16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2400 (Abstract ID)

Registration Code: S-E1464658642

A NEW APPROACH FOR AFTERSHOCK HAZARD ASSESSMENT THAT TAKES INTO ACCOUNT MAINSHOCK DEMAND

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Abstract

Aftershock hazard assessment is a critical issue in the post-earthquake safety evaluation of damaged buildings. Unfortunately, misevaluation of aftershock risk claimed many lives in the recent seismic sequences. Aftershock hazard is often assessed by means of probabilistic seismic hazard assessment (PSHA). But unlike the conventional PSHA, the rate of earthquakes (i.e. aftershocks) is considered to decay as a function of time. In this proceeding, a new approach for aftershock hazard assessment is proposed. The novelty of the proposed approach is the consideration of indicators related to the mainshock event in the assessment of aftershock hazard. Specifically, indicators such as instrumental recordings of the mainshock earthquake at the site of interest or the macroseismic observations from the site, are considered in the proposed framework.

The fundamental idea behind the Conditional Aftershock Hazard Assessment (CAHA) approach proposed in this proceeding is the estimation of the variability of aftershock ground motion intensity conditioned on observed mainshock intensity at the site of interest. For this purpose, the correlation between the mainshock and the aftershock ground motion intensities exhibited at a set of sites, are investigated. Specifically, the correlation between the epsilon values identified for the mainshock and the aftershock events are considered. The epsilon parameter is defined as the difference between measured and estimated spectral acceleration value divided by the standard deviation representing the total variability. The correlation structure of the epsilons is evaluated by analyzing pairs of recorded mainshock and aftershock ground motion records. Using the identified correlations, the aftershock ground motion variability is updated conditioned on the mainshock indicators based on the principles of probability theory.

For the site where aftershock hazard is to be evaluated, the instrumental recording of the mainshock ground motion are very often not available. This is the case, for example, when the site of interest is located away from the strong motion stations. In such cases, the macroseismic indicators are the only observable evidences that can be utilized to infer the intensity of shaking exhibited at the site. The CAHA framework proposed here, enables utilizing such macroseismic observations in order to obtain improved estimates of aftershock hazard. Specifically, the Modified Mercalli Intensity, *MMI* is used as the macroseismic indicator. This approach is expected to be very useful for regions with inadequate density of strong motion stations.

An example application of the proposed approach is presented. The aftershock hazard following the 2011 Van (Turkey) M7.2 earthquake, is considered in this application. The hazard at the site of a strong motion station located in the city of Van, is evaluated using the proposed CAHA method. The hazard curves estimates obtained using the CAHA method are compared against and the curves obtained using conventional methods. Subsequently, the likelihoods predicted for the actual strong motion intensities registered during the aftershocks were evaluated. The results indicate that the improved estimates of hazard could be obtained using the proposed CAHA method, compared to conventional approaches.

Keywords: aftershock hazard, epsilon correlation, macroseismic indicators

1. Introduction

Safety evaluation of partially damaged buildings following major earthquakes plays an important role in the immediate response and the recovery process. After damaging earthquakes, structures are subjected to aftershock hazard. The mainshock event is defined as the largest magnitude event in an earthquake sequence. Seismic events that occur within a specific time interval after the mainshock are referred as aftershock events [1]. The aftershock events have epicenters within close proximity of the mainshock rupture plane. Accurate assessment of aftershock hazard plays a key role in the evaluation of the post-earthquake risk associated with the structures in the affected region. Underestimation of the aftershock hazard often results in large number of casualties. The examples of such recent events are: 2015 M7.8 Khudi (Nepal), 2012 M6.1 Emilia Romagna (Italy) and 2011 M7.2 Van (Turkey).

Aftershock probabilistic hazard assessment (APSHA) is utilized to estimate the expected rate of ground motion intensity at a site exceeding a given threshold level, during the aftershock activity period. Yeo and Cornell [2] developed a probabilistic framework for aftershock hazard assessment. This framework aims at estimating the mean rate of aftershock ground motion intensity (e.g. peak ground motion acceleration *PGA*, spectral acceleration $Sa(T)$) exceeding a threshold level within a specific time interval. In principle, aftershock hazard is evaluated in a similar way to the conventional probabilistic seismic hazard assessment (PSHA) proposed by Cornell [3]. The main difference between APSHA and PSHA approaches is in the modelling of earthquake occurrence rates. In the PSHA, earthquake occurrence rates are assumed to be constant over time. The occurrence rates of aftershocks are known to decay with the time elapsed from mainshocks. This exponential decay characteristic was first proposed by Omori [4], [5]. Aftershock occurrence rates are modelled in APSHA by taking the exponentially decaying seismicity model known as Omori's law.

Indicators related to the impact of the mainshock are already evident throughout the affected region when the aftershock hazard starts to pose a risk. The ground motion intensity measured at a site may reveal the attenuation or amplification characteristics of the path of the seismic waves travelling from source to the site (i.e. common travel path effect). Since aftershock epicenters are located within close proximity of the mainshock rupture plane, seismic waves emitted during the aftershock event often propagate along similar paths. Therefore, the attenuation or amplification characteristics of aftershock events are expected to be similar to that of mainshock event. However, this case is only applicable for the linear site response. In order to use this phenomenon in APSHA, Yeo and Cornell [6] proposed a mathematical framework. They defined a hypothetical parameter that represents correlation between the mainshock and the aftershock epsilon values. The sensitivity of the estimated aftershock hazard to the mainshock ground motion intensity was investigated by changing this hypothetical parameter. However, the level of correlation was not investigated quantitatively by Yeo and Cornell.

This proceeding presents the quantitative investigation of the correlation of the mainshock and aftershock epsilon pairs noted above using pairs of recorded mainshock-aftershock ground motion sequences. In order to ensure this, spectral acceleration demands due to the mainshock and the aftershock events that are recorded at a set of stations, are evaluated. Specifically, the correlation between the mainshock and the aftershock recorded at a site, is determined for a range of vibration periods. In the proposed CAHA methodology, this correlation is utilized for estimating the aftershock hazard conditioned on the mainshock ground motion at the site of interest. However, aftershock hazard often needs to be estimated for the sites located away from strong motion stations. The instrumental recordings of mainshock ground motion are not available in such cases. In such cases, macroseismic indicators are the only source of information related to the mainshock ground motion exhibited at site. The most important novelty of proposed CAHA method is the direct consideration of such macroseismic indicators in the estimation of aftershock hazard. In this study, Modified Mercalli Intensity, *MMI* [7] is considered as the macroseismic indicator. However, other similar scales [8] may be implemented into the proposed methodology as well. This method is expected to be useful for the regions with low density of strong motion stations.

2. Conditional Aftershock Hazard Assessment (CAHA) Methodology

This part includes the summary of the fundamentals of APSHA and the novelties of the CAHA methodology. In the conventional APSHA approach proposed by Yeo and Cornell [2], mean number $\tilde{\mu}$ of aftershock ground motion intensity *Y* exceeding a given threshold level *y* at a site, during the time interval of *T* days which starts *t* days after the mainshock, is evaluated as follows:

$$\tilde{\mu}(y,t,T;m_m) = \mu^*(t,T;m_m)\int_R \int_{m_l}^{m_m} P[Y > y \mid m,r]\, f_{R|M}(r \mid m)\, f_M(m;m_m)\,dm\,dr \tag{1}$$

where $\mu^*(y,t,T;m_m)$ is the mean number of aftershocks within magnitudes $[m_l;m_m)$ that occur in the time interval $[t,t+T)$, m_m is the mainshock magnitude, m_l is the minimum magnitude that is of engineering interest, $P[Y>y|m,r]$ is the conditional probability of estimated motion intensity *Y* exceeding *y*, $f_{R|M}(r|m)$ is the conditional probability density function of closest distance *R* between the site and the aftershock rupture plane for a particular aftershock magnitude m, $f_M(m;m_m)$ is the truncated exponential probability density function of *M* that is bounded to the interval $[m_l;m_m)$. The graphical presentation of mean number of aftershocks $\tilde{\mu}(y,t,T;m_m)$ is presented in Fig. 1.

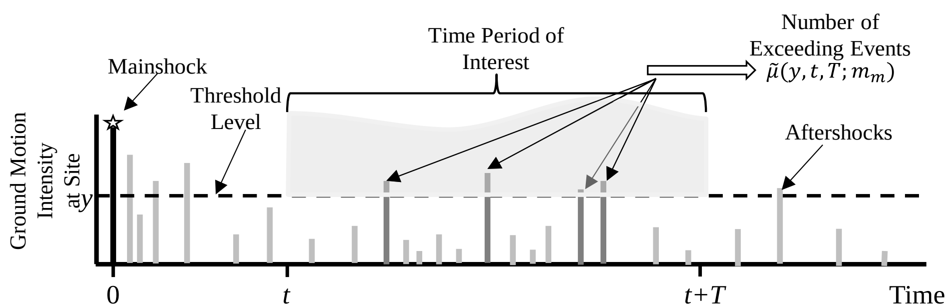

Fig. 1 – Graphical presentation of mean number of exceeding events

Proposed CAHA methodology introduces two novelties regarding the estimation of the aftershock hazard demand. These are: (1) utilization of mainshock-aftershock epsilon correlation in analysis and (2) considering mainshock related macroseismic indicators (e.g. *MMI*). These novelties are introduced by developing a new approach for calculating the term $P[Y>y|m,r]$ in Eq. (1). The conditional probability term $P[Y>y|m,r]$, is directly related to the variability of aftershock peak motion intensity *Y* estimated for the site. This variability is captured by the random variable E_a which represents the aftershock epsilon $E_a=(\ln Y-\mu_Y)/\sigma_Y$. Here, μ_Y and σ_Y are the mean and the standard deviation of the mainshock ground motion intensity *Y* estimated using ground motion prediction equation (GMPE). In the proposed method, probability distribution of E_a is estimated conditioned on the mainshock *MMI* level, *i* observed at the site. Basic schematic presentation of CAHA methodology is given in Fig. 2.

The aftershock peak motion intensity *Y* at the site can be estimated conditional to the observed mainshock *MMI* using a probabilistic approach. In this context, *MMI* intensity of the mainshock at the site is represented by parameter *i*. Depending on the observed effects of the mainshock, *i* may take any integer value from 1 to 10. In this case, the integral in Eq. (1) can be written as follows:

$$\tilde{\mu}(y,t,T;m_m,i,r_m) = \mu^*(t,T;m_m)\int_R \int_{m_l}^{m_m} \int_{\varepsilon_y}^{+\infty} f_{R|M}(r \mid m) f_M(m;m_m) f_{E_a|I}(\varepsilon \mid i,m_m,r_m)\,d\varepsilon\,dm\,dr \tag{2}$$

where ε_y=(ln$_Y$-μ_Y)/σ_Y and r_m is the distance between mainshock rupture plane and the site.

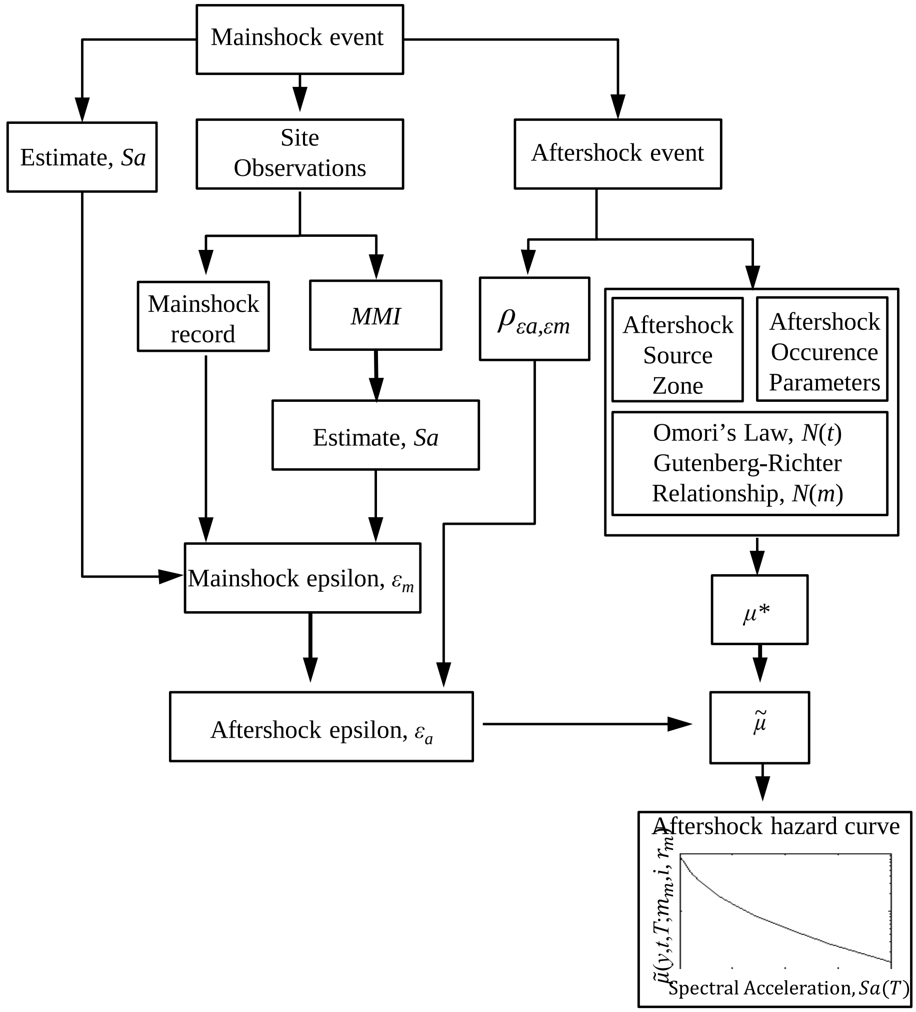

Fig. 2 – Schema of the proposed conditional aftershock hazard asessment (CAHA) methodology

The term $f_{Ea|I}(.|.)$ is evaluated by taking the convolution of two probability distributions as follows:

$$f_{E_a|I}(\varepsilon\,|\,i,m_m,r_m)=\int_{-\infty}^{+\infty} f_{E_a|E_m}(\varepsilon\,|\,\varepsilon_m)\,f_{E_m|I}(\varepsilon_m\,|\,i;m_m,r_m)\,d\varepsilon_m \qquad (3)$$

In the equation above $f_{Ea|Em}(.|.)$ is the probability density function of aftershock epsilon E_a conditioned on mainshock epsilon E_m and $f_{Em|I}(.|.)$ is the probability density function of mainshock epsilon E_m conditioned on *MMI* intensity *i* observed at the site.

2.1 Aftershock epsilon distribution conditioned on mainshock

One of the most important components of the conventional APSHA given in Eq. (1) is the conditional probability P[Y>y|m,r] of aftershock ground motion intensity Y exceeding a ground motion level y. Ground motion intensity Y is often represented by a lognormally distributed random variable with logarithmic mean E[ln$Y$] and logarithmic standard deviation $\sigma_{\ln Y}$. Typically, GMPEs are used for estimating E[ln$Y$] and $\sigma_{\ln Y}$ for a particular site that is affected by a particular earthquake. Using the resulting E[ln$Y$] and $\sigma_{\ln Y}$, the conditional probability P[Y>y|m,r] is evaluated as follows:

$$P[Y > y \mid m, r] = P[E_a > \varepsilon_a' \mid m, r] \tag{4a}$$

$$P[E_a > \varepsilon_a' \mid m, r] = \int_{\varepsilon_a'}^{+\infty} f_{E_a}(\varepsilon) d\varepsilon \tag{4b}$$

where ε_a' is the specific value of E_a that corresponds to $Y=y$. Note that in the conventional APSHA, $f_{Ea}(\varepsilon)$ In Eqs. (4a,4b) is equal to the standard normal distribution function and E_a is the standard error. In the proposed framework, $f_{Ea}(\varepsilon)$ is estimated conditional on the mainshock related observations from the site. Hence, the mean and standard deviation of the E_a is different than that of standard normal random variable.

2.1.1 Aftershock epsilon

The distribution function $f_{Ea}(\varepsilon)$ represents the variability of aftershock ground motion intensity Y occurring at the site. For a given site, the attenuation characteristics of the peak motion exhibited during the mainshock is expected to be related to those characteristics exhibited during the aftershock due to relationships noted in the introduction section Fig. 3. This expected relationship implies the presence of some level of statistical correlation $\rho_{Ea,Em}$ between the E_a and mainshock epsilon E_m parameters. This correlation represents the degree of consistency in the level of amplification or attenuation of seismic waves that are traveling from the rupture plane to the site. A high level of correlation $\rho_{Ea,Em}$ would suggest a strong casual relationship between mainshock and aftershock characteristics and the peak motions that are exhibited at the site during the mainshock and the aftershocks.

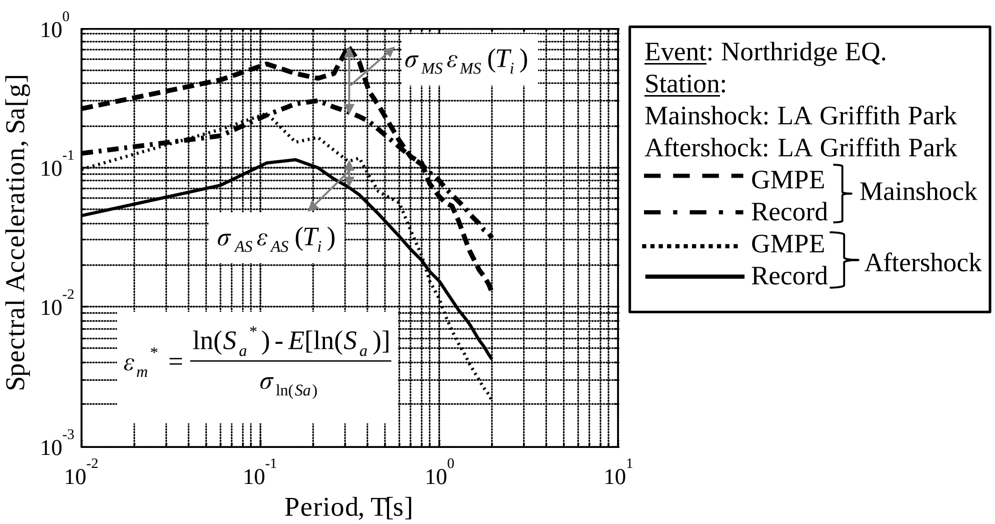

Fig. 3 – Recorded and estimated pseudo spectral accelerations and definition of the corresponding mainshock and aftershock epsilons

If the mainshock ground motion is recorded at the site, the observed value ε_m^* of the mainshock epsilon E_m can be identified using a suitable GMPE. Making use of the correlation $\rho_{Ea,Em}$ and the observed value ε_m*, the conditional distribution $f_{Ea|Em}(\varepsilon_a|\varepsilon_m*)$ of E_a can be expressed as follows:

$$f_{E_a|E_m}(\varepsilon_a \mid \varepsilon_m*, m_m, r_m) = \frac{f_{E_a,E_m}(\varepsilon_a, \varepsilon_m*; m_m, r_m)}{f_{E_m}(\varepsilon_m*; m_m, r_m)} \tag{5}$$

where $f_{Ea|Em}(.,.)$ is the probability density function with chosen model of standard bivariate Gaussian distribution for E_a and E_m. Since both E_m and E_a are standard random variables with zero mean and unit variance, $f_{Ea|Em}(\varepsilon_a|\varepsilon_m*)$ above can be practically evaluated as:

$$f_{E_a|E_m}\left(\varepsilon_a \mid \varepsilon_m*, m_m, r_m\right) = \Phi\left(\frac{\varepsilon_a - \rho_{Ea,E_m}.\varepsilon_m*}{\sqrt{1-(\rho_{Ea,E_m})^2}}\right) \quad (6)$$

where Φ(.) is the standard normal distribution function. A formulation similar to Eqs. (5-6) was proposed by Yeo and Cornell [6]. However, -to the author's knowledge- the level of correlation $\rho_{Ea,Em}$ has not been investigated quantitatively in the existing literature.

Level of correlation $\rho_{Ea,Em}$ influences the degree of impact for taking ε_m* into account in the estimation of E_a. If $\rho_{Ea,Em}$ is close to one (i.e. perfect correlation), the conditional distribution $f_{Ea|Em}(\varepsilon_a|\varepsilon_m*)$ of E_a in Eq. (6) would indicate a dispersion smaller than that of the corresponding unconditional distribution $f_{Ea}(\varepsilon)$ in Eq. (4).

2.1.2 Correlation model for epsilons

In order to enable implementation of Eq. (6) into the proposed framework, the level of correlation $\rho_{Ea,Em}$ was investigated using pairs of mainshock-aftershock strong motion records from Turkey and California [13]. The pseudo-spectral acceleration S_a (T) is utilized as the ground motion intensity measure. Epsilon values for the mainshock and aftershock pairs were computed using the Eq. in Fig. 3. A set of alternative GMPEs were considered to assess the sensitivity of the results to the assumed model. GMPEs utilized in the evaluation were: (1) Boore and Atkinson, 2008, (2) Campbell and Bozorgnia, 2008, Chiou and Youngs, 2008 and Kalkan and Gulkan, 2004. Details of these models were given in Douglas, 2011 [9]. Resulting correlation coefficients $\rho_{Ea,Em}$ obtained for S_a (T)'s that are corresponding to different periods values T are presented in Fig. 4. The highest correlation value 0.65 is obtained at T=0.9 seconds. For the lower vibration periods (T≤0.5s), the correlation coefficient ranges between 0.2 and 0.6 for the different GMPEs. For longer period systems (T≥1.0s), the correlation coefficient $\rho_{Ea,Em}$ is equal to and lower than 0.3. Therefore, level of statistical correlation $\rho_{Ea,Em}$ between aftershock E_a and mainshock E_m epsilon parameters is significant especially for the structures with periods of (T_n≤1.0s).

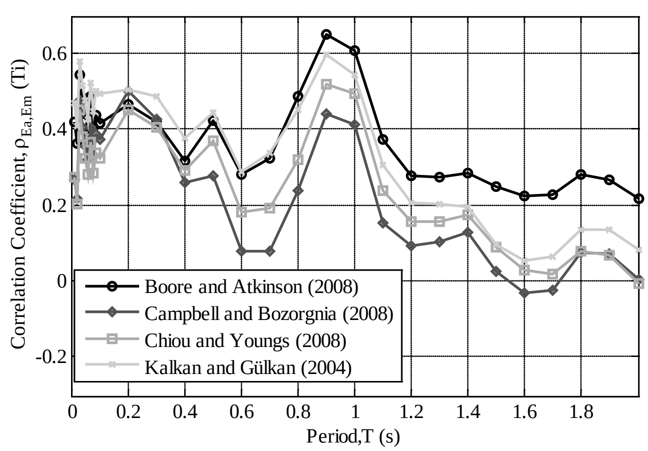

Fig. 4 – Correlation coefficients for recorded mainshock-aftershock epsilon pairs

2.2 Utilization of observed mainshock intensity value in aftershock hazard estimation

Mainshock ground motion level at a site may be estimated using macroseismic intensity scales when there are no instrumental recordings of the motion. In this case, improved estimates of aftershock hazard are obtained by considering the *MMI* indicators related to the mainshock. In order to investigate the relationship between observed mainshock *MMI* and the peak ground acceleration (*PGA*), the database of earthquakes recorded in Turkey were utilized. Comparison of this relationship with other literature studies (Faenza and Michelini [10], Murphy and O'Brien [11]) is presented in Fig. 5a. In addition to this, the ranges for coefficients c_1 and c_2 in relationship equation for different levels of spectral accelerations are given in Fig. 5b.

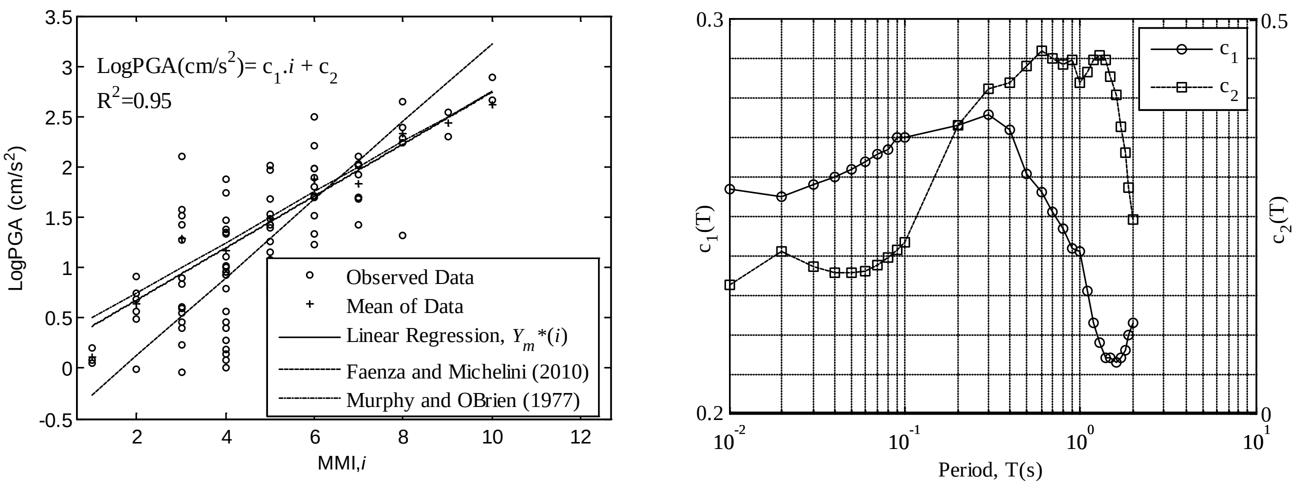

Fig. 5 – a) *MMI-PGA* conversion b) Regression coefficients for mean $S_a(T)$ prediction model based on *MMI*

The logarithm of the actual $S_a(T_1)$, Y_m* that corresponds to intensity,*i* observed at the site during the mainshock, is considered as a random variable. The expected value, E[lnY_m*] of this random variable is estimated as follows:

$$E[\ln Y_m*] = c_1 . i + c_2 \tag{7}$$

where c_1 and c_2 are period dependent coefficients presented in Fig. 5b. Accordingly, the expected value of the mainshock epsilon conditioned on the observed mainshock *MMI* value, E[E_m'] is estimated as follows:

$$\mu_E' = E[E_m \mid i] = \frac{E[\ln Y_m*] - \mu_m}{\sigma_m} \tag{8}$$

The standard deviation of mainshock epsilon is expressed as follows:

$$\sigma_E' = \frac{\sigma_m *}{\sigma_m} \tag{9}$$

where μ_m and σ_m are the logarithmic mean and the logarithmic standard deviation of the mainshock spectral acceleration estimated using GMPE respectively and σ_m* is the standard deviation of Y_m* estimated from the observed intensity, *i* value at the site that is equal to 0.75.

Considering the mean and the standard deviations obtained above, the probability function of expected value of aftershock epsilon parameter E_a parameter conditioned *MMI* level *i* is estimated as given below:

$$f_{E_a|I}(\varepsilon_a \mid i) = \int_{-\infty}^{\infty} f_{E_a|E_m}(\varepsilon_a \mid \varepsilon_m)\, f_{E_m|I}(\varepsilon_m \mid i) d\varepsilon_m \tag{10}$$

In the Eq. (10), $f_{Ea|Em}(\varepsilon_a|\varepsilon_m)$ was defined in Equation 6, $f_{Em|I}(\varepsilon_m|i)$ is the probability density function of mainshock epsilon conditioned on *MMI* intensity observed at the site. Here, the terms $\rho_{Ea,Em}$ and $f_{Ea|I}(\varepsilon_a|i)$ form the basis of CAHA approach. An example application is presented in next chapter by taking an actual event into consider to compare the two approaches.

3. Conditional Aftershock Hazard Assessment Case Study

Proposed CAHA method is applied to assess the aftershock hazard following 2011 Van (Turkey) *M*7.2 Earthquake. The earthquake sequence is considered as a case study, to illustrate the proposed method. Following the mainshock in 2011, several strong aftershocks caused loses in region. Especially, an aftershock of *M*5.6 magnitude occurred and unfortunately, 40 casualties, 30 injuries were registered for this event by AFAD [12]. Greatest strong motions exhibited after the mainshock were recorded at the stations given in Fig. 6a. Acceleration response spectra of these of the recorded accelerations are presented in Fig. 6b.

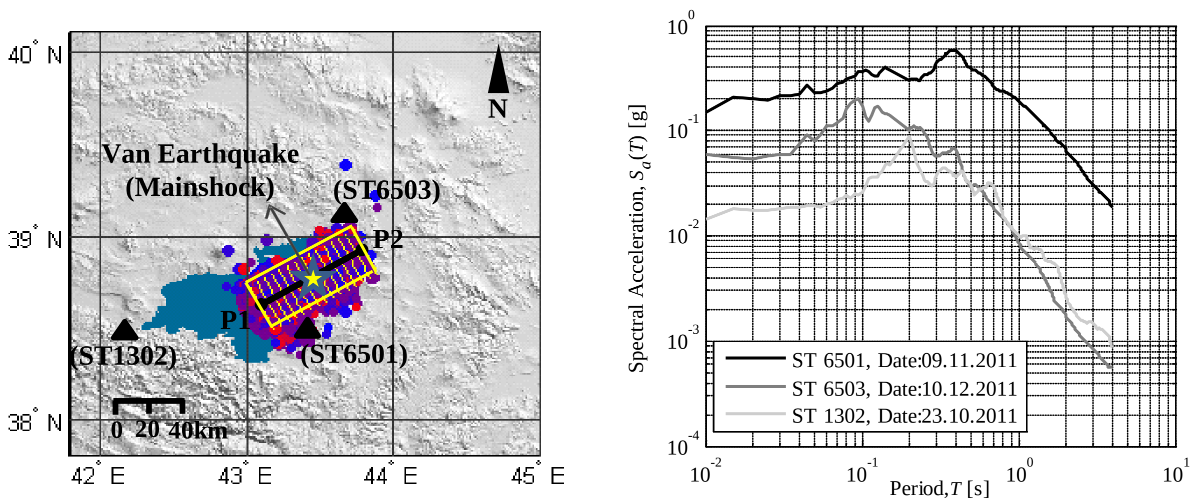

Fig. 6 – 2011 Van (Turkey) Earthquake sequence: (a) Greatest strong motions recorded stations after mainshock b) Acceleration spectra of the strong motions recorded during the aftershocks

Aftershock occurrence rate parameters that are used in estimation of mean number of aftershocks $\mu^*(y,t,T;m_m)$ are calculated by considering the aftershocks that occurred in Turkey [13]. In order to provide a realistic application, it is assumed that Van 2011 Earthquake sequence has not been observed at the time of the assessment. Therefore, the occurrence rate parameter values utilized in the case study, are set equal to the expected values identified using a set of aftershock sequences from Turkey other than the 2011 Van sequence. The resulting aftershock rate parameters were: *a*= -2.03, *b*=1.15, *c*=0.05, *p*=1.08.

3.1 Event and station properties

Epicenter of the 2011 Van Mainshock was located at 43.497°E and 38.691°N. The estimated aftershock source zone is compatible with rupture plane model proposed by Hayes, 2011 [16]. The rupture length is considered as L_{rup}=70km. The attenuation relationship developed by Abrahamson and Silva [17] is used for ground motion prediction. Minimum aftershock magnitude for hazard analysis is considered as 5.0. Aftershock hazard analysis is done for the duration of T=365 days starting from t=7 days after the mainshock. Evaluation of the aftershock hazard for the period that starts 7 days after the mainshock is a customary choice. *MMI* values of mainshock and aftershocks are obtained from AFAD database. After 2011 Van Earthquake, mainshock *MMI* value observed at the site of the station ST6501 was VIII.

3.2 Results

One of the main novelties of CAHA approach is the capability of taking the observed mainshock *MMI* level at site into account in the hazard assessment. The importance of *MMI* level arises as a macroseismic indicator in case of lack of instrumental recordings of the mainshock. Fig. 7 shows the annual aftershock hazard curve obtained by assuming different mainshock *MMI* levels for the T=365 days long period that starts t=7 days after the mainshock. Exceeding rates do not show any significant difference for low (i.e. <0.05g) spectral accelerations. The estimated aftershock hazard increases for increasing intensity level of the mainshock at the site. Also as seen from the figure, the aftershock hazard is estimated to be significantly higher for the sites where mainshock has caused severe damages in structures (e.g. MMI≥VIII). This result shows the importance of estimating aftershock hazard conditioned on the mainshock intensity level at the site.

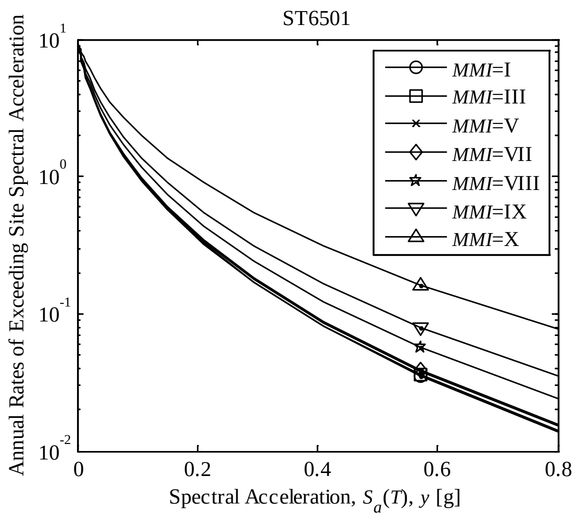

Fig. 7 – Effects of observed MMI value at the site on the estimated aftershock hazard

The effectiveness of estimating aftershock hazard conditioned on observed mainshock demand, is tested by comparing the two approaches APSHA and CAHA. In this context, APSHA is considered as the conventional method and CAHA is the proposed method. The aftershock spectral acceleration levels that were actually recorded at the site, are considered in this comparisons. Specifically, the likelihood estimated for the actual aftershock spectral acceleration level is used as the benchmark parameter. For any prediction model, assignment of high likelihood to an event that is actually observed, indicates that the prediction model is successful. Based on this premise, the likelihoods estimated using the conventional APSHA and the proposed CAHA methods, for the spectral acceleration levels that are actually recorded, are compared here. In order to achieve this, the relative likelihood of peak spectral acceleration being equal to a given value, y is determined as follows:

$$f_Y(y) = \frac{\mathrm{d}}{\mathrm{dy}}\left[1-(1-e^{-\lambda(y)T_y})\right] = \frac{\mathrm{d}}{\mathrm{dy}}[e^{-\lambda(y)T_y}] \quad (11)$$

where the term $1\text{-}e^{-\lambda(y)Ty}$ expresses the probability of exceedance of threshold spectral acceleration, y at the site, $\lambda(y)$ is the mean number of aftershock ground motion intensity Y exceeding a given threshold level y at the site and T_y is the time period. T_y is considered as 1 year in analyzes presented below.

Probability densities estimated using APSHA and CAHA approaches are compared for the hazard corresponding to spectral acceleration $S_a(T=0.9s)$. The selected period T=0.9s corresponds to the period where the correlation factor, is observed to reach its peak (i.e. $\rho_{Ea,Em}$ (0.9s)=0.65). As seen from Fig. 6, the actual spectral acceleration at T=0.9s is measured at stations ST6501, ST6503 and ST1302 as 0.22g, 0.012g and 0.012g, respectively. As the spectral accelerations measured at the stations ST6503 and ST1302 are very low (i.e < 0.013g) to be considered in hazard analysis. Therefore, the comparison of the two approaches are only based on station ST6501. Fig. 8a demonstrates the comparison of probability of densities for a range of aftershock spectral acceleration. Vertical axis presents the probability of density of the site spectral acceleration value while the horizontal one presents the selected spectral acceleration value. The peak aftershock spectral acceleration that was measured at the site of ST6501 is marked in Fig. 8a. It is seen that the probability density corresponding to this spectral acceleration value is higher when the CAHA method is adopted.

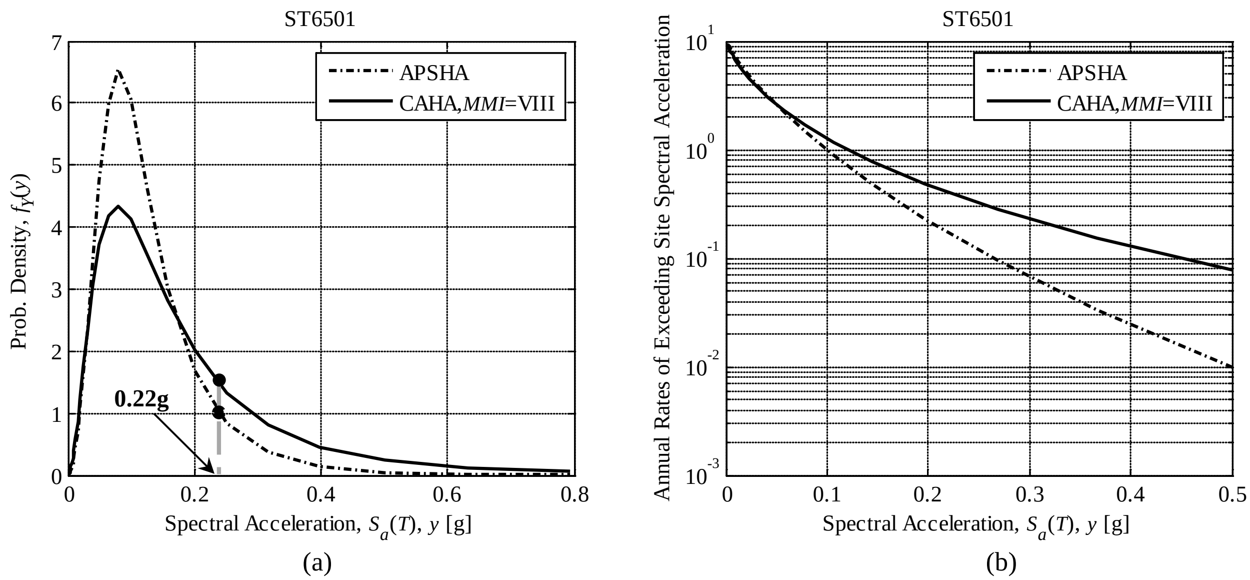

Fig. 8 – Comparison of: (a) Probability of density distributions estimated using APSHA and CAHA approaches b) Annual rates of exceedance the site spectral acceleration

Fig. 8b shows the annual rates of exceeding spectral accelerations at the site of the station ST6501 site estimated by utilizing the two approaches, APSHA and CAHA. Negligible difference is estimated for lower spectral acceleration values. However, greater exceedance rates are estimated using the CAHA for significant (i.e. > 0.1g) aftershock spectral acceleration values.

4. Conclusions

A new aftershock hazard assessment approach that is based on direct consideration of the mainshock demand is presented in this proceeding. Application of the proposed methodology is illustrated for the case of aftershock hazard following the 2011 Van (Turkey) earthquake. In this example application, both the proposed approach as well as the conventional approach is considered. The effectiveness of proposed hazard assessment method is assessed by using the spectral accelerations that were actually measured at the effected sites.

The results indicate that:

- The coefficient of correlation between mainshock and aftershock epsilon parameters, $\rho_{Ea,Em}$ was quantitatively investigated. Results show that, the correlation coefficient, $\rho_{Ea,Em}$ is higher for the range of vibration perios from 0.8s to 1.1. It was also observed that the level of this correlation was only marginally dependent on the utilized ground motion prediction equation.
- Proposed CAHA method enables taking into account the mainshock MMI intensity observed at the site in order to provide aftershock hazard estimates conditioned on that observation. The results of the example

application showed that higher levels of aftershock hazard are estimated for increasing mainshock *MMI* levels. This was especially the case for the intensity values that correspond to observation of significant damages in structures.

- The effectiveness of proposed CAHA methodology is discussed by assessing the aftershock hazard following 2011 Van (Turkey) *M*7.2 Earthquake. In this evaluation, probability density estimates of the peak aftershock spectral acceleration demands are evaluated. In order to assess the relative performance of the CAHA method compared to conventional methods, the probability densities estimated for the level of spectral acceleration that was actually measured at the site, are compared. The results of this example application indicate that higher probability densities are estimated for the levels that were actually recorded at that site, when the CAHA method is used instead of the conventional methods.

Acknowledgements

This study is funded by The Scientific and Technological Research Council of Turkey (TUBITAK) with project number of 213M454. This support is greatly acknowledged.

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