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Ensembles of hazard consistent surface ground motions for clustered seismicity

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Summary

This report contains the methodology for selecting ground motions for clustered seismicity and the results of that operation for the case-study site. This report begins with a brief overview of the methodology employed for hazard-consistent mainshock-aftershock (MS-AS) ground motion record selection. Using the methods described in D5.2, we obtained the target spectra for the AS, given the MS hazard at case-study site, which is then used to find matching AS records. The format of the record sets selected for the case-study site is described for both MS and sequences. Finally, the records are assembled into MS AS pairs, which can be used for back-to-back response analysis with the purpose of deriving damage-state dependent fragility curves for SSCs.

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Ensembles of hazard consistent surface ground motions for clustered seismicity

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Version N°1

Authors: Pablo García de Quevedo, Nevena Šipčić, Paolo Bazzurro (IUSS)

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Abbreviations and Acronyms

Acronym	Description
WP	Work Package
MS	Mainshock
AS	Aftershock
CS	Conditional Spectrum
IM	Intensity measure

Summary

This report contains the methodology for selecting ground motions for clustered seismicity and the results of that operation for the METIS case-study rock hazard. This report begins with a brief overview of the methodology employed for hazard-consistent mainshock-aftershock (MS-AS) ground motion record selection. Using the methods described in D5.2, we obtained the target spectra for the AS, given the MS hazard at case-study site, which is then used to find matching AS records. The format of the record sets selected for the case-study site is described for both MS and sequences. Finally, the records are assembled into MS AS pairs, which can be used for site response and back-to-back response analysis with the purpose of deriving damage-state dependent fragility curves for SSCs.

Keywords

Ground motions, Clustered Seismicity, Aftershocks, Record selection, METIS case study

Introduction

Considering sequences in seismic assessment has gained even more attention after observing the recent cases of damaging sequences, such as Christchurch 2011, Central Italy 2016-2017 and Turkey 2023. These events showed that the earthquake sequences pose an additional risk to society as the financial losses increase when compared to cases characterized by only one main event (i.e., mainshock-only cases). The additional risk posed to NPPs due to clusters of events before the plant is safely shut down is an open question that has been addressed in the METIS project.

Traditional approaches for seismic risk assessment focus solely on mainshocks, a practice that may lead to underestimation of seismic risk. This is the case especially in the aftermath of major events that, invariably, are followed by a cluster of aftershocks, several of which could be of large magnitude and cause further damage. This issue has been long recognized and several researchers have been studying how to incorporate clustered seismicity into risk assessment both in terms of hazard and vulnerability of civil structures. Indeed, for nuclear structures, the situation is slightly different due to the shutdown of the plants after a major damaging earthquake. This will not be analyzed further here but this work focusses on the definition of mainshock aftershock sequences.

This report will present a brief summary of the procedure employed to select MS-consistent seismic sequences and related ground motions consistent with the METIS site hazard at the rock level. These ground motions can be used for site response and back-to-back time history analysis for the purpose of deriving damage-state-dependent fragility curves. The format and structure of these ground motions will also be described herein.

1. Hazard-consistent MS AS Record selection

To realistically assess the effects of seismic sequences at a given site, it is necessary to evaluate the response of SSCs using as input, ground motions of realistic MS-AS sequences. Given that real MS-AS recordings at the same station are scarce in general and given the need for them to be representative of the hazard at a specific site for different levels of intensity, the selection of records needs to be guided by MS-AS hazard consistency. The *four-step procedure* used herein for this MS-AS consistent record selection is based on the work of Papadopolous et al. 2020, which is described in depth in Deliverable 5.2. Therefore, only a brief summary will be included here. It is acknowledged here that the selection of mainshock-aftershock pairs is not based on recorded suites, but the selection is based on spectral shape.

The *first step* of the selection is to find the appropriate MS records using the Conditional Spectrum (CS) approach (further details in Section 1.2 of D5.1 and D5.4). The records are chosen to match the target distribution in spectral ordinates conditioned on the intensity measure IM* at the hazard level of interest. Using seismic hazard disaggregation we find scenarios that contribute to exceeding the selected IM* level (IML), where the scenarios are specified by magnitude, M, source-to-site distance, R, and residual ε (where ε is the number of standard deviations that the ground motion intensity is away from the log mean for that earthquake scenario). Next, a random rupture scenario is assigned to each record, taking into account the IM* level's disaggregation probability mass function. Using this information, a random realization of an MS ground motion response spectrum is created by selecting correlated *ln(Sa)* values from a multivariate normal distribution. Then, a record is chosen from the available ground motions database (described in D5.1) which best matches the realization's spectral shape. This procedure is repeated until we obtain a set of MS records that best fits the target distribution. The spectral match is measured by means of the sum of square errors (SSEs) that accounts for the goodness of fit between both the set's target mean and dispersion at different vibration periods. Here, the additional consideration of the causative parameters is relevant as it will be used to generate the sequence of events.

The *second step* involves generating realistic aftershock sequences using the M and R values of each selected MS ground motion. Some approaches exist in the literature to define these sequences, as described in D5.2. The approach considered here, which follows the approach proposed by Papadopoulos et al. 2020, involves using the Epidemic-Type Aftershock Sequence (ETAS) model proposed by Ogata (1988) to generate realistic seismic sequences assuming that the MS is the parent event. This parent event's characteristics, paired with a set of region-specific ETAS parameters, are used to simulate offspring events that can then generate offspring of their own. Each event in the sequence is associated with a magnitude, location (in terms of latitude and longitude) and time stamp. To avoid considering undamaging events for SSCs, small and distant earthquakes are screened out of the generated sequence and only those above a minimum magnitude of engineering significance and within a given threshold distance are kept. Table 1 shows an example of the causative parameters and number of events in the sequence generated for each of the MS at a given intensity level for the case-study site. It is worth noting that in the case of ETAS, parent events are not to be mistaken as mainshocks. Sometimes a parent event may trigger an offspring earthquake of larger magnitude, such as in the case of MS 10 in Table 1.

MS ID	MS M_w	MS R_{jb}	number of AS	Max AS M_w	AS R_{jb}
1	5.75	15	4	4.9	19
2	4.75	5	2	4.1	9.6
3	5.75	15	11	5.9	12.6
4	5.75	25	1	4.4	26.6
5	5.25	15	1	4.6	12.8
6	6.00	5	12	4.6	8.5
7	5.75	5	8	5.5	13.4
8	5.75	15	8	5.8	13
9	5.75	5	2	4.2	4.8
10	5.75	5	6	5.9	2.6
11	5.25	5	5	4.9	8.1
12	5.75	15	2	3.8	14
13	5.75	5	2	4.5	1.9
14	5.75	5	4	4.3	3.1
15	5.75	25	2	4.2	21.7
16	5.25	5	8	5.7	3.8
17	5.75	5	10	5.2	4.5
18	5.75	5	16	5	5.2
19	5.75	15	24	5.4	11.8
20	5.75	15	8	4.8	13.4

Table 1: Sequences generated for all 20 MS ground motions considered for a return period of 20,000 years (IML8).

The *third step* involves selecting the AS ground motions. This process utilizes the AS M and R inputs (e.g., those in Table 1), along with the MS spectral shape. To define the AS ground motions, it is essential to determine the distribution of the AS response spectrum, based on the spectral accelerations of the specific MS record, as well as the magnitude and rupture-to-site distance of the MS. The MSAS-CS technique, developed by Papadopoulos et al. (2020), is employed to establish the joint distributions of spectral accelerations at multiple oscillator periods. This distribution can be effectively modeled as a multivariate lognormal distribution. This technique relies on the adoption of a Ground Motion Prediction Equation (GMPE), specifically the Kotha et al., 2020 and Lanzano et al., 2019 models in this report, which have been deemed suitable for the site and are utilized in the PSHA analysis as stated in Deliverable D4.6. Subsequently, through the correlation between MS and AS, we can obtain the MS-consistent AS spectrum, such as the one shown in Figure 1.

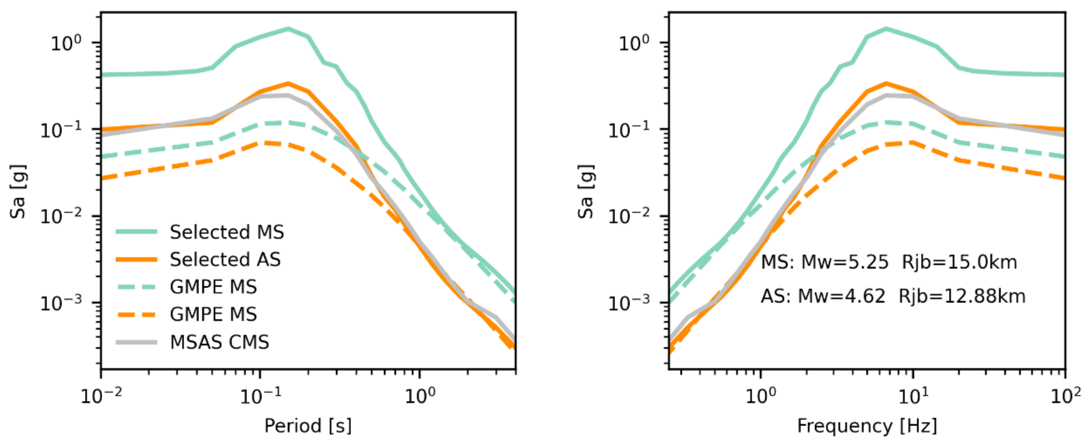

Figure 1 – Mainshock-consistent aftershock conditional mean spectrum in time and frequency for MS5 of IML8.

After obtaining the MS-consistent AS target, the *fourth step* consists of drawing a sample of the AS response spectrum from the joint AS *Sa* distribution, followed by the selection of the ground motion that best matches the simulated target spectrum. Scaling of the ground motion is usually necessary. For simplicity of computation, only one instance of the AS ground motion is drawn in this process. Since many selected AS ground motions may have very low intensity, a threshold can be set below which all sampled ground motions are discarded, and the simulation is rerun. According to Papadopoulos et al. (2020), the potential bias is not expected to be significant as long as the intensity threshold for discarding is kept reasonably low. This ensures that small magnitude and/or large distance MS ruptures are not compelled to produce AS sequences with unrealistically large M and, in turn, associated ground motions. For more comprehensive details on the MSAS-CS procedure briefly outlined here, the reader is referred to D5.2 report and to Papadopoulos et al. 2020.

1.1. Selection for METIS case study

The procedure described in the previous section for rock condition MS and AS selection was performed for the METIS case-study site in the Tuscany region of Italy, shown in Figure 2. The MS selection encompasses 10 ground motion intensity measure levels (IMLs), which correspond to return periods ranging from 40 to 100,000 years of the average spectral acceleration (*AvgSa*). Table 2 shows the different IMLs considered in the case study, along with their corresponding *AvgSa* values. The choice of *AvgSa* was made considering the scope of this exercise, namely selecting ground motions for developing damage-state dependent fragility curves. Given the nature of the clustered seismicity analyses, we can expect the structures to sustain some damage as they are struck by successive events. The accumulation of damage makes the fundamental period of vibration of the structure to increase. Therefore, the spectral acceleration, *Sa(T1)*, at the fundamental period, T1, of the elastic (undamaged) structure has been proven (Kohrangi et al, 2017, De Biasio et al 2014, 2015) to be a less efficient parameter than *AvgSa* to assess the structural demand due to the period elongation. Additionally, in seismic PRA multiple components are considered with varying fundamental periods, making the selection for a single fundamental period less useful. In this record selection exercise given the characteristics of typical SSCs we utilized *AvgSa* from 0.1s to 0.4s at a step of 0.02. We will denote this as *AvgSa(0.1:0.4s).*

Here, for each IML we initially selected 20 MS ground motions to match the target CS spectrum, following the methodology described previously. Note that in this exercise we did not use the groups of MS records smaller than 20 (i.e., 9, 11, 15) that were considered in the MS-only selection, since here we need to generate enough sequences to obtain high-intensity AS motions. A limited set MS input motions would result in too few AS motions capable of damaging structures. For each record associated with an MS earthquake ground motion, the sequence of AS events is simulated using the ETAS model and parameters calibrated for Central Italy (Šipčić et al., 2022). For every AS in the sequence, we defined the target spectrum of the ground motion at the site using the Papadopoulos et al. 2020 methodology. We consider only AS events that are triggered in the period of one year after the MS, with a minimum magnitude of 3.5 and within a radius of 100km from the site. Only ground motions with *PGA* higher than 0.05g are retained. An additional set of 50 MS records with their corresponding AS ground motions starting at IML6 is available as well. The omission of the lower intensity IMLs in this case is because the ground motions associated with lower IMLs at the site of interest produce very small magnitude events, which in turn cannot trigger enough significant aftershocks. Hence, such ground motions would not cause any significant structural demand and would be below the minimum intensity threshold.

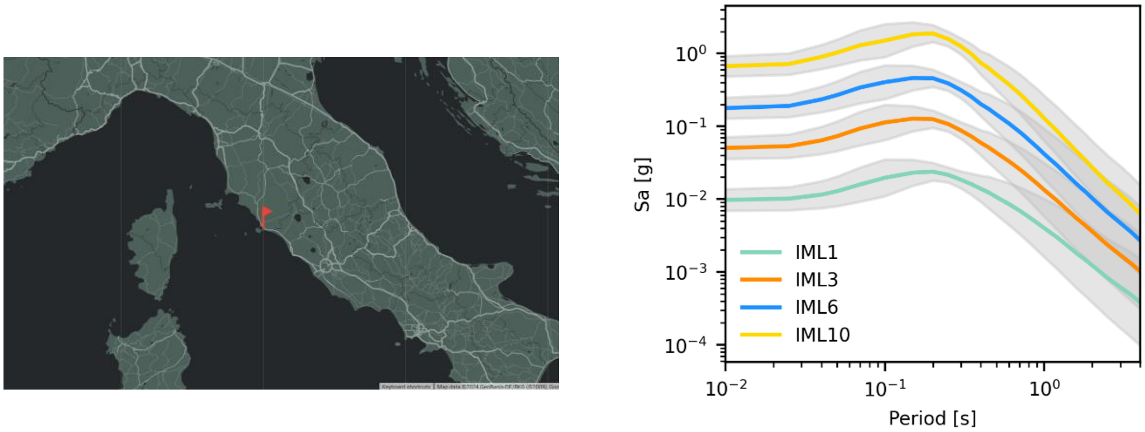

Figure 2 – Location of the METIS case-study site and target spectra for MS selection

IML	poe in 50 years	*AvgSa* (0.1:0.4s) [g]	*Mw*	*Rjb [km]*
1	0.7180	0.019	5.27	62
2	0.2855	0.049	5.20	34
3	0.0998	0.097	5.25	22
4	0.0488	0.147	5.25	19
5	0.0198	0.242	5.35	16
6	0.0100	0.347	5.47	15
7	0.0050	0.491	5.45	12
8	0.0025	0.683	5.62	10
9	0.0010	1.023	5.50	8.5
10	0.0005	1.364	5.55	8.0

Table 2: Values of the AvgSA at the 10 intensity levels at the METIS site and median causative parameters found from disaggregation.

The selected sets of ground motions, containing all the relevant information for each MS and its associated sequence, such as causative parameters and spectral properties, are collected into pickle files (.pkl). The following sections describe the organization of these files and the process of assembling the final time history acceleration files for analysis.

2. Format of the selected sets

The format of the files containing the results of the MS selection (in this case done for *AvgSa*) can be found in Table 3. These files share a similar format to that described for the bedrock mainshock ground motion files presented in Deliverable 5.4. The main difference for this file is that the level and fields related to the different number groups, corresponding to the number of records per IML were omitted, as selection was done for a fixed number of records (here 20).

Level	Field name	Description
Level 1	Periods	List of considered periods of the spectrum
	Poes	List of probabilities of exceedance in 50 years
	imls	List of intensity measure values (AvgSa) in g per level
	IM#	Directories from 1 to 10, containing the data per IML. *Detailed in level 2*
Level 2	Spectra	Contains the spectral acceleration values for each record, for the periods listed on the periods field
	Filename_1	Names of the ground motion record files in the first horizontal direction
	Filename _2	Names of the ground motion record files in the second horizontal direction
	Rups	Directory containing 2 lists, the first one corresponds to the Magnitude of each record, and the second to the distance associated
	SSEs	Matching error associated with this group and IML in %
	dt	Time step for each record
	nstp	Number of points for each record
	DB	Database of origin for each record file
	SF	scale factor applied to each record to match the target CS

Table 3: Description of fields and structure of the mainshock record selection files

For the Aftershock records, the format is described in Table 4, where the individual AS information (level 3) can be found inside each of the MS that are assumed to trigger that sequence.

Level	Field name	Description
Level 1	IM#	Directories from 1 to 10, containing the data per IML. *Detailed in level 2*
Level 2	Inside each IM directory, there are 20 subdirectories, corresponding to each MS record at that IM level. *Contents are detailed in level 3*	
Level 3	*This level will contain, for each field, 'n' number of values, which depend on the number of AS generated and selected for that MS*	
	CS_mean	Contains the target spectral acceleration values for each AS, for the periods listed on the periods field
	CS_std	Contains the target spectra dispersion values for each AS

	Filename_h1	Names of the ground motion record files on the first horizontal direction
	Filename _h2	Names of the ground motion record files on the second horizontal direction
	Mag_MS	Mainshock magnitude
	R_MS	Mainshock distance
	MS_spectra	Mainshock record spectral acceleration values
	Rups	Causative parameters (M and R) for each AS
	SFs	scale factor applied to each AS record to match the target
	Spectra	Contains the spectral acceleration values of each selected AS
	Periods	List of considered periods of the spectrum

Table 4: Description of fields and structure of the aftershock record selection files

3. Assembling the sequences

The MS and AS consistent record selection results in a large number of seismic sequences (and, therefore, pairs of MS-AS ground motions) that can then be used for back-to-back nonlinear time history analysis. Since the information of the full sequence can be found in the described files, one can assemble the sequences either using all the events in the sequence, one after the other, or pairing the MS with individual AS. Here we will focus on the latter case, as the intended use of these records was to develop damage-state (DS) dependent fragility curves. In those types of analysis, the relevant inputs are the current damage state of the structure (after the MS) and the intensity of the current (AS) event. Therefore, the loading history that could have caused that DS is not of importance, and using more than one AS event should not influence the results.

In the provided set of records, we first defined a maximum of 20 AS ground motions allowed for each MS record to limit the number of analyses. The intensities of each MS-AS pair of the set are shown in Figure 3. Here, we can observe how the selection results in stripes at the MS intensity levels, each one with a distribution of AS intensities. It should be noted that the maximum intensity is mostly due to the MS. However, there are many pairs where this is not the case. Each MS and AS pair of records was scaled and assembled back-to-back, as shown in Figure 3, leaving 10 seconds between signals to allow the structure to come to rest and damp any remaining cycles from the MS motion. For compatibility, in some cases, one of the signals had to be resampled to have the same *dt* as the other record in the pair. In this resampling exercise we kept the largest *dt* of the two.

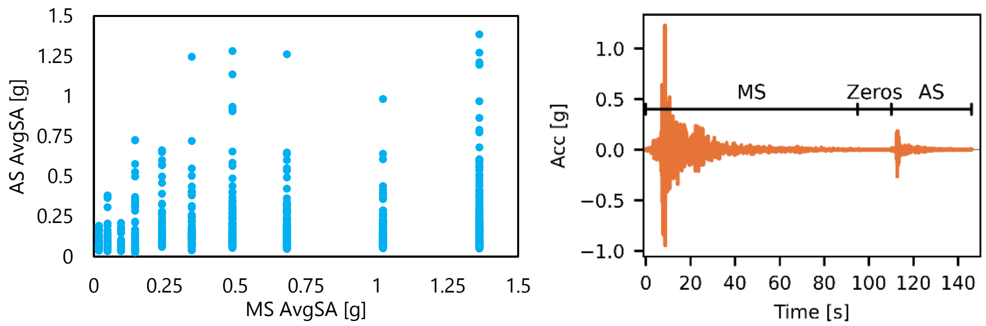

Figure 3 – *AvgSA* intensities of MS-AS sequences and example of a back-to-back MS-AS ground motion pair

The sequences were compiled into text files (.txt), named according to the intensity level, MS and AS number. For example, *IML6MS2AS1* refers to the AS ground motion number 1 of the second MS ground motion of IML6. In addition to those files, one can find also auxiliary files containing the *dt* of the pairs, as well as the MS ground motion length (after resampling). This value is important if one wants to assess the state of the structure between the MS and AS, to understand the change caused only by the AS.

4. Conclusions and Recommendations

This report summarizes the procedure employed to select rock hazard-consistent MS and AS records for METIS case study. They are intended for developing damage-state-dependent fragility curves with the objective of assessing clustered seismicity risk. We provided information about the main outputs of the selection for the METIS case study and a description of how the dataset is organized for future use in the site response and subsequent fragility analysis.

As mentioned above, these records have been assembled for assessing the response of subject to earthquake sequences. Events were also organized in pairs, where the ground motion MS of the sequence is paired with AS records associated to it. For this case, a maximum number of 20 AS per MS was established, to limit repeated analysis that may not yield useful results. This is done since for developing damage state-dependent fragility curves one should only look at the current state of damage of the structure and assess the effects after the AS (considering its intensity) while the loading history that caused this current state is unimportant. The records are selected for rock hazard.

It is advised to be mindful when generating MS AS pairs outside from the text files provided (to go beyond 20 AS per MS), from the sequence files. One must take into consideration that when assembled in a back-to-back fashion, it may lead to very large files, as the duration of the motions is added. Therefore, it is advised to process the ground motions to remove any leading and trailing zeroes. Additionally, special care must be given when assembling the records as the time steps of MS and AS ground motions can be different.

The text files provided contain MS AS pairs, which have been processed to remove the leading and trailing zeroes, as well as resampled for time step compatibility. A period of 10s is introduced in between motions to allow the structure to rest.

Examples of applications of this set of ground motion pairs, as well as the development of damage-state-dependent fragility curves and its implications on risk assessment, can be found in Deliverable D6.7.

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