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Design of Specifications for Compilation of a Global Database of Soil Classification

Report produced in the context of the Global Project
"GEM Ground Motion Prediction Equations"

Jonathan P. Stewart[1], David M. Boore[2], Kenneth W. Campbell [3], Mustafa Erdik[4], Walter Silva[5]

[1] University of California, Los Angeles [2] U.S. Geological Survey [3] EQECAT [4] Bogazici University [5] Pacific Engineering and Analysis

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GEM Ground Motion Prediction Equations

Version: 1.0.0

Author(s): Jonathan P. Stewart, David M. Boore, Kenneth W. Campbell , Mustafa Erdik, Walter Silva

Date: March 2013

Citation: Stewart, J.P., D.M. Boore, K.W. Campbell , M. Erdik, W. Silva (2013) [Design of Specifications for Compilation of a Global Database of Soil Classification, report produced in context of GEM GMPE project, available from http://www.nexus.globalquakemodel.org/gem-gmpes

ABSTRACT

We present the results of work conducted for Task 6 of the PEER-GEM project. We develop a roadmap describing the process by which maps of the principal site parameters used in GMPEs could be prepared for global application. Those parameters are time-averaged shear wave velocity in the upper 30 m of the site (V_{s30}) and the depth to a shear wave isosurface of x km/s (Z_x) (pre-selected models from Task 2 use x = 1.0 and 2.5 km/s). Our main focus is on V_{s30}, which is the principal site parameter in modern GMPEs, and we describe procedures for developing maps of V_{s30} for a target region that are conditional on the amount of V_s profile data available for that region.

We suggest that the reliability of V_{s30} mapping is strongly affected by whether a V_s profile database can be developed for the region and by the quality of that database. Accordingly, our recommendations for V_{s30} mapping are conditional on the presence and quality of such a database. We describe specifications for the development of a V_s profile database. Assuming that the GMPEs selected in Task 3 are to be applied in subsequent GEM applications on a broad, as opposed to site-specific, scale, it follows that site parameters will be taken from relatively approximate site condition maps and not site-specific measurements. We describe how a profile database can be used to optimize correlation relationships that produce estimates of site parameters (median, standard deviation) conditional on information such as geologic and topographic conditions that are available for all, or most, global regions. We also briefly describe processes by which basin models can be developed, which are useful for estimation of Z_x. However, we anticipate that global application of GMPEs for hazard mapping will in most cases not have access to basin depth information, and instead will need to utilize default procedures for depth estimation.

Keywords: Site effect, geologic mapping, shear-wave velocity

ACKNOWLEDGEMENTS

This study was funded by the GEM Foundation as part of the Pacific Earthquake Engineering Research Center's (PEER's) Global GMPEs project. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsors.

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1 Introduction

This report has been prepared as part of the "Global Ground Motion Predication Equations" project, which has the objective of recommending a appropriate suite of ground motion prediction equations (GMPEs) that can be used at the global, regional and national levels for hazard analysis and ground shaking related loss estimation studies. The scope of this project is as follows:

- ***Task 1*** identifies consistent protocols for selection of input parameters required for ground motion estimation and also identifies approaches for ground motion estimation (e.g., empirical vs simulation based methods).
- ***Tasks 2 and 3*** recommends suites of GMPEs for various tectonic regimes based on application of appropriate review criteria.
- ***Task 4*** recommends modifications to the selected GMPEs from Task 3 for near-fault effects and for considerations related to ground motion directionality.
- ***Task 5*** provides a global inventory of waveforms suitable for engineering application from recordings of shallow-crustal earthquakes in active tectonic regions, earthquakes in stable continental regions, and earthquakes in subduction zones (inter-face and intra-plate).
- ***Task 6*** develops through expert consensus a set of specifications for future work having the objective of developing a global database of site classifications based on V_{s30} and possibly basin depth.

This report presents the results of work conducted for Task 6. The PEER-GEM proposal describes the objectives of Task 6 as "to define a set of specifications to compile a consistent global database of soil classifications based on V_{s30} and designed to be consistent with the soil categories in the NEHRP and EuroCode 8 building codes." Our interpretation of Task 6 was to develop a roadmap describing the process by which maps of the principal site parameters used in GMPEs could be prepared. As described in the Task 1b report, those parameters are time-averaged shear wave velocity in the upper 30 m of the site (V_{s30}) and the depth to a shear wave isosurface of x km/sec (Z_x) (pre-selected models from Task 2 use x = 1.0 and 2.5 km/sec). Our main focus is on V_{s30}, which is the principal site parameter in modern GMPEs, and we describe procedures for developing maps of V_{s30} for a target region that are conditional on the amount of V_s profile data available for that region.

We suggest that the reliability of V_{s30} mapping is strongly affected by whether a V_s profile database can be developed for the region and by the quality of that database. Accordingly, our recommendations for V_{s30} mapping are conditional on the presence and quality of such a database. Chapter 2 of this report describes the specifications for the development of a V_s profile database.

The underlying assumption of this work is that the GMPEs selected in Task 3 are to be applied in subsequent GEM applications on a broad, as opposed to site-specific, scale. As a result of regional- or global-scale application, site parameters will be taken from relatively approximate site condition maps and not site-specific measurements. In Task 1b, we recommended correlation relationships that can produce estimates of site parameters (median, standard deviation) conditional on information such as geologic and topographic conditions that are available for all, or most, global regions. In Chapter 3, we describe how a profile database can be used to optimize such relationships for application to a target region for the purpose of V_{s30} mapping.

In Chapter 4, we briefly describe processes by which basin models can be developed, which are useful for estimation of Z_x. However, we anticipate that global application of GMPEs for hazard mapping will in most cases not have access to basin depth information, and instead will need to utilize default procedures for depth estimation provided in the Task 1b report.

2 Requirements for V_s Profile Database for Study Region

A profile database is a compilation of profile attributes at sites that have been the subject of geophysical and/or geotechnical exploration, along with the relevant proxies for those sites. The term 'proxy' in this context refers to parameters or information used to estimate V_{s30} using the correlation relationships in the Task 1b report. Each 'row' in the profile database provides the available attributes for a given site, having a specific location. We encourage the compilation of data for sites even when profile depth z_p < 30 m, because of the availability of estimation procedures for V_{s30} conditional on z_p and the time-averaged shear wave velocity to depth z_p, denoted as V_{sz}.

A site with geophysical measurements of shear wave velocity (V_s) is an obvious candidate for inclusion in a profile database. Additional sites that can be considered for inclusion in a profile database are those for which penetration resistance data is available, such as the standard penetration test blow count (N), because such data can be correlated to V_s (e.g., Brandenberg *et al*, 2010). With this in mind, the profile database should be formulated to include the following attributes:

- Data source (reference to relevant report, including date of publication)
- Description of type of V_s measurement. Distinguish surface wave techniques from borehole techniques. Briefly describe surface wave techniques in terms of array spacing, configuration, and vibration source.
- Description of SPT procedures, including hammer weight, drop height, and lift mechanism. Type of sampler (inside and outside diameters). Values of energy efficiency if measured.
- Site location, which should include the latitude and longitude of the profile, preferably at a level of resolution of 0.001 degree or finer. Ground surface elevation should be provided.
- Web links to graphical depictions of profile data, possibly including geotechnical log, SPT N-profile, surface wave test dispersion curves (phase velocity plotted against wavelength), H/V spectrum, and full V_s profile.
- Depth-related parameters, including profile depth z_p, depth to groundwater z_w, and depth to the 1.0 km/sec and 2.5 km/sec V_s horizons ($Z_{1.0}$ and $Z_{2.5}$, respectively).
- Predominant period and the basis for its estimation (e.g., period of peak in H/V spectrum).
- Value of V_{s30} or V_{sz} when z_p < 30 m. We encourage V_s profiling efforts to collect data to depths beyond 30 m.

The V_{s30} or V_{sz} value given in the profile database is computed from a V_s profile, and certain features of profiles from various measurement techniques can complicate the interpretation. Examples specific to several widely used techniques are as follows:

- *Suspension logging* data provides velocities at a relatively dense vertical spacing (typically 1.0 m). Time-averaged velocities for the profile can be taken from 'raw' or 'smoothed' V_s profiles; we recommend the use of the raw data (the time-averaging process will effectively smooth the data).

Boore (2003) explains common pitfalls in the interpretation of data from *downhole testing*; in particular, the inversion of V_s profiles in terms of interval velocities needs to reflect overall surface to geophone travel times (using a piecewise continuous set of straight line segments; see Boore and Thompson, 2007) and not simply velocities from within-layer gradients of measured travel time.

- *Surface wave techniques* produce plots of Rayleigh wave phase velocity with frequency (referred to as dispersion curves), which can be interpreted to provide estimates of V_s profiles through an inversion process. Those profiles have been shown to compare favorably to results from other techniques (e.g., Brown *et al* [2002]), but poor results can also be obtained either in the dispersion curves or the inversion to V_s profiles. General consensus has yet to emerge on acceptable techniques, but experience has shown that linear arrays used with passive vibration sources can produce highly variable phase velocities, particularly at low frequencies [Cox and Beekman, 2011]. In addition, velocities inferred from surface wave measurements represent a different spatial average than those from downhole measurements, and in regions of lateral nonuniformity in material properties this can lead to differences in the inferred velocity profiles with depth.

Another issue is that many shear wave velocity measurement techniques (other than surface wave methods) do not provide profile data near the ground surface (approximately the upper 2-5 m). Our recommendation is that the profile be extended to the surface for V_{s30} or V_{sz} calculations by extending a trend line consistent with the shape of the shallow portion of the profile or 'vertical extrapolation' of shallow measurements to the surface. The method of extrapolation should reflect knowledge of the local geotechnical conditions, and should be explained in the documentation (web links).

Additional attributes that should be included in the profile database are unrelated to the profile itself, but rather to proxies associated with the profile location. The compiled proxies should include:

- Ground slope at various levels of resolution given the available Digital Elevation Model (DEM) resolutions. Ground slope is available world-wide at 30 arc-sec resolution, and should be provided at all sites. Where available, slopes based on 3 and 10 arc-sec resolution should also be provided. Data sources for these DEMs are provided in the Task 1b report and the references therein. As described in the Task 1b report, ground slopes computed from these DEMs are utilized in proxy-based V_{s30} estimation procedures by Wald and Allen [2007] and Wills and Gutierrez [2008].
- Terrain-type classification derived from 30 arc-sec DEMs using the procedure of Iwahashi and Pyke [2007]. As described in the Task 1b report, these terrain-type classifications are used in proxy-based V_{s30} estimation procedures by Yong *et al* [2012].
- Information on the surface geologic conditions at the site, including geologic age, depositional environment (for sediments), and any other descriptive data (e.g., rock type).
- Geomatrix 3rd letter classification (see Table 3.2 of Task 1b report).

3 Specifications for Developing Maps of V_{s30} or V_{s30}-Based Site Categories

3.1 Proposed Mapping Protocols

To develop a V_{s30} map for a target region, we propose procedures that differ with the amount of geotechnical/geophysical data in that region. The proposed methods are structured as indicated below.

3.1.1 *Case 1: Substantial V_s and Geotechnical Data Available; Good Geological Maps Available*

In this case, V_s measurements can be assembled into a profile database for the target region. The profile database can then be used to investigate the relationships between V_{s30} and various proxies, with the objective of customizing the V_{s30}-proxy relationships for the conditions in the target region. We recommend that V_{s30} mapping proceed as follows:

- Develop a profile database following the procedures given in Chapter 2 of this report.
- Develop region-specific correlations between V_{s30} and geology, geomorphic categories, slope, and perhaps a hybrid of slope and geology.
- Identify the best proxy or proxies for the region on the basis of the standard deviation of prediction residuals of the correlations. Examples of residuals analyses of this type are given in the Task 1b report.
- Map the proxy across the study region. On an appropriate grid of locations, convert the proxy to V_{s30}. On this basis, produce maps of V_{s30} or V_{s30}-based site categories.
- Indicate the epistemic uncertainty on the estimates, which can be computed from the standard deviation of the mean (i.e., the standard error) of prediction residuals (from Step 3) and/or from variations of mean estimates computed by alternate proxy relationships for a given region.

Examples of Case 1 regions include Japan, California, and Taiwan. Maps of V_{s30} have been prepared for Japan and California using the geomorphological proxy of Matsuoka *et al* [2006] and the geologic proxy of Wills and Clahan [2006], respectively. Details on those proxy methods are provided in the Task 1b report.

3.1.2 *Case 2: V_s and Geotechnical Data Available but Sparse; Good Geological Maps Available*

In this case there is not enough data available to develop region-specific correlations directly from a profile database. The objective therefore shifts towards utilizing the available data so as to confirm or disprove the suitability of proxy-based methods developed for other regions for application in the target region.

- Develop a profile database following the procedures given in Chapter 2 of this report. Consider supplementing the sparse V_s data set using V_{s30} estimates derived from penetration resistance data, as described further in Section 3.2.
- Use the available data to compute prediction residuals for suitable proxies. Identify general conditions (e.g., geologic categories) where the median (typically of an assumed normal or lognormal distribution) of prediction residuals is not statistically distinct from zero (using hypothesis

testing or other suitable statistical tests). For such conditions, the proxy-based relationships can be applied with a reasonable degree of confidence to the study region. Also during this process, identify the best performing proxy relationships to the extent practical.

- For conditions where the prediction residuals computed in Step 2 have significantly non-zero medians, adopt suitable proxy relationships from other regions with some local calibration, to the extent practical. Communicate the relatively large epistemic uncertainty associated with these estimates.
- For conditions where no data exits whatsoever for the checking of proxy performance, the procedures in Case 3 should be adopted.
- Map the proxy and V_{s30} for the study region as described in Step (4) of Case 1. Indicate epistemic uncertainties as described in Step (5) of Case 1.

Steps (1) to (3) of the procedure described herein were originally proposed by Scasserra *et al* (2009) and applied to Italy. The proxy tested in that case was surface geology using the correlation of Wills and Clahan (2006), which was originally developed for application in California. Scasserra *et al* (2009) found that the V_{s30} recommendations for Quaternary alluvial categories from Wills and Clahan (2006) were unbiased for comparable conditions in Italy. For rock categories, however, the California-based models were not applicable and approximate relations were developed from the limited available Italian data (with substantial epistemic uncertainty).

Aside from Italy, other regions for which Case 2 procedures are likely applicable are central and eastern north America (CENA), Chile, China, Greece, and New Zealand. Prior work on seismic velocity in these regions has been presented for Mexico by Stephenson and Lomnitz (2005) and for New Zealand by Christensen and Okaya (2007).

3.1.3 Case 3: Practically No Geotechnical/Geophysical Data Available

In the absence of data, no local calibration of proxy-based V_{s30} estimation is possible, as was described for Case 2. Accordingly, the only practical approach is to apply proxy-based relationships developed for other regions without calibration, in which case a higher degree of epistemic uncertainty should be associated with the mapped values. Judgment should be exercised in this process so that proxy-based relations applied to a target region are reasonably likely to be applicable. For example, it is desirable for the host region and application region to have similar types of tectonics (e.g., both active crustal regions).

There are many examples of regions of this type given currently-available information, including many developing countries. Example application of this type include use of ground slope techniques in Romania [Bose *et al*, 2009] and Hawaii [Atkinson, 2008] and terrain techniques in Pakistan [Yong *et al*, 2008].

3.2 Application of Penetration Resistance Data

When shear wave velocity data is sparse but penetration resistance data is available from geotechnical site investigations, the penetration resistance data can be used to develop estimates of V_s profiles, from which V_{s30} can be computed for application in the procedures described in Section 3.1.

There is a relatively large literature on V_s estimation from penetration resistance data, but most of it fails to adequately separate the correlations by soil type or to properly capture the influence of effective confining stress. A relationship that captures these effects using a California database is presented by Brandenberg *et al* [2010]. The correlation estimates a conditional mean and standard deviation of V_s given SPT blow count at

60% efficiency (N_{60}) and the effective vertical stress. Ideally relationships between N_{60} and V_s would undergo regional calibration before application for V_s mapping.

We recognize that the relationship between N_{60} and V_s introduces uncertainty that is not present to any significant degree when V_s profiles are measured directly. Natural log standard deviations are on the order of 0.3 to 0.5 in these V_s estimates [Brandenberg *et al*, 2010], which is substantial. While this uncertainty is reduced to some extent by the time-averaging process used to compute V_{s30}, the uncertainty associated with the use of penetration resistance data should be recognized when setting epistemic uncertainty levels for V_{s30} maps.

4 Specifications for Maps of Sediment Depth

In active crustal regions, three of the pre-selected GMPEs from Task 2 use basin depth parameters Z_x that represent depth to a shear wave isosurface with $V_s = x$ kkm

ec. Values of x that have been used to date are 1.0 km/sec and 2.5 km/sec. The Task 1b report describes the basin models available world-wide that can be used to estimate depth parameters. Such models are not available for most areas, and the Task 1b report provides recommendations for selecting default values of Z_x in such circumstances. We anticipate that this will be the most common GEM practice, in part because of the relatively small number of GMPEs that use depth parameters.

Nonetheless, if sediment depth maps are to be created for a subject region, the most straightforward manner by which they can be produced is by compilation within a profile database (Chapter 2) of multiple locations having relevant depth parameters, and then mapping depth parameters established in a consistent manner (e.g., depth to a shear wave isosurface or depths to basement rock) using suitable spatial interpolation techniques such as Kriging. A basin model for portions of southern California has been generated by Süss and Shaw [2003] using procedures similar to these.

Most often, available borehole data will not be sufficient to constrain basin geometries, and additional data sources are needed for mapping purposes. We describe the southern California 3D seismic velocity model of Magistrale *et al* [2000] as an example of utilizing diverse data sources for model building. The most recent version of this model is referred to as CVM-Version 4, available at http://www.data.scec.org/3Dvelocity/. This model is referred to below as the SCEC basin model.

The SCEC basin model consists of detailed, rule-based representations of southern California basins embedded in a 3D crust and overlying a variable depth Moho. The basins are parameterized as *objects* (constructed from data) and *rules* for (1) estimation of real-valued parameters based on object properties and for (2) interpolation of those quantities between objects. Outside of the basins, the model crust is based on regional tomographic results.

The *objects* consist of reference surfaces within basins having known depth and age. The depth and age data for the objects are based on structural geologic cross sections and maps developed from oil and water exploration activities and other geologic studies. The reference surfaces correspond to stratigraphic horizons, sediment-basement contacts, and faults. *Rules* used in the development of the velocity model include (1) a V_p-depth-age relationship by Faust [1951] that was calibrated by Magistrale *et al* [2000] using 11 sonic logs and (2) empirical relationships between V_p and density [Nafe and Drake, 1960]) and between density and Poisson's ratio, υ [Ludwig *et al*, 1970]. Shear wave velocity V_s was then estimated from V_p and υ using principles of elasticity.

With this in mind, we recommend the following steps be part of specifications for development of 3D basin models:

- Develop a profile database as described in Chapter 2, with an emphasis on deep boreholes penetrating reference rock. Velocity profiles within the boreholes, either as V_p or V_s, are especially useful.

- Compile structural geologic cross sections and maps using data from the geological literature or for commissioned studies. Typical sources of data to consider include oil and water exploration activities, gravimetric surveys, and geophysical reflection surveys.
- From the data sources in Steps (1) and (2), develop reference surfaces corresponding to stratigraphic horizons, sediment-basement contacts, and faults.
- Using available data from Step (1), estimate velocity thresholds associated with the reference surfaces from Step (3). Interpolate as needed to develop surfaces for Z_x on the basis of these results.

5 Summary and Conclusions

This report presents the results of Task 6 in the GEM-PEER Global GMPEs project. We present a framework for developing maps of the site parameters used in GMPEs, including time-averaged shear wave velocity in the upper 30 m of the site (V_{s30}) and basin depth parameters. Of the two types of site parameters, V_{s30} is more important for regional mapping due to its use (directly or indirectly) in virtually all of the pre-selected GMPEs having site terms from Task 2, whereas basin depth is used much less frequently.

We argue that an essential starting point for site condition mapping is to develop, or at least attempt to develop, a velocity profile database. Chapter 2 describes recommended components of such a database, including various metrics of site condition that can be obtained from high quality geotechnical and geological investigations, as well as a listing of the various proxies used for V_{s30} estimation.

In Chapter 3 we describe three alternate approaches for V_{s30} mapping. The first applies to regions with abundant V_s profile data, and utilizes locally developed proxy relationships for V_{s30} estimation as the basis for the mapping. The second applies to regions with relatively sparse V_s profile data, which could possibly be augmented with estimated V_s profiles from geotechnical penetration resistance testing. This situation, which we expect to occur relatively frequently world-wide, does not enable the development of proxy relationships for V_{s30} based solely on local data sources, so we recommend validation (and as necessary, re-calibration) of techniques developed for other regions for application in the target region. The third approach applies when virtually no local V_s data sources are available, in which case proxy relationships for other regions must be applied without calibration.

It is important that epistemic uncertainties be provided along with median V_{s30} maps. Those epistemic uncertainties should reflect the uncertainty of the proxy-V_{s30} relationship (higher for rock than soil) as well as the uncertainty in the underlying V_{s30} value (higher when based on penetration resistance correlations). These epistemic uncertainties would be expected to be much larger for Approaches 2 and 3 than for Approach 1.

Mapping of basin depth parameters (Z_x) requires a 3D velocity model for sedimentary basins. Where such models are not available, we recommend they be developed from a combination of appropriate depths from a profile database, geological cross sections and maps, and geophysical data. The development of such models is a major undertaking. We refer interested readers to Magistrale *et al* [2000] and Süss and Shaw (2003) for further details on the development of 3D basin models from these data sources.

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