Assessment of Seismic Hazard in the Middle East and Caucasus: EMME (Earthquake Model of Middle East) Project

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SUMMARY:
The present paper summarizes the efforts towards the uniform assessment of the seismic hazard in the Middle East region under the framework of the EMME (Earthquake Model of the Middle East) project. The wider Middle East region extending from the Eastern Mediterranean to the Himalayas in the East – West direction and from the Gulf of Oman to the Greater Caucasus in the North – South direction has been continuously devastated by large earthquakes throughout the history. The aim of the present study is to homogeneously compute the seismic hazard in the region incorporating both local and international data and expertise and to build the pave towards and to provide one of the basic inputs for the assessment and mitigation of the earthquake risk in the region which will be obtained in terms of physical (building) damages as well as socio-economic impacts.

Keywords: Earthquake model, Middle East Region, Seismicity, Fault database, Ground motion prediction

1. INTRODUCTION

As a consequence of the high probability of earthquake occurrence combined with high population growth, inadequate construction standards and practice and lack of proper mitigation strategies, Middle East and Caucasus represents one of the most seismically vulnerable regions worldwide. EMME (Earthquake Model of the Middle East Region) aims at the assessment of seismic hazard, the associated risk in terms of structural damages, casualties and economic losses and also at the evaluation of the effects of relevant mitigation measures in the Middle East region in concert with the aims and tools of GEM (Global Earth Model). EMME is jointly directed by Eidgenössische Technische Hochschule Zürich (ETHZ) and Kandilli Observatory and Earthquake Research Institute (KOERI). The institutions contributing to the seismic hazard related work packages of EMME are: Boğaziçi University, Middle East Technical University and Sakarya University from Turkey, IIEES from Iran, University of Peshawar from Pakistan, Yarmouk University from Jordan, American University of Beirut from Lebanon, Ivane Javakhishvili Tbilisi State University from Georgia, National Academy of Sciences from Armenia, National Academy of Sciences from Azerbaijan and ETHZ from Switzerland.

Mainly four work packages contribute to the modeling and computation of the seismic hazard in the EMME region: Earthquake Catalog, Seismic Sources, Ground Motion Prediction Equations and Model Building. The WP1 (Earthquake Catalog) team has compiled a unified historical and instrumental catalog of the region from both local and global sources. The WP2 (Seismic Sources) team has prepared a digital active fault map of the region including information on the geometry and rates of movement of faults in a "Fault Section Database". Seismic source zones in the Middle East region have been delineated and parameterized using all available data. The ground-motion prediction models that will be used in the hazard calculations are identified considering the overall neotectonic features of EMME regions of abundant strong-motion data and by extending their applicability via host-to-target relationships and by proxy site characterization methods by the WP3 (Ground Motion Prediction Models) team of the project. The computation of the seismic hazard with several models, logic tree considerations, sensitivity analyses and deaggregration are covered in WP7 (Model Building). The present paper summarizes the achievements obtained towards the complete seismic hazard modeling of the Middle East and Caucasus regions.

2. THE TECTONIC FRAMEWORK

The active tectonics of the EMME Project region has been shaped by the northward motion of the African, Arabian, and the Indian plates with respect to the Eurasian plate. After the elimination of the Neo-Tethys Ocean that had existed in the intervening areas between these plates, continental collision of the Arabian and Indian plates with the Eurasian plate created the Bitlis-Zagros and the Himalayan Fold and Thrust Belts, respectively. Even today the continental convergence and active crustal shortening is still going on between these plates as evidenced by GPS measurements and high seismic activity observed in the EMME Project region. The intense tectonic deformations along the Caucasus region are also the result of the continental collision and the continuing continental convergence. The northward subduction process is active along the Hellenic Trench, Cyprian Trench, Central Caspian, Makran and the Hindu-Kush.

The left-lateral strike slip Dead Sea Fault takes up the differential motion between the African and the Arabian Plates. The North Anatolian, East Anatolian, Northeast Anatolian, Sevan, Main Recent, Elbruz, Doruneh, Ashkabad, Nayband, Neh, Herat, and the Chaman Faults are the prominent strike-slip faults that are capable of generating large magnitude earthquakes in the region. Figure 2.1 after Allen et al. (2004) presents the active slip rates and total deformations at plate boundaries and along major faults in the EMME region.

3. EARTHQUAKE CATALOGUE

The earthquake catalogue has been investigated both for the historical and instrumental periods and has been based on both international and local sources. Three main international sources used for the instrumental part of the catalogue were NEIC, ISC and the EHB Bulletin. NOAA was consulted for the historical part of the catalogue. The catalogue compilation effort has also relied on the local data provided by partner institutions. Table 3.1 summarizes the data bases and the associated number of entries from both international and local sources. As most of the catalogues overlap both time- and region-wise, an extensive effort has been put to remove the duplicate events by both automated and manual methods. As it can be observed from Table 3.1 catalogues report the earthquakes in different magnitude scale. As the final catalogue was intended to provide the earthquake magnitude in Mw scale, several magnitude conversion relationships have been used. Regional conversion equations between Mw and mb, Ms and ML have been derived from records that had Mw and at least on the other magnitudes. The suggested regional conversion equations compare favorably with models provided by Scordilis (2006). The final conversion equations for Mw were:

$$Mw = 0.87\, mb + 0.83 \qquad 3.5 \le mb \le 6.0 \qquad (3.1)$$
$$Mw = 0.66\, Ms + 2.11 \qquad 2.8 \le Ms \le 6.1 \qquad (3.2)$$
$$Mw = 0.93\, Ms + 0.45 \qquad 6.2 \le Ms \le 8.2 \qquad (3.3)$$
$$Mw = 1.01\, ML - 0.05 \qquad 4.0 \le ML \le 8.3 \qquad (3.4)$$

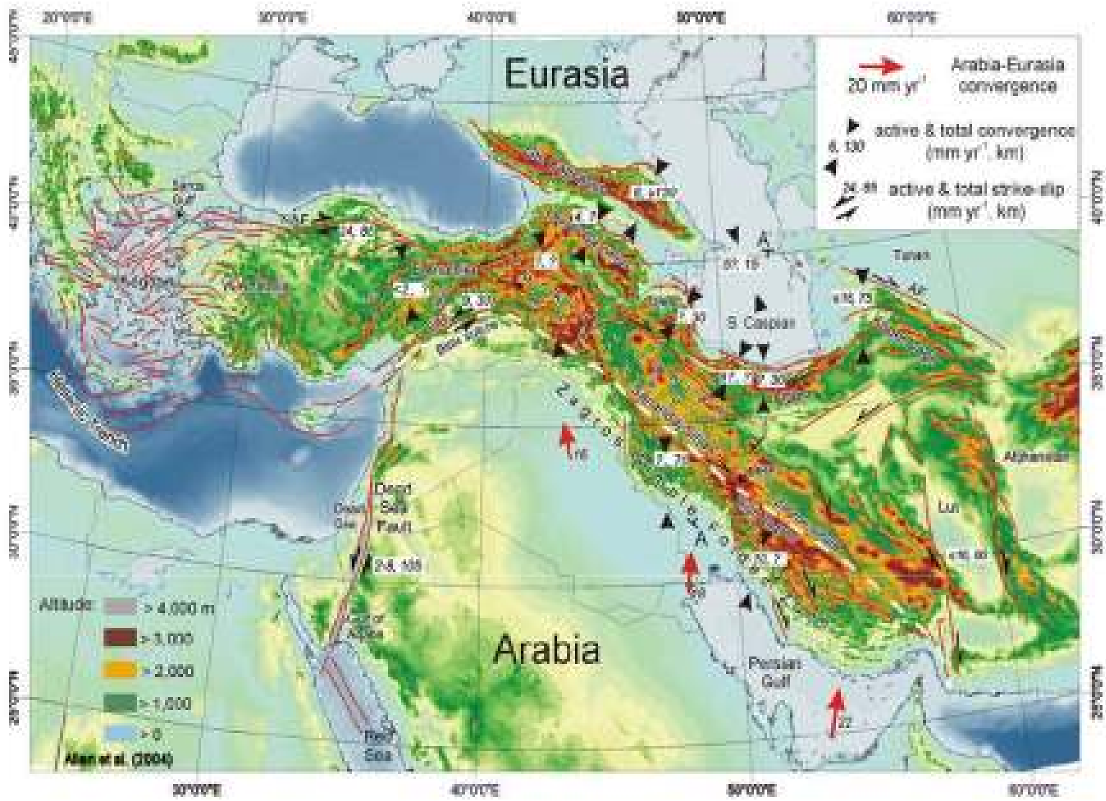

Figure2.1. Active slip rates and total deformations in the EMME region (Allen et al., 2004)

Table 3.1. Data bases and associated number of entries from both international and local sources

Original Source of Data	Number of Records	Time Period	Magnitude Types	The selected name for the main source in our final catalog
Armenia catalague	17415	1900 - 2008	Ms	Armenia
Armenia catalogue, 2nd part	1692	1932 - 2008	Ms, Mw	
Armenia historical data	82		Ms, Mw, Intensity	
Georgia catalague	2188	1250 BC - 2009	Ms, Mw	Same as original
Georgia catalogue, , 2nd part	30	2009	Ms, Mw	SMCG
Azerbaijan catalague	613	427 AD - 2009	Mw, Mlh	Same as original
Pakistan catalague	10147	1668 - 2010	Mw, Ml, mb	The same as original
Turkey catalague	8933	1900 - 2009	Mw, mb	ISK
Turkey historical data	1061	2100 BC – 1899 AD	Mw	
Jordan catalague	206	31 AD - 2007	Ms	
Iraq Historical data	67	1260 BC – 1873 AD	Mw, Intensity	Same as original
IIEES online catalague	7782	2000 - 2010	Ms, Mw, Ml, mb, MD, Pv	IIEES
BHRC catalogue	4560	1900 - 2006	Ms, mb, Ml	BHRC
IRSC online catalague	7502	2006 - 2009	MN, Unknown	IRSC
NEIC Online Bulletins	51470	2000 BC – 2010	Ms, mb, cont.Values	NOAA, PDE
ISC Online Bulletins	24323	1964 - 2008	Mw	ISC Online Bulletin
	361	1995 - 2006	Ms, mb	HRVD
EHB Online Bulletin	6877	1960 - 2007	Ms, Mw, mb	EHB Bulletin

The historical catalogue compiled so far includes more than 2,000 records for the time period of 19750 BC to 1899. It should be noted that approximately 25% of the records do not include intensity or magnitude estimates. The instrumental catalogue covering the time period from 1900 to 2010 includes 6,102 records with Mw ≥ 5, 526 of them with Mw ≥ 6, 134 with Mw ≥ 6.5 and 41 with Mw ≥ 7.

The recent improvements of the earthquake catalogue were obtained in the following domains:

1. Checking the coverage of the catalog all over the EMME region. The existence of local seismicity data / historical earthquake data for all sub-regions was certified.
2. Investigation of the range of depths for different regions as well as seismic sources. The teleseismic depths are estimated in the region of EMME countries to be about 5 to 25 km for Iran and Eastern Anatolian regions, 5 to 45 for Makran and Pakistan regions, and 5 to 30 for Caucasus region, and 5 to 35 for Kopet-Dagh region.
3. Checking the range of uncertainties for Mmax for different regions. The magnitude discrepancies were also checked with the international catalogues.
4. The border regions were checked to match the seismicity parameters and Mmax for sub-regions located in the border areas.
5. Investigation the level of completeness for different regions, considering differences in regions with abundant seismicity as well as those with less seismicity.
6. Declustering of the catalog data.

The earthquake catalogue of the EMME region with Mw ≥ 5 is presented in Figure 3.1.

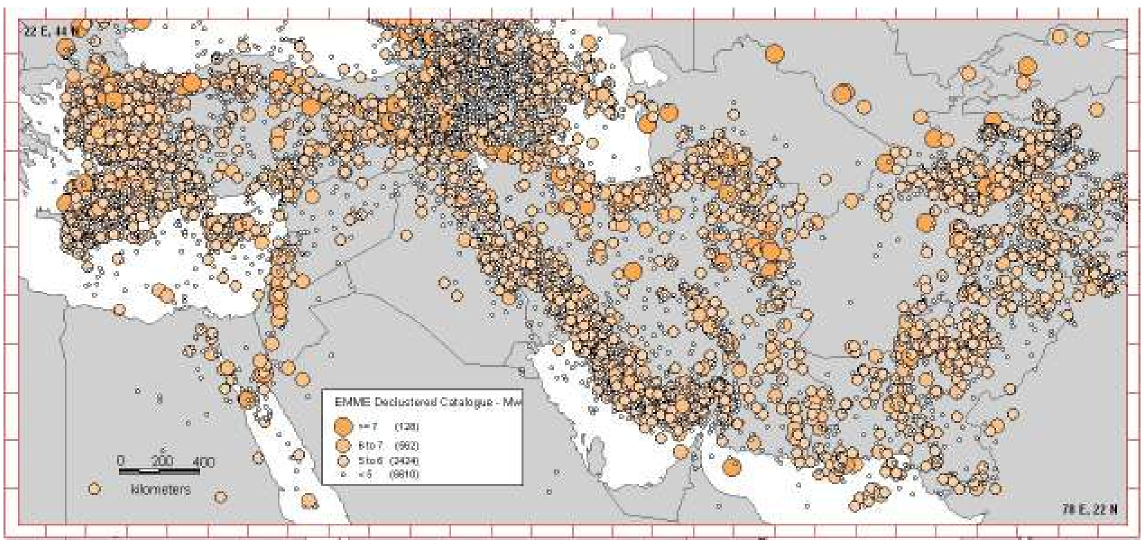

Figure 3.1. The declustered catalogue for the EMME Project region

4. ACTIVE FAULTS

Active faults are the places where earthquakes occur, so the delineation of the active fault zones and the parameterization of their characteristics is the first step in seismic hazard assessment. A digital active tectonic map of the Middle East region is generated in ArcGIS format. A total of 3,397 active fault sections are defined and faults with a total length of 91,551 km are parameterized for the EMME Project (Figure 4.1). Additionally, the digital active fault map of Afghanistan, which was prepared by the USGS (Ruleman et al., 2007) was added to the EMME Project active fault map. We developed a database of fault parameters for active faults that are capable of generating earthquakes above a threshold magnitude Mw ≥ 5.5. This database includes information on the geometry and rates of movement of faults in a "Fault Section Database" following a revised and extended version of the WGCEP-2007 format (Wills et al., 2008) and information on the timing and amounts of fault displacement in a separate "PaleoSites Database".

4.1. Fault Section Database

The "Fault Section Database" contains 36 entries for each fault section. Some of the important parameters are as following: fault name & code, segment name & code, section name & code, fault trace (list of latitudes and longitudes), faulting type, fault section length, average strike, average dip estimate, average rake estimate, average upper seismogenic depth estimate, average lower seismogenic depth estimate, average long term slip-rate estimate (both horizontal and vertical), maximum displacement (both horizontal and vertical) and average aseismic-slip-factor estimate.

The reference codes for each fault parameter data are given as multiple entries in the database and full references are also supplied in a separate reference database. Note that "Fault Section" is different than "Fault Segment", because geologists associate the word segment with the occurrence of characteristic earthquakes that are limited by a segment's boundaries. We may use "fault segment" in conjunction with earthquake recurrence models, but "fault section" is intended to include basic descriptive information about faults, not the recurrence model information (Wills et al., 2008). A new "Fault Section" is defined wherever any of the fault parameters change, thus "Fault Section" has a physical meaning. "Fault segments" may have more than one "fault sections".

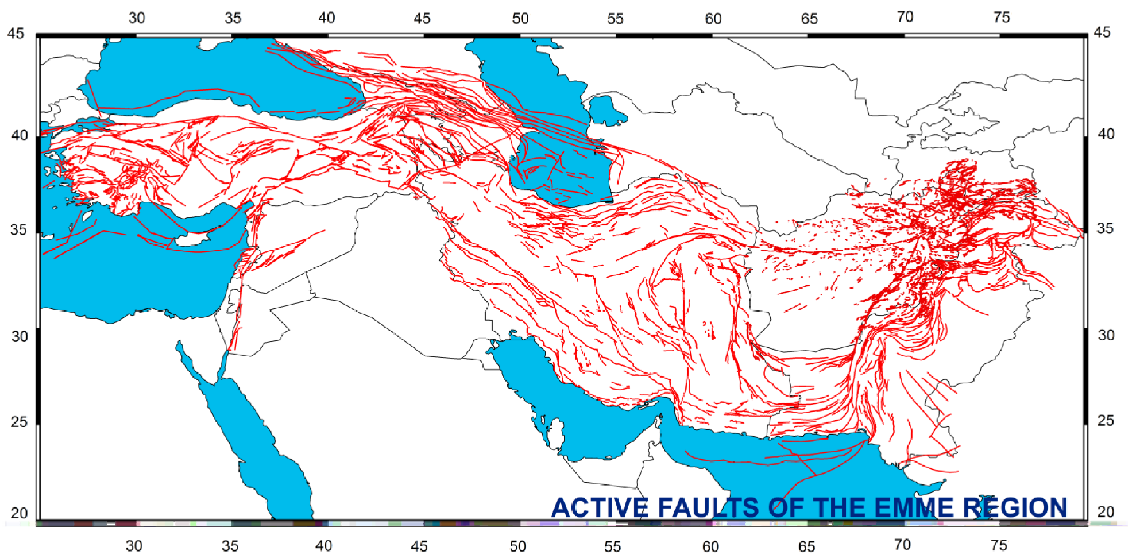

Figure 4.1. Active fault map of the EMME Project region

4.2. Paleo-Sites Database

Paleoseismic data for some major faults in the Middle East region have been acquired at more than 30 sites and published in the literature. These data have been compiled and information on the timing and amounts of fault displacements provided in a "PaleoSites Database" that also includes the published recurrence intervals and their references.

5. SEISMIC SOURCE ZONATION

The delineation of the seismic source zones as probable locations of future earthquakes forms a major step towards the probabilistic assessment of the seismic hazard. The databases and information compiled in the form of fault geometry and seismicity and the associated parameters such as fault rupture characteristics, earthquake epicenter, depth, magnitude and mechanisms culminate in a final seismic source zonation model, where individual source zones are characterized in terms of maximum magnitude that the source zone is able to produce, the magnitude recurrence model and associated parameters, rupture mechanism and depth distribution. The areal source zonation model developed for the EMME region is presented in Figure 5.1. The source zonation model with 200 areal sources is a consensus model among the participating countries as it is based on individual country models provided by different institutions combined and homogenized at the border regions. The source zones are characterized by tectonic regionalization, maximum magnitude (based on both historical seismicity and fault length), pre-dominant rupture mechanism, depth distribution and earthquake recurrence parameters, all parameters being assigned based on the earthquake catalogue and fault section databases compiled for the project region.

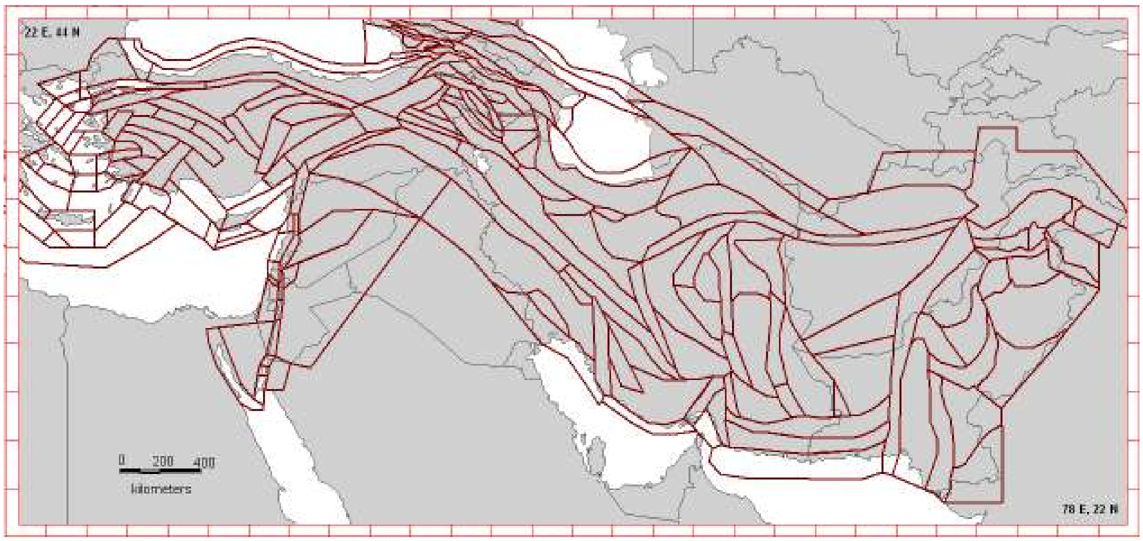

Figure 5.1. The areal source zonation map for the EMME region

6. GROUND MOTION PREDICTION MODELS

The overall seismotectonic features of the EMME region suggest the consideration of shallow active crustal and subduction regions (SACRs and SRs, respectively) for seismic hazard calculations. A total of 14 ground-motion predictive models were selected as candidate GMPEs while establishing the GMPE logic-tree for SACRs in EMME. The candidate GMPEs comprise of local and global equations that fulfil the pre-selection criteria set by Cotton et al. (2006). Detailed information on the general features of candidate GMPEs for SACRs can be found in Kale and Akkar (2012). The candidate models representing SACRs were subjected to 2 analytical testing and ranking methods using a subset of EMME strong-motion (SM) databank. The EMME SM databank almost exclusively consists of ground-motions compiled from the SACRs in EMME territory. The general information about EMME SM databank as well as detailed seismological features of the ground-motion dataset used for testing the GMPEs are presented in Kale and Akkar (2012). In brief, the dataset comprises of 1703 horizontal-component accelerograms from Turkey (984 records), Iran (602 records), Caucasus (100 records), Jordan (6 records) and Pakistan (11 records). The moment magnitude (M_w) vs. Joyner-Boore distance (R_{JB}; closest distance to the horizontal surface projection of fault rupture) scatter that shows country-based distribution is given in Figure 6.1. The dominant rupture mechanism is strike-slip (S) in the database that is followed by reverse (R) and normal (N) fault events. Accelerograms of B and C soil categories according to Eurocode 8 (CEN, 2004) site classification (corresponding to Vs30 ranges of 360–800 m/s and 180–360 m/s respectively) dominate the site conditions. Notwithstanding there are quite a few accelerograms satisfying rock conditions (described as site class A in Eurocode 8, i.e. Vs30>800 m/s). A uniform data processing scheme was implemented to the records in the dataset that is based on band-pass acausal filtering. The high-pass and low-pass filter cut-off values were mainly identified by following the discussions in Akkar and Bommer (2006) and Akkar et al. (2011). The number of recordings from subduction earthquakes is negligible in EMME SM databank so no testing procedure was applied for selecting the GMPEs for SRs in EMME. Instead the predictive models that are chosen in the context of another regional GEM project (SHARE; **S**eismic **H**azard h**AR**monization in **E**urope) are adopted for GMPE logic-tree of SRs in EMME. These GMPEs were tested with subduction events recorded in Europe and they were recommended by expert elicitation in SHARE (Delavaud et al., 2012). The following paragraph explains the implemented methodology while selecting the GMPEs for SCARs in EMME.

The analytical testing methods proposed by Scherbaum et al. (2009) and Kale and Akkar (2012) were used in ranking the above mentioned candidate GMPEs and to select the final set for the logic-tree application of SACRs in EMME territory. The log-likelihood (LLH) testing method (Scherbaum et al., 2009) computes the occurrence probability of the observed data point by assuming that the estimated and observed data are log-normally distributed with median and sigma (σ) values of the tested GMPE. The Euclidean distance based (EDR) ranking method considers the bias in the median ground motion estimation and computes the probability of differences between the observed and estimated ground motions for a range of sigma values of the considered GMPE. In this study the sigma range for EDR is chosen as $\pm 3\sigma$. The resulting EDR and LLH indices describe the performance of the GMPE under the given ground-motion dataset. A low-value EDR or LLH index indicates a better performance of the predictive model. The computed indices can also serve for assigning weights to GMPE logic-tree. Details of EDR and LLH methods as well as many other alternative testing and raking procedures can be found in Kale and Akkar (2012). The following multi-step approach was carried out while ranking the 14 candidate ground-motion equations:

1. Use entire dataset and compute LLH and EDR indices for spectral periods of T = 0.0s, 0.1s, 0.2s, 0.5s, 0.75s, 1.0s, 1.5s and 2.0s.
2. Rerun LLH and EDR using the subsets of the ground-motion dataset assembled according the specific features of each predictive model (i.e., limitations/constraints on magnitude, distance, SoF and site classification functional forms).
3. Subdivide the ground-motion dataset for different magnitude and distance bins (4 magnitude intervals; $4 \leq M_w < 5$, $5 \leq M_w < 6$, $6 \leq M_w < 7$, $M_w \geq 7$ and 4 distance intervals; $0km \leq R_{JB} < 25km$, $25km \leq R_{JB} < 50km$, $50km \leq R_{JB} < 100km$, $100km \leq R_{JB} < 200km$) and rerun the LLH and EDR once again to compute the corresponding indices.

Both LLH and EDR methods yielded very similar results in this multi-stage testing approach and the testing of each GMPE was evaluated from EDR and LLH indices computed after every step. The overall performances of Akkar and Bommer (2010), Zhao et al. (2006), Akkar and Cagnan (2010) and Chiou and Youngs (2008) were relatively better than the rest of the candidate GMPEs. The EDR indices were then used to assign weights in GMPE logic-tree for SACRs in EMME region. Figure 6.2 summarizes the above process and Table 6.1 lists the ground-motion models selected for GMPE logic-tree for this project.

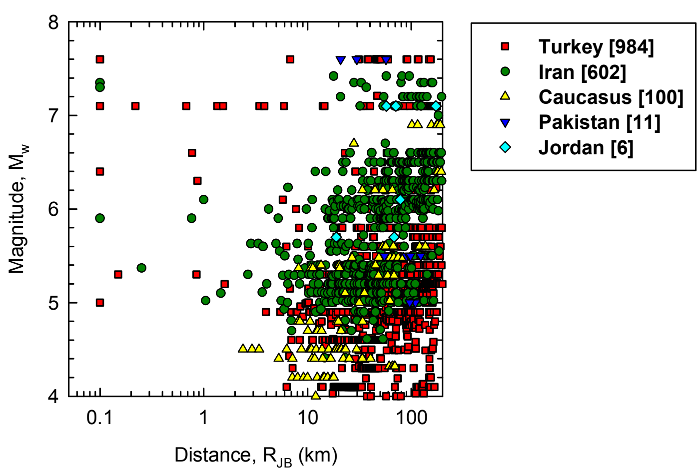

Figure 6.1. Database used in testing of candidate GMPEs for SACRs in EMME territory

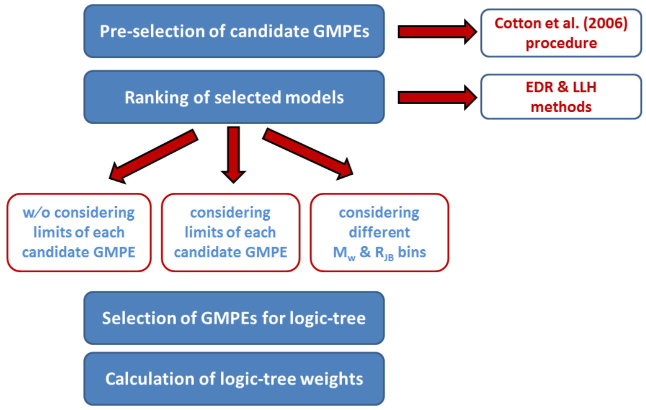

Figure 6.2. Methodology followed while selecting and ranging the candidate GMPEs for SACRs in EMME

Table 6.1. GMPE logic-tree in EMME (bold numbers denote suggested logic-tree weights)

GMPEs for SACRs	GMPEs for SRs
Akkar and Bommer (2010) **0.25**	Boore and Atkinson (2003) **0.20**
Akkar and Cagnan (2010) **0.25**	Lin and Lee (2008) **0.20**
Chiou and Youngs (2008) **0.25**	Youngs et al. (1997) **0.20**
Zhao et al. (2006) **0.25**	Zhao et al. (2006) **0.40**

7. TOWARDS BUILDING THE UNIFIED HAZARD MODEL

The unified seismic source zonation model of the EMME region forms the basis of the probabilistic seismic hazard assessment model. As parameters assigned to the seismic source zones are subject to both epistemic and aleatory uncertainties these two kinds of uncertainties need to be addressed by proper methodologies. A logic tree structure will be used for the treatment of the epistemic uncertainties, which are related with the maximum magnitude that that can be generated by a specific seismic source and the associated earthquake recurrence parameters. The GMPE logic tree is also incorporated at this level. Uncertainties are associated with the depth of the events and their rupture mechanism. Appropriate percentages assigned to possible values of these parameters obtained from the seismicity data are used to model these uncertainties. Expert judgment is also used when and where the seismicity data are not sufficient to define the range of variability in these parameters.

Two hazard computation software are used in the computation of the probabilistic seismic hazard. These are the OPENQUAKE, the publicly available software developed within the context of the GEM (Global Earthquake Model, www.globalearthquakemodel.org) project, and the EZ-FRISK™, developed by Risk Inc. US which is widely used commercial software.

The specifications for the seismic hazard outputs of the EMME project are as follows:

- Hazard maps for selected return periods for the median (from the logic tree) of PGA, PGV, PGD and spectral ordinates at a reference bedrock level.
- PSHA disaggregation in terms of PGA and spectral ordinates at selected locations.
- Uniform Hazard Spectra at selected locations.
- The period ordinates for the computation of spectral acceleration are 0.03, 0.1, 0.2, 0.5, 1, 2 and 4 seconds.
- The hazard will be computed for the return periods of 25, 100, 500, 2500 years; 10’000 and 100’000 years ground motions will be obtained for sanity checks.
- Reference bedrock of Type A based on the Eurocode 8 definition is rock or other rock like geological formation, including at most 5 m of weathered material at the surface ($Vs30 \geq 800$ m/ s).

The output specification is also in accordance with the EU-FP7 SHARE project, which aims to develop a homogenized hazard model for Europe. Turkey being the pivot region between these two projects, the seismic hazard results obtained from both projects will also provide a validation of the methodologies and approaches used.

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