A “Roadmap”
for
Next Generation Attenuation Models for
Central & Eastern North America (NGA-East)

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To:

US Nuclear Regulatory Commission
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CONTENTS

INTRODUCTION

This "roadmap" summarizes the planning for a major multidisciplinary research program to develop Next Generation Attenuation Models for Central & Eastern North America (CENA), NGA-East. The NGA-East is a follow up of a successful multi-institution, multi-investigator, multi-sponsor collaborative project called the Next Generation Attenuation Relationship (NGA-West) project (originally referred to as NGA) which was coordinated over five years by the Pacific Earthquake Engineering Research Center (PEER). PEER is a US national earthquake engineering research center with headquarters at the University of California, Berkeley. The NGA-West project was sponsored by a group of California-based agencies, principally the California Department of Transportation, California Energy Commission, and Pacific Gas & Electric Company. The newly developed Ground Motion Prediction Equations (GMPEs) for the Western North America (WNA) have met their objectives and have been adopted by the United States Geological Survey (USGS) for development of the latest version of the US National Seismic Hazard Maps.

For CENA, the GMPEs have constituted a major source of uncertainty for seismic hazard calculations. This is a result of the ad hoc nature of attenuation relationship developments in the past, lack of sufficient recorded ground motions, and lack of coordinated efforts to develop a consistent, yet independent, set of GMPEs for CENA.

Currently PEER has a contract with the US Nuclear Regulatory Commission (NRC) to:

- Bring together a group of experts in GMPEs for CENA,
- Organize two invitational workshops and a public workshop on the NGA-East program to cast a tentative plan for the execution of the NGA-East program, and obtain feedback from experts, stakeholders, and a larger earthquake community, and
- Draft this report on execution of the NGA-East program.

This report summarizes a tentative plan for the NGA-East program. The report is based on the NGA-East planning workshops, and numerous interactions with various experts in the field of GMPEs. The report provides a background on the NGA-West program for the Western US, a summary of the NGA-East workshops held, a list of technical issues to be addressed during the course of NGA-East, plan for management of the NGA-East, and its tentative budget and the timeline.

BACKGROUND ON NGA-WEST

Probably the biggest changes in the 2008 US National Seismic Hazard Maps are due to changes in the ground motion attenuation relations selected to estimate ground motions from shallow crustal earthquakes in the Western United States. New attenuation relations were developed in a comprehensive 5-year NGA-West program coordinated by PEER, in partnership with the U.S. Geological Survey (USGS) and the Southern California Earthquake Center (SCEC). The NGA-West project involved development of attenuation relations by five expert teams (the ground motion model “developers”). They developed their own separate attenuation models but interacted extensively with each other and with other scientists and engineers during the model development process. To ensure that the best available science was incorporated in the development of the ground motion relations, the NGA-West program included important supporting components, including:

1. development of an updated and expanded PEER strong-ground motion database,
2. conduct of supporting research projects in key technical areas, and
3. conduct of a program of interactions throughout the development process.

The NGA-West database is one of the largest uniformly processed databases of earthquake ground motion recordings, with 3551 recordings from 173 shallow crustal earthquakes. It also includes a comprehensive list of supporting information (metadata) about the recordings, such as various earthquake source parameters, source-to-site distance measures, site classification schemes, among other parameters. The database is fully available to the public via PEER Internet web site: http://peer.berkeley.edu/. The NGA models were developed for horizontal components of peak ground acceleration, peak ground velocity, and response spectral ordinates at periods ranging from 0.01 to 10 seconds, for distances ranging from 0 to 200 km, and for magnitudes ranging from 5 to 8.5. Most NGA models also directly use site amplifications based on the parameter V_{S30} (average shear wave velocity in the upper 30 meters of soil), which is important for implementation of the models for the US National Seismic Hazard Maps. According to the

NGA-West developers, the new models supersede their previous GMPEs. During the course of NGA-West:

- Six working groups were organized to provide input to the model developers in specific technical areas,
- Eight workshops, each involving 40 to 80 scientists and engineers, were organized to provide periodic review of the project,
- Numerous information-exchange meetings among the model developers were held, and
- Extensive review processes were conducted to review the NGA-West database and the newly developed attenuation relations.

A peer review of the attenuation relations was carried out by the USGS, the California Geological Survey (CGS), and an independent national review panel selected by the USGS. The review panel consisted of prominent US seismologists, geotechnical engineers, and structural engineers. As a result of this process, the USGS adopted the documented NGA-West ground motion relations for development of the new US National Seismic Hazard Maps.

The impacts of the NGA-West relations on the National Seismic Hazard Maps are illustrated in Figures 1 and 2, developed by the USGS National Seismic Hazard Maps team. These figures show the ratio of the estimated ground motion based on the NGA-West values over those based on the existing (2002) National Seismic Hazard Maps. These figures are for a return period of 2500 years (i.e., 2% probability of exceedance in 50 years). Figures 1 and 2 are for oscillator periods of 0.2 and 1.0 sec, respectively. The impact of NGA-West relations are significant, especially for a period of 1.0 sec, where there is a significant reduction in the estimated ground motions based on the NGA-West relations. There are two main reasons for such a significant reduction, as indicated by Dr. Arthur Frankel (ATC Workshop, December 2006): (a) correction of soil shear-wave velocity assigned for “rock sites” in the 2002 hazard maps; and (b) having additional data from moderate and large earthquakes and improved functional forms to fit the observed data.

NGA-EAST PLAN

As previously indicated, the goal of the NGA-East program is to develop next generation attenuation relations (GMPEs) for central & eastern north America (CENA). In the NGA-East program a set of well-coordinated and yet independent, well-reviewed, GMPEs for CENA will be developed.

During the course of the NGA-East program, the database developers, GMPE developers, researchers, stake holders, and end-users of the GMPEs will all be involved in a multi-disciplinary and fully transparent process. Similar to the NGA-West program, researchers and practitioners will work on various tasks of the NGA-East program. The compiled database along with its documentation will be fully available to the public via a dedicated NGA-East web site. The draft and final reports of the supporting research projects will be also available to the public. There will be various small and large workshops to collect feedback and comments from experts as well as the earthquake community at large. The GMPEs developed in the NGA-East program will be reviewed by independent reviewers, various stakeholders and end-users including the NRC, DOE, NEHRP, USGS staff and their designated review panel(s). The end-users such as engineers and utilities will have an opportunity to see the preliminary results and provide feedback.

The end products of the NGA-East will include:

- A comprehensive database of recorded and simulated ground motions for Stable Continental Regions, such as the CENA,
- Outcome, findings and reports of various supporting research projects, and
- A set of well-coordinated yet separate GMPEs that are based on a well-reviewed database and vetted ground motion simulation techniques.

These NGA-East products can be used for a wide range of applications within CENA. A short list of such applications include seismic design and analysis of nuclear power plants, DOE facilities, industrial facilities, buildings, bridges and all civil engineering facilities. Another important aspect of the NGA-East GMPEs is their implementation for development of the US National Seismic Hazard Maps. Building code committees use these maps to generate a set of design maps for use in seismic design according to building codes. In summary, the NGA-East GMPEs have the potential to impact almost the entire spectrum of seismic design in CENA.

List of Technical Issues to be Addressed by NGA-East

During the planning phase of the NGA-East program, through several communications, meetings and workshops with numerous experts, a list of technical issues to be addressed during the course of NGA-East was compiled. The technical issues were organized into eight large topics, as briefly summarized below. The complete consolidated list of the technical issues is listed in **Attachment A** of this report.

I. **Development of Ground Motion Database:** An important element of NGA-East is the development of a very comprehensive database of ground motions recorded worldwide in Stable Continental Regions (SCR). The database will include the recorded time series and their spectra, as well as their supporting metadata, such as magnitude, various distance measures, site conditions, among other parameters. The database will be heavily used by the model developers.

II. **Source Rupture Characterization:** Under this topic, seismic source parameters will be compiled, such as rupture area, seismic moment, rise time, average slip, average slip velocity, number and size of asperities, dynamic stress drop/corner frequency, and finite fault rupture models of CENA and other SCR earthquakes. Other projects under this topic include, among others, the determination of appropriate stress parameters required for use with stochastic ground motion simulation models.

III. **Source-Site Path:** Several issues will be addressed under this topic, including physical causes for a geometrical spreading steeper than 1/R. Recent studies have shown that this issue plays an important role for ground motion predictions in CENA. It will also be determined if there are differences in the geometrical spreading coefficient within CENA, or between WNA and CENA. Also, appropriate Q models, as a function of depth and frequency, will be derived, among other issues listed in Attachment A.

IV. Site Effects: Technical issues to be addressed include the use of small earthquakes in CENA to empirically derive basin/sediment depth effects; use of 1-D site-response analysis to determine whether shallow site-response effects are transferable from WNA to CENA; among other projects. Site response effects for hard-rock site conditions (VS30>1500 m/s) will be addressed since this site condition is common in the CENA region.

V. Other Constraints: In this topic, data for Modified Mercalli Intensity (MMI) values and liquefaction data in CENA and other SCRs will be collected to constrain and check the predicted spectral levels for large earthquakes. Other issues to be addressed include resolving the apparent contradiction between the predicted relative ground motions in CENA and WNA and those inferred from intensity studies; among other issues.

VI. Ground Motion Simulation: Due to the limited number of recorded ground motions in CENA, ground motion simulations play an important role in the NGA-East program. Such projects include calibration and validation of viable ground motion simulation models using CENA and other SCR ground motions and showing that forward predictions compare favorably with observed recordings, including time series and elastic and inelastic response spectra. Both point-source and finite-source models will be included, although it is anticipated that finite-source models will be preferred by the model developers. Additionally, validated and calibrated simulation models will be used to generate suites of ground motions for various magnitude, distances, source geometry, and faulting mechanisms to be used by the GMPE developers.

VII. Development of Ground Motion Prediction Equations: Next generation GMPEs will be developed under this topic. GMPEs will be applicable to magnitude range of 4.0 to 8.0 and distances up to 500-1000 km. GMPEs for both horizontal and vertical components will be developed. The models will be carefully checked against the compiled ground motion data. As part of development of GMPEs, aleatory uncertainty models for CENA will also be developed, including determining whether aleatory uncertainty is a function of magnitude, distance, and site conditions. Quantification of uncertainty is a key issue when conducting a defensible PSHA for the CENA.

VIII. PSHA Implementation: Under this topic, an epistemic uncertainty model will be developed for the NGA-East GMPEs. This can be used in PSHA implementation of the developed ground motion relations. For the PSHA implementation, if it is needed, a conversion between magnitude measures (e.g., moment magnitude and m_N/m_{LG}) will be also developed.

Management Organization of NGA-East Program

The NGA-East program will be managed by a Joint Management Committee (JMC). Figure 3 shows a conceptual management organization chart for the NGA-East. The members of the JMC include representatives of key funding agencies, who fund the program by contributing $500,000 or more, and PEER. For each subaward (project), the JMC reviews and finally approves:

- Scope of work,
- Budget,
- Principal Investigator (PI),
- Duration, and
- Deliverables.

In the decision making process in the JMC, each group member (e.g., PEER) will collectively have one vote. The decision of the JMC must be unanimous among the JMC members. The JMC is advised by a Technical Advisory Committee (TAC). The members of the TAC will be well-known experts in the earthquake community. After the initiation of the NGA-East program, the TAC members will be selected by the JMC.

Timeline and Estimated Budget

The plan is to finish all the supporting research projects and GMPEs in five years after the starting date of the NGA-East program. The sixth year of the NGA-East program will be devoted to the PSHA implementation, and review of the data and models. The review will be carried out by various experts including the USGS and its independent review panel. This will allow the

USGS to adopt the attenuation relations for the next revision of the US National Seismic Hazard Maps.

The total budget for the NGA-East program from all funding sources is $4.4M. The tentative distribution of the overall budget for the eight technical topics is shown in Table 1. The overall time-distribution of the budget (i.e., budget profile) is listed in the last row of Table 1. As indicated above, within each topic, the final budget for each sub-project will be decided upon by the JMC with input from the Technical Advisory Committee.

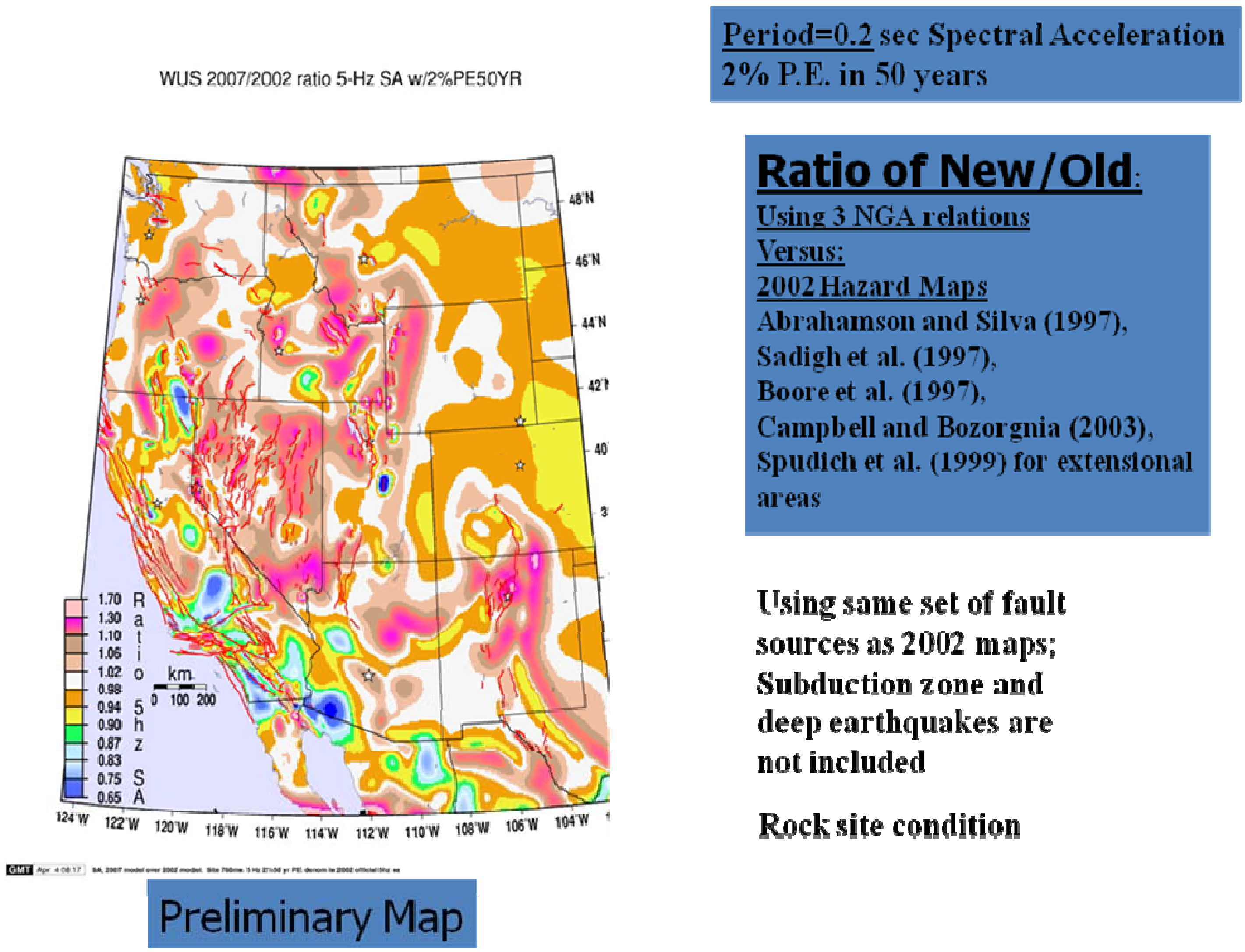

Figure 1: Impact of NGA-West on the US National Seismic Hazard Map (UNSHM). This map shows the ratio of the NGA-based values over the values in the 2002 UNSHM for period 0.2 sec for the same set of faults.

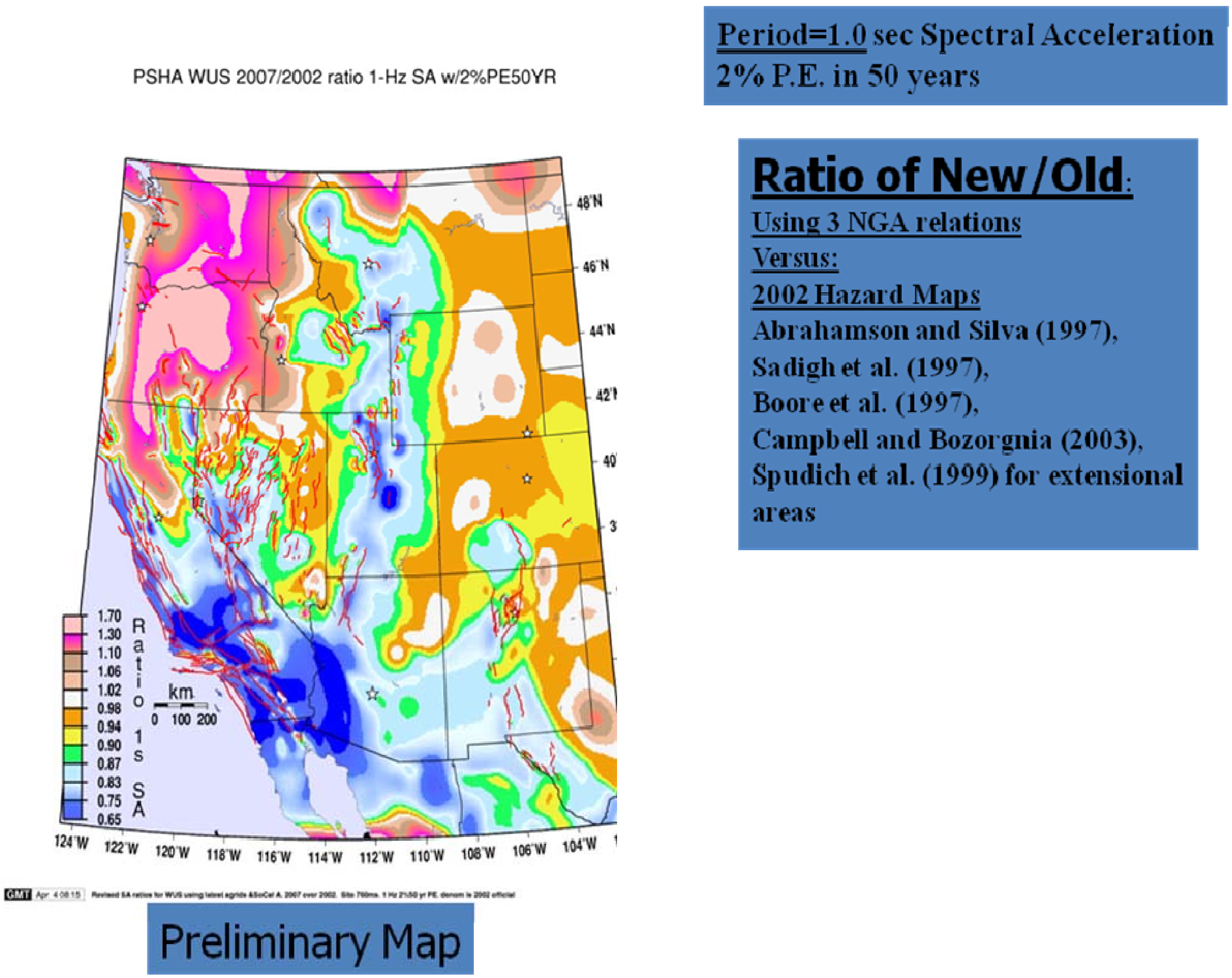

Figure 2: Impact of NGA-West on the US National Seismic Hazard Map (UNSHM). This map shows the ratio of the NGA-based values over the values in the 2002 UNSHM for period 1.0 sec for the same set of faults.

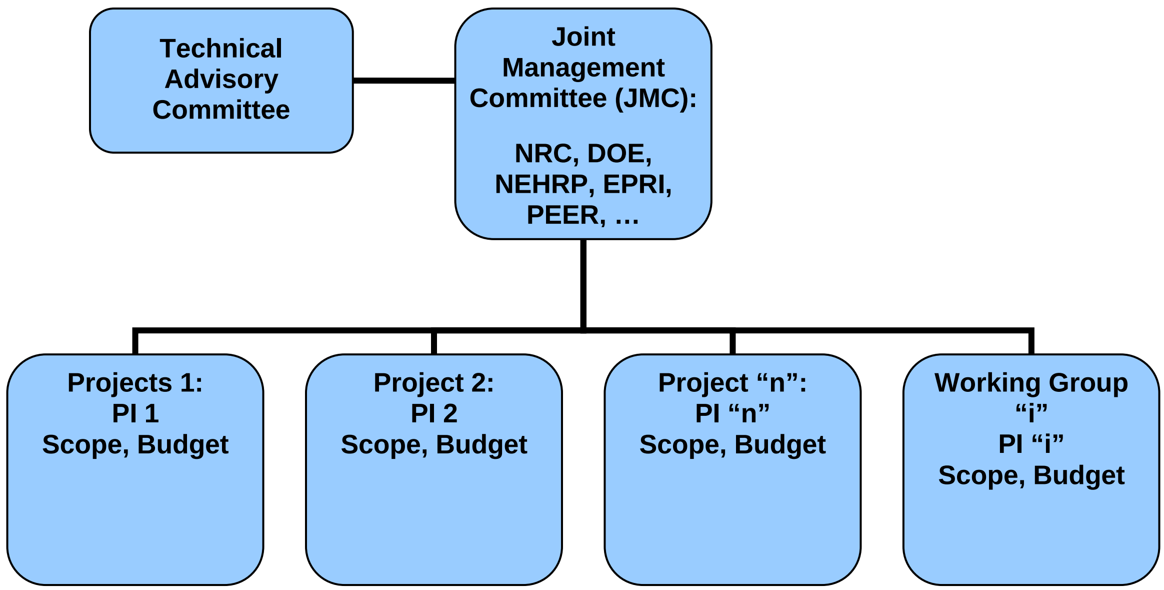

Figure 3: Conceptual organization chart for the NGA-East program

Table 1: Tentative Budget for NGA-East Program (*)

Year ==>	**1**	**2**	**3**	**4**	**5**	**6** (Review & Adoption of models)	**Total**
I. Database (**)	0.3	0.3	0.2	0	0	0	0.8
II. Source Characteristics	0.2	0.1	0.1	0	0	0	0.4
III. Source-Site Path	0	0.2	0.2	0	0	0	0.4
IV. Site Effects	0	0.1	0.1	0.2	0	0	0.4
V. Other Constraints	0.1	0.1	0.1	0	0	0	0.3
VI. GM Simulation	0	0.2	0.3	0.2	0	0	0.7
VII. GMPEs	0.1	0.1	0.1	0.3	0.4	0.1	1.1
VIII. PSHA Implementation					0.1	0.2	0.3
Review Process by USGS, NRC, etc.	0	0	0	0	0	0	0
Total Estimate ($M)	0.7	1.1	1.1	0.7	0.5	0.3	4.4
Total Adjusted Estimate, $M (***)	**0.73**	**0.94**	**0.95**	**0.75**	**0.62**	**0.42**	**4.4**

(*) **Note 1:** Numbers are in $M, and include overhead, travel expenses, workshops and meeting expenses, office expenses, labor to organize projects, etc.

(**) **Note 2:** Each topic will have various sub-projects. The scopes, budgets, Principal Investigators (PIs) of each sub-project will be determined by the NGA-East Joint Management Committee (JMC).

(***) **Note 3**: In the time-profile of the "adjusted budget", estimated expenses that are uniformly distributed over time have been taken into account.

Attachment A

Consolidated List of Technical Issues to be Resolved In the Course of NGA-East Program

Next Generation Ground Motion Prediction Equations ("Attenuation") for Central and Eastern North America (CENA)

NGA-East

Consolidated List of Technical Issues to Be Addressed

I. Ground Motion Database

1. Collect and archive ground motion records from Central and Eastern North America (CENA) events along with pertinent metadata. If possible, ground motion data as far as 1000 km from the source should be collected.
2. Collect and include relevant international data (records and metadata) from Stable Continental Regions (SCRs) that are believed to have similar tectonic characteristics as CENA.
3. Form a Database Working Group to advise on various technical issues related to the database and to recommend short-term and intermediate-term supporting projects related to the database development. Because it is critical path, the Working Group should start its activities before the start of the other NGA-East tasks.
4. The database should be well-documented, including documentation of Quality Assurance (QA) of the record collection, record processing, and metadata collection.
5. Record processing should be carried out uniformly. In this regard, the experience gained from the record processing tasks in the NGA-West project will be helpful.
6. Metadata should include an estimate of moment magnitude and various distance measures, including closest distance to rupture (rupture distance), closest distance to the surface projection of rupture (i.e., Joyner-Boore distance), epicentral distance, and hypocentral distance.
7. Obtain measurements of V_{S30} for all recording sites included in the database. If this is not possible for some sites, V_{S30} should be estimated using correlations between surface geology and V_{S30} specifically developed for CENA.
8. Measure or estimate the depth to hard rock and to the 1.0, 1.5 and 2.5 km/sec shear-wave velocity horizons for all recording sites included in the database.
9. Compile information about the recording instruments, including component orientations, instrument type, etc.
10. Compile or calculate all ground motion components of interest, including the vertical component and various definitions of the horizontal components, such as the as-recorded components, the geometric mean of the as-recorded components, the GMRotI50 geometric mean component, the maximum rotated component, the strike-normal component, and the strike-parallel component.
11. Calculate all ground motion parameters of engineering and seismological interest, including the Fourier amplitude spectra, PGA, PGV, PGD, and Pseudo Spectral Acceleration (PSA) for multiple damping values at the same periods used in the NGA-West project.

12. If available, collect more detailed information about the earthquake that might be available, such as the finite-fault rupture model inversion (both for CENA and other SCR events).
13. The highest priority in data collection and processing should be given to the larger events (M>4), but it is also important to collect good quality data for smaller events down to magnitudes of 3.0.
14. Ground motion database should only include information regarding the recordings, the recording site, and the earthquake and, except the items listed above, should not contain data that is inferred from modeling.

II. Source Rupture Characterization

1. Source Parameter Database: Compile source parameters such as rupture area, moment, rise time, average slip, average slip velocity, number and size of asperities, dynamic stress drop/corner frequency, and finite fault rupture models of CENA and analogous earthquakes.
2. Refine or develop scaling relations for CENA, such as area vs. moment, area vs. rise time, average slip vs. moment, average slip velocity, number and size of asperities, dynamic stress drop/corner frequency, etc., and determine whether these scaling relations are model dependent.
3. Directly compare source characteristics of earthquakes in the magnitude range of 4-5 in the WNA and CENA and determine whether the shapes of the source spectra are the same in CENA and WNA and, if not, what parameters cause the observed differences.
4. Determine appropriate stress parameters (required for stochastic models) in CENA. Issues to be addressed are the average stress drop and its variability, whether there are regional differences, and whether it depends on magnitude, focal mechanism, depth, etc.

III. Source-Site Path

1. Determine near-source geometrical spreading effects (especially within 70 km of the source). Issues to be addressed are: whether there are regional differences within CENA, what is the physical cause for a geometrical spreading steeper than 1/R, whether there are differences between WNA and CENA, whether there are regional differences within CENA, whether they are dependent on fault mechanism, etc.
2. Determine the effect of mid-crustal and Moho reflections on the amplitude decay with distance, including its dependence on magnitude and wave frequency.
3. Derive appropriate Q models as a function of depth and frequency and determine whether there are regional differences in these models. Note that Q and geometrical spreading are closely linked and need to be developed together.
4. Scattering model: Treat scattering as a Source-Site Path parameter, separate from Q. This is motivated by the concept that the parameter that is currently measured as Q may partly reflect a scattering process, not just an absorption process.
5. Derive regional velocity structures.

6. Examine regional differences in ground motions for CENA, and possibility of dividing the CENA into ground motion regions.

IV. Site Effects

1. Define a reference site condition to use in the development of the GMPEs (e.g., NEHRP B-C, hard rock, V_{S30} = 2000 m/sec, V_{S30} = 2800 m/sec, etc.)
2. Develop one or more reference NEHRP B-C site profiles for CENA, including layer thickness, total profile depth, Vp, Vs, density, lithology, Q, and kappa. Issues to be addressed are whether these profiles should be dependent on depth to hard rock and, if only one profile is to be selected, what depth it should represent.
3. Determine whether WNA and CENA reference NEHRP B-C and other NEHRP Site Class site profiles should be regionalized.
4. Derive reference soil profiles for NEHRP Site Classes A, B, C, D and E (see parameters defined in item 5) and use these profiles to determine whether the NEHRP site factors should be revised for CENA (e.g., whether they are different from the current set of factors developed for WNA) and whether the relationship between ground motion and Vs30 should be a function of profile depth and other measures that characterize the deeper structure of the profile.
5. Using the reference soil profiles, use 1-D site-response analysis to determine whether shallow site-response effects are transferable from WNA to CENA.
6. Extend the site response range to high VS30 values (up to 3000 m/s) for application to hard-rock conditions in the CENA.
7. Use small earthquakes in CENA to empirically derive basin/sediment depth effects in CENA.

V. Other Constraints

1. Develop and use MMI distributions for CENA and other SCR earthquakes to help constrain and check spectral levels for large magnitudes.
2. Collect and analyze liquefaction data in CENA and other SCR earthquakes to help constrain and check spectral levels for large magnitudes.
3. Explain the apparent contradiction between the predicted relative amplitudes of CENA and WNA ground motions and those inferred from intensity studies.
4. For average soil sites, determine whether observed spectral accelerations are greater for CENA earthquakes than for WNA earthquakes of the same magnitude for all distances as implied by intensity data, and if they are determine why this is the case.
5. Use intensity, liquefaction and ground motion data to help determine whether there is a spectral sag in the CENA source spectra at intermediate frequencies and, if so, how deep the sag is.

VI. Ground Motion Simulation

1. Calibrate and validate viable ground motion simulation models using CENA and other SCR ground motion data and show that forward predictions compare favorably with observed recordings, including time series and elastic and inelastic response spectra. Both finite-source and point-source models will be included.
2. Use validated and calibrated simulation models to generate suites of ground motions for various magnitude, distances, source geometry, and faulting mechanisms to be used by GMPE modelers.
3. Determine whether ground motion saturation effects are transferable from WNA to CENA.
4. Derive source spectral shapes. Issues to be addressed are whether there exists a spectral sag at intermediate frequencies and whether the shapes are different between WNA and CENA.
5. Determine whether faulting mechanism, hanging-wall, and source depth effects are transferable from WNA to CENA and, if not, what these effects are in CENA.
6. Determine whether basin/sediment-depth effects are transferable from WNA to CENA.

VII. Ground Motion Prediction Equations (GMPEs): Modeling Issues and Supporting Research Topics

1. Develop true Next Generation GMPEs as opposed to using or updating existing models (i.e., in a process consistent with NGA-West).
2. GMPEs should be applicable to M 4.0 to 8.0 and distances of 500 to1000 km.
3. Develop GMPEs for horizontal (GMRotI50) and vertical components of ground motion.
4. Demonstrate that the NGA-East GMPE models agree with the observed ground motion data in the ground motion database (including relevant data from worldwide SCRs such as the Bhuj earthquake) over the magnitude and distance ranges defined in item 2.
5. Demonstrate that the attenuation characteristics predicted by the GMPE models take into account the range in crustal structures and the transition between crustal provinces in CENA as identified in other tasks of the NGA-East project.
6. Consider the following issues when developing GMPE models:
    a. Most recorded data come from magnitudes-distance combinations that are not of engineering interest.
    b. The models will have already used these data to define functional forms and constrain parameter values; thus, the models are not independent from the data.
    c. The models are not independent of each other and might, as a group, underestimate epistemic uncertainty.
7. Develop aleatory uncertainty models for CENA and determine whether aleatory uncertainty is a function of magnitude, distance, and site conditions. Issues to be addressed are whether there should be a single aleatory uncertainty model independent of the median models, whether it should be different than in WNA, and whether there are negative correlations amongst parameters that will reduce it.

VIII. PSHA Implementation

1. Derive an epistemic uncertainty model. Issues to be addressed are whether uncertainty in addition to that corresponding to the suite of GMPE models should be included, whether it is a function of magnitude, distance and other parameters, and what weights should be assigned to the GMPE models.
2. Develop conversions between magnitude measures (e.g., **M** and m_N/m_{LG}) and distance measures (e.g., R_{RUP} and hypocentral distance) to use when source and site parameters are defined in terms parameters not used to develop the GMPE models.

IX. Other Issues Related to, But Outside Scope of, NGA-East

1. Develop V_{S30} and depth to bedrock maps for CENA.