the seismic actions.

Figure 5 shows the expected M_W map for RP = 2,475 years based on the ESHM catalogue (panel a) as well as the magnitude difference (ΔM_W) between the results of the proposed method computed from the two earthquake catalogues considered in this study (panel b). Although this difference is only illustrated for the longest considered RP, it was calculated for all three RPs, showing that ΔM_W is generally small: the difference in expected magnitude due to the choice of earthquake catalogues is negligible for most grid points, being limited to ±0.1 magnitude units. As discussed in Section 5 for the case study of Ferno, these ΔM_W differences stem from slight variations in epicentre location and magnitude of historical events. These are primarily concentrated in northwest Italy and the western part of Sicily, where the magnitude difference for some few grid points reaches values of up to ±0.5 units.

7 | Concluding Remarks

This article proposes a procedure for estimating the magnitude to be used in soil liquefaction triggering analyses cast in a semi-probabilistic or fully probabilistic framework. The proposed methodology relies on historical seismicity data from earthquake catalogues, modelled using the classical truncated G-R model, combined with empirical correlations that relate M_W to the maximum source-to-site distance at which soil liquefaction has been observed in historical earthquakes. The procedure is practical and can be applied to any geographic location a complete earthquake catalogue is available. Unlike traditional approaches based on predefined seismogenic zones, the truncated G-R model is applied over circular areas. The proposed method is intended solely for determining the hazard-compatible, expected M_W. Once the M_W

corresponding to a given RP is established, the liquefaction triggering assessment should proceed using the standard well-established procedures of earthquake geotechnical engineering based on considering the ground motion characteristics in terms of PGA, the soil cyclic resistance ratio and in situ CSR.

The proposed method is fully compatible with a probabilistic framework, as it enables the prediction of M_W as a function of the RP. This compatibility is crucial in engineering practice, where seismic design, according to advanced building codes such as Eurocode 8, is typically performed using probabilistic or semi-probabilistic approaches. Additionally, the method demonstrates robustness by being independent of any specific IM. This IM-independency is a significant advantage, as it circumvents the need to choose between PGA, commonly adopted in current state-of-the-art methods (NASEM 2021), and more physically informed, duration-compatible integral IMs, which, on the contrary, are less practical for PSHA compared to PGA. In summary, the magnitude derived from this method can be readily integrated into the existing PGA-based framework of liquefaction assessment, as well as into future methodologies that may explicitly require the earthquake magnitude as a primary parameter.

A sensitivity study was carried out to investigate the influence of the selected earthquake catalogue on the predicted moment magnitudes. For this purpose, two catalogues were considered: the Italian CPTI archive and the European ESHM dataset, which were used alternatively to calculate the a_{GR} and b_{GR} parameters of the truncated G-R model. The results obtained from the two catalogues are generally consistent, with the exception of Northwest Italy, which is a region characterised by low seismic hazard and a seismic history that introduces uncertainties in the localisation and characterisation of historical events. Consequently, the occurrence of a rare, high-magnitude event exceeding the largest M_W included in the earthquake catalogue would result in increasing the high magnitude truncation value of the G-R distribution. Consequently, increased values of M_W are expected particularly for the RPs.

Maps of expected M_W were produced for Italy for the RPs of 475, 975, and 2,475 years, with the aim of providing a practical tool for probabilistic soil liquefaction triggering analyses. Although the proposed method was developed specifically for the Italian territory, its flexibility allows for application in any region where a comprehensive historical earthquake catalogue is available. A natural extension of this work involves applying the proposed methodology to the entire European territory using the ESHM catalogue, which represents a key direction for future research.

Author Contributions

Ali Güney Özcebe: methodology, implementation, analysis, writing, reviewing. **Francesca Bozzoni**: methodology, input and output data curation, writing, reviewing. **Carlo Giovanni Lai**: conceptualisation, methodology, writing, reviewing. **Elisa Zuccolo**: methodology, validation, writing, reviewing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

- CPTI15 v1.5 (Rovida et al. 2016), available online on: http://doi.org/10.6092/INGV.IT-CPTI15.
- DBMI15 v4.0 (Locati et al. 2022), available online on: https://emidius.mi.ingv.it/CPTI15-DBMI15/.
- ESHM2020 Unified Earthquake Catalogue (Danciu et al. 2021) available online on EFEHR | Earthquake Catalogue, from the webpage of EFEHR: http://hazard.efehr.org/en/Documentation/specific-hazard-models/europe/eshm2020-overview/eshm20-unified-earthquake-catalogue/. Grünthal and Wahlström 2012; Rovida and Antonucci 2021.

- MILQ-Map of liquefaction triggering potential of Italy (Barani et al. 2023; 2024), available online on: https://distav.unige.it/rsni/milq.php?lang=en.
- MPS04 seismic hazard model (MPS Working Group 2004; Stucchi et al. 2011), available online on: INGV WebGIS portal: https://esse1-gis.mi.ingv.it/.

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