FINAL REPORT:
TOPIC AREAS 1 – 3
PEER-LIFELINES PROGRAM (PHASE 1)

by

Cliff ROBLEE, Brian CHIOU, Tom SHANTZ, and Loren TURNER
Caltrans' Geo-Research Group
Division of Research and Innovation
Sacramento

AND

Norm ABRAHAMSON
Pacific Gas & Electric
San Francisco

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1.0 INTRODUCTION

The projects comprising Topic Areas 1 and 2 were developed in response to a core objective of the Lifelines Program: **reducing uncertainty in earthquake ground motion estimation**. This objective reflects recognition from industry sponsors that improvements in earthquake ground motion estimation will result in significant cost savings and will result in improved system performance in the event of a large earthquake. The collection of projects in Topic Areas 1 and 2, as a program, aim to better predict where, and under what circumstances, high levels of ground motion might occur, so that these instances can be suitably addressed (or avoided) while forgoing unnecessarily high costs resulting from over-estimation of seismic demand in other areas.

Topic Area 3 projects address seismic hazards resulting from fault rupture and ground deformation caused by the phenomenon of liquefaction. Recent earthquakes in Taiwan and Turkey demonstrated the heavy damage that can occur along faults ruptures. Current procedures for estimation of fault rupture hazard are lacking in significant aspects, making practical application difficult. A key objective in this area is to develop a more comprehensive treatment of fault rupture that can be readily employed in the design of utility and transportation projects.

Liquefaction and resulting ground spreading have been major causes of damage to lifelines in past earthquakes. Limitations of current design procedures often lead to costly, over-conservative solutions. Key objectives in liquefaction are the development of improved triggering criteria (primarily for probabilistic assessment), the extension of these methods to additional soil characterization tools, improved estimates of slope movement, and improved estimates of loading resulting from slope movements.

Meeting the objectives of these topic areas involves tackling numerous complex issues. Strategies typically involved expending significant effort on data collection, while laboratory or controlled testing, model development, and pilot application were also employed. Since each topic area consisted of a large number of individual projects (Topic Areas 1 and 2 consisted of over 50), the results in this report are presented from an *objective* based viewpoint. This viewpoint emphases important issues related to program objectives, and avoids dwelling on small details of specific, narrowly focused projects.

Table 1 outlines the organization of this report. The discussion is structured around the primary deployable products of the program which support the broader objectives described above. Each major subsection describes research activities leading toward development of that product. The products, in turn, are grouped under four ‘principal needs’ that correspond to major section titles.

Table 1 - Organization of Manuscript by Activities Supporting Specific Deployable Products

Topic Area/ Objective	Principal Needs	Deployable Product	Described in Subsection
I & II Reduced Uncertainty in Ground Motion Estimation for Engineering Design	Improved Design Response Spectra for EQ Shaking Hazard Estimation	Next Generation Attenuation Relationships that Accounts for Near-Source and Basin Depth Effects.	2.1
		Test Problems and Consensus Solutions for Qualification of Probabilistic Hazard Codes.	2.2
	Improved Methods for Time History Selection and Scaling	Design Ground Motion Library of Recommended Empirical Time Histories and Scaling Methods.	3.1
		Guidelines Regarding Appropriate Scaling Limits and Efficient Indicators of Damage.	3.2
	Improved Modeling of Geotechnical Site Effects	Database of Site Characterization Information from SMR Sites for Various Regions.	4.1
		Depth-Dependent Non-Linear Material Models and Database of Laboratory Test Results.	4.2
		Pilot Geotechnical Virtual Data Center for Electronic Archive and Exchange of Geotechnical Site Characterization Information.	4.3
III Improved Estimation of Load Transfer to Pipelines and Piling Due to Ground Failure	Improved Models for Ground-Deformation Hazard Estimation	Fault Surface-Rupture Model that Accounts for Uncertainties in Mapping, the Distribution of Slip Along Strike, and the Complexity of Faulting.	5.1
		Probabilistic Liquefaction Triggering Assessment Methodology for SPT, CPT and Vs Criteria	5.2
		GIS-Based Database of Lateral Spread Case Histories	5.3
		Pilot Regional-Scale Liquefaction Ground-Deformation Hazard Map and Methodology	5.4
		Guidelines and Experimental Data for Modeling of Soil-Structure-Interaction in Liquefied and Laterally-Spreading Ground	5.5

For each Principal Need in Table 1, an introductory section is provided to identify and discuss key research issues in addition to reviewing fundamental concepts and nomenclature. Each subsection then describes research results and status.

2.0 IMPROVED DESIGN RESPONSE SPECTRA

Seismic design of bridges, buildings, and other civil infrastructure starts with establishment of a design response spectrum to represent the ground shaking hazard level considered appropriate for the region and facility. Because of its central role in design, this represents the single most important earthquake hazard to estimate.

Existing design tools for estimating shaking hazard level typically involve use of a ground-motion map and/or a rule-based procedure to develop a design spectrum based on map parameters. Hazard estimates can be developed within either a deterministic framework, e.g. Caltrans [2], or a probabilistic framework, e.g. Frankel and Leyendecker [3]. Regardless of the framework employed, maps of ground shaking are based on an inventory of faults, each having magnitude estimates, and “attenuation relations” that quantify the functional relationship between ground shaking and the distance from a causative fault having a specified magnitude. Attenuation relationships for many different shaking parameters are available, but the most commonly used are peak acceleration and spectral acceleration. Numerous attenuation relationships have been developed over the years by different seismologists and engineers, each using different data sets and assumptions regarding the most appropriate functional form.

A number of developments have arisen recently to suggest that a new generation of attenuation relationships is warranted. Recordings from recent large earthquakes have shown significant differences from those predicted by attenuation relations. Furthermore, these new recordings provide important new information for key seismological conditions (high magnitude, close distance) that previously had not been well constrained. Near-field effects, including “directivity pulse” and “fling”, are clearly suggested in new empirical data, and appear to be correlated to regions of unanticipated structural damage. Both new experimental and theoretical models also support the existence of near-field effects, however uncertainty remains regarding the magnitude of these effects and the most appropriate way to predict them for design purposes. Existing attenuation models do not incorporate these effects directly, although alternative “corrections” to existing attenuation models have been proposed. Those that have been proposed have been undergoing revision, thus making adoption for design difficult. Users are seeking broad consensus and/or alternative formulations for predicting near-field effects.

Existing attenuation models also do not fully account for recent advances in characterizing “path” and “site” effects. New computer simulation techniques that account for wave propagation in a 3-dimensional medium have been used to examine “basin” effects. Basins are recognized to increase motions near edges due to wave interactions much like water waves near a seawall. They also increase the duration of motion within the basin due to reflections and trapped energy. The 3-D simulations, as well as several recent empirical studies, also suggest a systematic increase in long-period motions caused by increased depth-to-bedrock. This effect has not been incorporated into existing attenuation models in part because depth data is not available for many recording stations.

Finally, it has long been recognized that near-surface soil can significantly amplify or modify motions (somewhat like the movement of the tip of a whip amplifies movement of the handle). The magnitude of these “geotechnical site effects” varies depending upon the type, stiffness and thickness of soils underlying a site. Attenuation relations typically account for site effects in a broad way by categorizing a site using any of several simplified site classification schemes. These schemes range from a simple “rock’ vs. ‘soil’ designation to somewhat more refined categories based on surface geology groupings or the average stiffness of near-surface layers. In the development of attenuation relations, separate model coefficients are developed for each site category and variations in site-specific amplification within a site category are treated as part of the overall uncertainty. Clearly, accurate categorization of recording sites is important to the development of attenuation relations. However, recent field drilling programs have shown that many recording sites had previously been misclassified, thus adding unnecessary uncertainty and prediction bias into the attenuation models. These new data, and the use of improved correlations for uncharacterized sites, needs to be incorporated into new-generation models.

2.1 Next Generation Attenuation (NGA) Models *(PEER-LL, SCEC, USGS Collaboration)*

Simply stated, attenuation relationships are the backbone of modern earthquake hazard assessment. These relationships are used in *all* earthquake hazard assessment ranging from the national and California seismic hazards maps, produced jointly by the USGS and CGS, to site-specific assessments, both deterministic and probabilistic, used for specific facilities ranging from bridges to dams to power plants. Hazard assessment results are used to establish design strategies and details of the built environment and to predict their performance. Significant recent seismological advances including new earthquake data, new computer simulation capabilities, and improved scientific understanding warrant the development of next generation attenuation models.

2.1.1 Technical Issues and Goals

Although leading attenuation modelers have periodically updated their design models, these updates were typically performed using independently assembled data sets and varying assumptions regarding optimal combinations of predictor variables and functional forms to account for particular seismological and geotechnical effects. Simultaneously, numerous research seismologists and engineers have developed a wide array of theories to better account for observed effects, and numerous adjustments to the models have been proposed. Unfortunately, these proposed adjustments are not fully consistent, and proposed usage is not necessarily compatible with existing attenuation models. The end result is that designers lack clear and consistent guidance from the research community as to best methods for hazard estimation. This can lead to widely varying estimates of hazard for a particular facility as different individuals often apply different combinations of attenuation models and adjustments.

The overarching goal of the NGA program is to develop broad consensus among attenuation model developers and researchers as to which seismological effects and predictive models are sufficiently mature to warrant their incorporation into routine hazard estimation. Chiou [5] outlines the specific issues being addressed under the NGA program to include:

- Development and review of a common strong-motion database including extension of the database to incorporate new predictor variables;
- Validation and use of both 1-D and 3-D ground-motion simulation procedures to guide model development for data regions that are sparsely populated by recordings;
- Consideration of the following "fixed effects" for attenuation models:
  - Rupture directivity effects (directivity pulse and fling step)
  - Near-field orientation effects (strike normal vs. strike parallel)
  - Footwall vs. hanging wall effects for dipping faults
  - Style of faulting effects (strike-slip, reverse, normal)
  - Depth to faulting effects (i.e. buried vs. surface rupture)
  - Static stress drop (or ruptured area)
  - 3-D basin effects (depth to basement rock, distance to basin edge)
  - Site effects relative to a reference "rock" condition
- Consideration of the following random effects:
  - Measurement errors in predictor variables (e.g. uncertainty in magnitude)
  - Dependency of standard error on magnitude, distance, basin location, and soil type
  - A general covariance structure to allow modeling of the following types of correlation in residuals:
    - Correlation between neighboring frequencies
    - Correlation (spatial) between neighboring recordings

2.1.2 Program Approach

The NGA project represents a capstone initiative that is undoubtedly the most complex research coordination and consensus-building effort initiated to date by PEER-LL. It involves coordination of over 30 individuals and synthesis of results from over 40 projects. Fortunately, partnerships have been established with SCEC and USGS to assure broad technical participation and review, additional research capabilities, and assistance in the leadership and coordination of key working group activities.

The NGA program aims to develop general "consensus" among five leading model development teams (identified below as "developers") and a broad array of leading researchers (identified below under "Task PI's", "Co-PI's" and "Review"). In this case, "consensus" is not focused on development of a single attenuation model; rather, it is meant to fully recognize and support multiple valid views that allows for individual expert judgment to be exercised regarding optimal means of modeling complex ground-shaking phenomena. However, to facilitate consensus building, each development team has been provided with common resources and exposed to the same resources and research findings including:

- A comprehensive, current, consistent, and verified strong-motion database;
- Results of multiple jointly-validated 1-D and 3-D simulations meant to supplement the empirical database into regions where recorded data is sparse;
- Periodic interactions with issue-focused working groups comprised of researchers from PEER-LL, USGS, SCEC and other organizations to take advantage of the collective breadth of current knowledge, experience and ideas.
- Emerging statistical techniques and tools to analyze the data for correlations in the residuals (e.g. neighboring recording stations, neighboring spectral frequencies, etc.).

Though a common set of predictor variables and functional forms have not been mandated, each development team is required to formally consider recommendations of researchers and working groups and justify their modeling decisions. This approach provides needed flexibility to developers who may have divergent views on how to best model certain seismological phenomena, but also provides clear documentation of key decisions that lead to differences between models. To capture the effect of different decisions, a sensitivity study will be performed for a limited set of intensity measures.

Through this process, the NGA program aims to merge views of experienced attenuation modelers with current research results to develop a suite of new design attenuation models. Specific anticipated products will be a set of five new NGA attenuation models for PGA, PGV, PGD, and response spectra. The common requirements of all NGA models is that they will be applicable to:

- Both separate (fault normal, fault parallel) and combined (average) horizontal components
- Three shallow crustal earthquake types (strike slip, reverse, normal)
- Magnitude range of 5 to 8.5 (high value needed for modern hazard analyses)
- Distance range of 0 to 200 km
- Period range of 0 (PGA) to 10 seconds (including a common set of period values)
- Commonly used site classification schemes

Supporting documentation will include working group recommendations on specific issues and views of the various development teams regarding their decisions to incorporate or reject these views.

The NGA program of research will generate two versions of “next generation attenuation” models. The first version, called NGA-E models, is being driven mainly by empirical data, though guided by findings from current research and synthetic motions generated from validated simulation procedures. The second version, called NGA-H models, will advance one step further by combining synthetic data with empirical data as a means to further constrain near-field features of the attenuation model. The development of NGA-H models will depend on the achievements of the NGA-E collaboration and the availability of additional funding. Supplemental ‘fling step’ and ‘site amplification’ models will be developed to be compatible with either the NGA-E or NGA-H models and are intended to be used in combination with these models at the discretion of the designer.

2.1.3 Research Team (alphabetical order)

Manager:	Maury Power
Coordination:	Norm Abrahamson, Brian Chiou, Cliff Roblee
Inter-Agency:	Bill Ellsworth, Tom Jordan, Jack Moehle, Woody Savage, Paul Somerville
Developers:	Norm Abrahamson & Walt Silva, Dave Boore, Ken Campbell & Yousef Bozorgnia, Brian Chiou & Bob Youngs, I.M. Idriss
Task PI’s:	Jim Brune, Greg Beroza, Steve Day, Pedro De Alba, Rob Graves, Ruth Harris, Walt Silva, Paul Somerville, Paul Spudich, Joseph Sun, Chris Wills, Bob Youngs, Yuehua Zeng
Task Co-PI’s:	Rashool Anooshehpoor, Jacobo Bielak, Bob Darragh, Doug Dreger, Nick Gregor, Shawn Larson, Kim Olsen, Faiz Makdisi, Arben Pitarka, Tom Shantz, Zhi-Liang Wang, Don Wells
Review:	John Anderson, Ralph Archuletta, Jack Boatwright, Roger Borcherdt, Jon Bray, Dave Brillinger, Ned Field, Bill Foxall, Bill Iwan, Robert Nigbor, Mark Petersen, Tony Shakal, Chris Stevens, Jon Stewart

2.1.4 Selected Accomplishments

As of the time of writing this Final Report, September 2004, the NGA project has been underway for 2 years. During this time, a review process was established, a common data set was developed, and extensive programs of both 1-D and 3-D computer simulations were completed. Completed attenuation models are expected in March, 2005.

2.1.4.1 NGA Collaboration Framework

The collaboration framework established involved holding a series of focused workshops, and the establishment of six working groups, headed by PEER-LL, SCEC, and USGS researchers, and the development of seven major technical tasks to be addressed by various combinations of the working groups as outlined in Table 2. Four workshops have been held to date. The kickoff workshop focused on establishing the coordination framework and clarification of program scope with all participants. The next two workshops focused primarily on the development of the common database, proposed guidelines for simulation validation, and plans for extensive programs of 1-D and 3-D simulations. The final workshop presented initial results from attenuation development.

Table 2 - Major Technical Tasks and Related Working Groups for NGA Program (Chiou, 2003 [6])

Technical Tasks	Working Group(s)
1. Database Development, Validation of Record Processing, and Evaluation of Fling Step Processing Procedures	WG#1a Record Processing WG#1b Static Fling Step Processing WG#2 Ground Motion Database WG#4 Source/Path Effects WG#5 Site Effects
2. 1-D Rock Simulation and Validation with Emphasis on Directivity Modeling	WG#3 Validation of 1-D Rock Simulation WG#4 Source/Path Effects
3. Evaluation of Alternative Source/Path Predictor Variables	WG#4 Source/Path Effects
4. Evaluation of Site Classification Schemes and Site Effects	WG#5 Site Effects
5. Evaluation of Site Response Analysis Procedures and Development of Site Amplification Factors	WG#5 Site Effects
6. Development of Statistical Methods and Tools for NGA Applications	WG#6 Statistical Modeling of Data
7. 3-D Simulations for Evaluation of Basin Effects	WG#4 Source/Path Effects WG#5 Site Effects

2.1.4.2 NGA Empirical Strong Motion Data Set

Development, enhancement, and review of the empirical data set of strong ground-motion recordings was a major component of the NGA effort. The data set is an extension of the PEER Strong Motion Database (http://peer.berkeley.edu/smcat/). The extended NGA data set now includes 175 earthquakes, 1700 recording stations, and over 3500 multi-component recordings. New earthquakes that have been added to the database include the 1995 Kobe event in Japan, the 1999 Hector Mine event in California, both the 1999 Kocaeli and Duzce events in Turkey, the 1999 Chi Chi event and six major aftershocks from Taiwan, several well-recorded moderate events in California, and the very recent 2003 Denali event in Alaska.

All database recordings have been uniformly processed for a common set of spectral frequencies with independently assigned filter corners for each record so as to retain the maximum possible useable bandwidth. A quality assurance process was established whereby spectra and time histories of all recordings originally collected by both the USGS and the CSMIP programs were directly compared with those in the database and reviewed by a working group. Also, recordings within 50 km of the causative fault have been rotated to fault normal and fault parallel directions so that separate attenuation models can be developed for each.

Metadata about each earthquake and recording site needed for attenuation modeling was compiled from numerous literature sources and researchers. Where conflicts occurred, preferred values were assigned by developers and appropriate working groups. The NGA data set now represents the most complete and thoroughly reviewed strong-motion data set in existence for shallow crustal earthquakes applicable to the western United States. It serves as a unique common resource for all NGA model developers as well as other researchers and designers. The final data set will soon be publicly accessible via an on-line database at the PEER web site.

The NGA data set, even with the addition of recent earthquakes, is only sparsely populated for magnitude-distance combinations of greatest concern to design. Therefore, the NGA program is systematically advancing several alternative simulation procedures for purposes of supplementing the empirical database. It is not intended for the model developers to use these results directly as “data” during the current (NGA-E) stage of the program, rather the simulation results will be used to guide or check the selection of functional forms used in the statistical regression of the empirical data.

2.1.4.3 NGA Simulation Programs: 1-D and 3-D

The need for simulated ground-motions is prompted by lack of empirical data needed to constrain design models for critical phenomena such as near-source effects and basin effect. Simulation procedures involve relatively complex computer codes that incorporate a range of assumptions that need to be verified, calibrated, and validated before they can be meaningfully applied to hazard estimation.

Many simulation procedures having varied levels of sophistication have been developed and implemented over the years. Broadly, these procedures can be grouped into 1-D approaches, which represent the earth's crust as a layer cake extending laterally to infinity, and 3-D approaches that allow for laterally varying features such as sediment basins. Another key distinction between procedures is how the earthquake fault is modeled. All of the codes considered here represent the fault as a plane rectangle of finite dimensions where varying amounts of energy release (or fault slip) can occur at different points along the extent of the fault plane. These codes also model propagation of a rupture front moving along the fault plane starting from a specified hypocenter (or nucleation point).

The use of seismological simulations remains somewhat controversial, and must be applied in a cautious and systematic manner. Early comparisons of results from alternative simulation procedures yielded wildly variable results having little practical benefit to design hazard estimation. More recently, systematic programs of joint code verification and calibration have yielded much more consistent results. The strategy implemented by the NGA program was to use multiple verified and calibrated simulation methods to investigate various seismological phenomena.

An example of a very successful verification exercise was a program sponsored by PEER-LL in collaboration with SCEC to systematically test four independent 3-D numerical procedures against a series of progressively more challenging test cases. Figure 3 shows results summarized by Day [8] that were produced by the four codes and a closed form solution for a fundamental test problem before and after the joint verification process. The 'after' results were produced after the discovery and elimination of coding bugs and refinement of scaling coefficients. These same codes have now been advanced from a series of test problems through consistent modeling of real earthquakes. The results from this joint validation program clearly illustrate both the need and benefit of close coordination in the application of sophisticated simulation procedures.

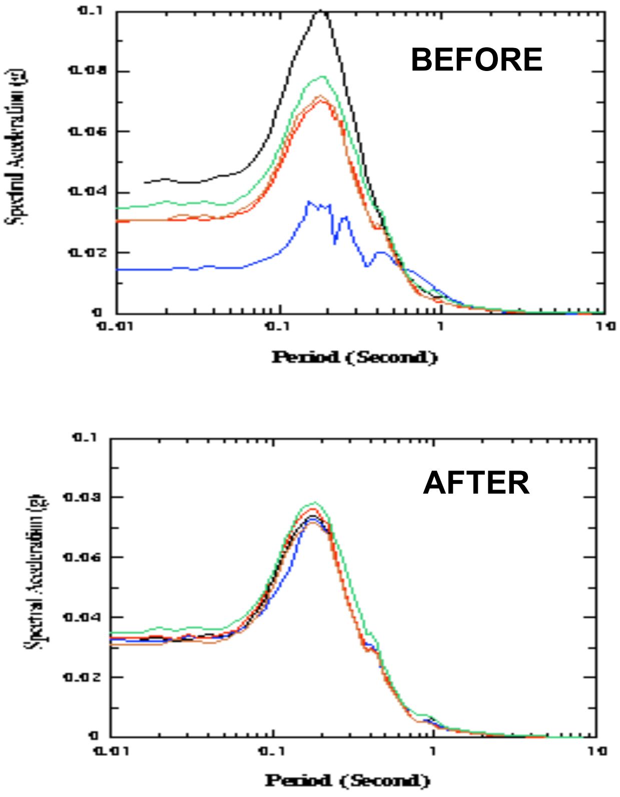
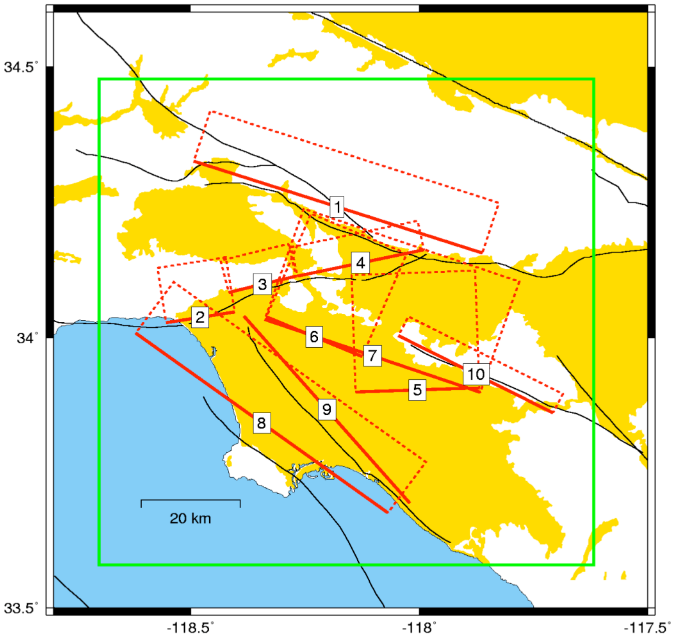


Figure 3. Results from early joint verification of 3-D simulation codes. (Day, 2002 [8])

The same modeling teams, in a jointly funded program by PEER-LL and SCEC, applied 3-D modeling procedures to investigate basin effects. Day [9] reports that simulations were completed for six individual rupture scenarios (varied hypocenter and slip distribution) for each of 10 earthquakes for Los Angeles area basins that are shown in Fig. 4. For efficiency, the work was distributed among the four modeling teams, but each earthquake was crosschecked by at least one other modeler. For each scenario, 3-component simulated long-period (2-10 sec) motions were generated for a dense grid of 1600 uniformly distributed locations at 2-km spacing covering the region.



1) smad: Mw 7.0 Sierra_Madre
2) smon1: Mw 6.3 Santa_Monica_south_west
3) hwood: Mw 6.4 Hollywood
4) raym2: Mw 6.6 Raymond_connectors
5) ph2e: Mw 6.8 Puente_Hills_Santa_Fe_Coyote_Hills
6) phla: Mw 6.7 Puente_Hills_Los_Angeles
7) phall: Mw 7.1 Puente_Hills_all
8) comp: Mw 6.9 Compton
9) nin: Mw 6.9 Newport_Inglewood_north
10) whitn: Mw 6.7 Whittier_north

Figure 4. Earthquakes simulated using 3-D codes for development of engineering model for basin effects. (Day, 2003 [9])

The simulation results are being used to guide development of, and verify, a simplified “engineering model” that can be used in conjunction with design attenuation relationships to correct for basin depth effects. Figure 5 presents an example of simulation results for 2-second spectral acceleration at each of 1600 locations for a single M7 scenario earthquake. These single-scenario results show the wide dispersion of shaking level with distance. The results have been color-coded on the basis of 3 ranges of depth to the 2.5-km shear-wave velocity isosurface. These results show that the deeper sites (light blue and red) experience much higher median motions than the shallow sites (dark blue). It is important to note that the deeper sites are also in the direction of forward rupture directivity. Therefore, the trend toward higher spectral response for deeper sites is, in this case, a combination of both forward directivity effects and basin depth effects. Separating these effects is the subject of on-going work where results from the other 59 scenarios will be closely examined.

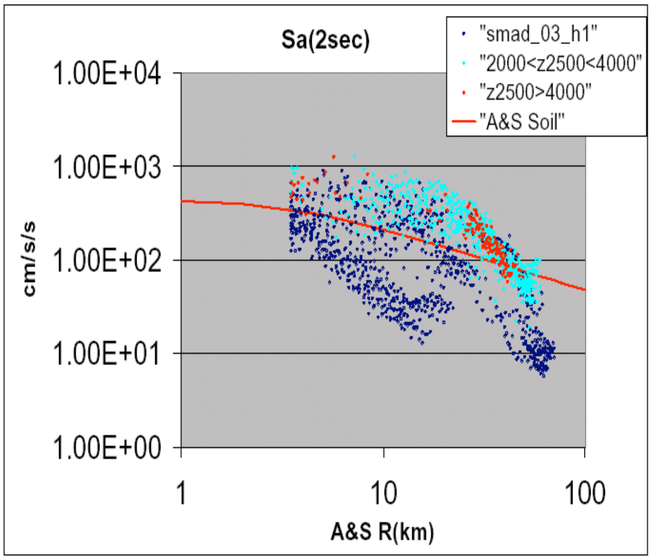


Figure 5. Example 3-D simulation results for 1600 sites for a single scenario (Day, 2003 [9])

A similar program of coordinated simulations was pursued with 1-D finite-fault models. This program largely focused on broad-band (25 Hz to 10 sec) simulations for near-field effects for large magnitude earthquakes where empirical data needed for attenuation models are very sparse. The PEER-LL program supported the advancement of three relatively mature 1-D finite-fault simulation techniques developed independently by Walt Silva, Paul Somerville, and Yuehua Zeng. Over several years, each of these techniques have been used in joint verification and calibration exercises to model the Kobe, Kocaeli, Duzce, and Chi Chi earthquakes as a means to improve their predictive capability and both identify and address any systematic bias and uncertainty in each of the models relative to actual recordings.

In a parallel effort, the PEER-LL program also supported an NSF effort headed by Pedro De Alba of University of New Hampshire that aimed to advance a greater number of 1-D simulation codes. A code qualification procedure was developed through this project that has served as the template for the NGA validation element described below. De Alba [10] reports that seven simulation codes qualified, including the three being used extensively in the NGA project. Unlike the NGA project, the NSF project developed suites of design ‘rock’ motions for the Treasure

Island National Geotechnical Experimental Site. These motions were used in subsequent geotechnical research studies focused on both site response and liquefaction analysis procedures.

Two additional initiatives were undertaken to improve 1-D modeling reliability in the near field. First, Rashool Anooshehpoor and Jim Brune at University of Nevada-Reno [11] developed new experimental data sets for the near-fault region by recording motions produced by forced offset of large foam-rubber blocks in a laboratory. The example data set in Fig. 6 shows a clear forward directivity pulse. Utilization of so-called “foamquakes” provided unprecedented recording coverage of the near-fault region as well as direct recordings of displacements on the fault plane. The laboratory environment also provided the unique ability to control quake conditions that allows separation of ground shaking effects caused by directivity from similar effects caused by fault asperities (or zones of high energy release). To connect new insights from the foamquake experiments to modeling capability used in the NGA project, Steve Day of SDSU coordinated the joint validation of the three 1-D simulation codes (by Silva, Somerville, and Zeng) against the foamquake data. This exercise resulted in significant code modifications that improved modeling of near-field effects.

Additional constraints on 1-D simulation was provided through research performed by Greg Beroza of Stanford [12]. The three 1-D simulation techniques employed by the NGA project all utilize so-called “kinematic rupture” models that make use of simple, and somewhat arbitrary, rules to specify rupture propagation along a fault. More recent “dynamic rupture” models provide a more complete physics-based approach to specify rupture propagation. Beroza’s work involved development and translation of dynamic rupture models to constrain fault rupture propagation that can be employed by all three 1-D kinematic models in a consistent manner.

Finally, these models were employed in a comprehensive simulation of 10 strike-slip and 12 reverse earthquakes. These simulations included multiple source models (20), and multiple site locations (131 for strike slip, 178 for reverse) for each earthquake. The complete simulation series will produce over 71,000 pairs of motions (two horizontal components) from each of the participating models. These results are being synthesized and trends extracted to support NGA attenuation relation development.

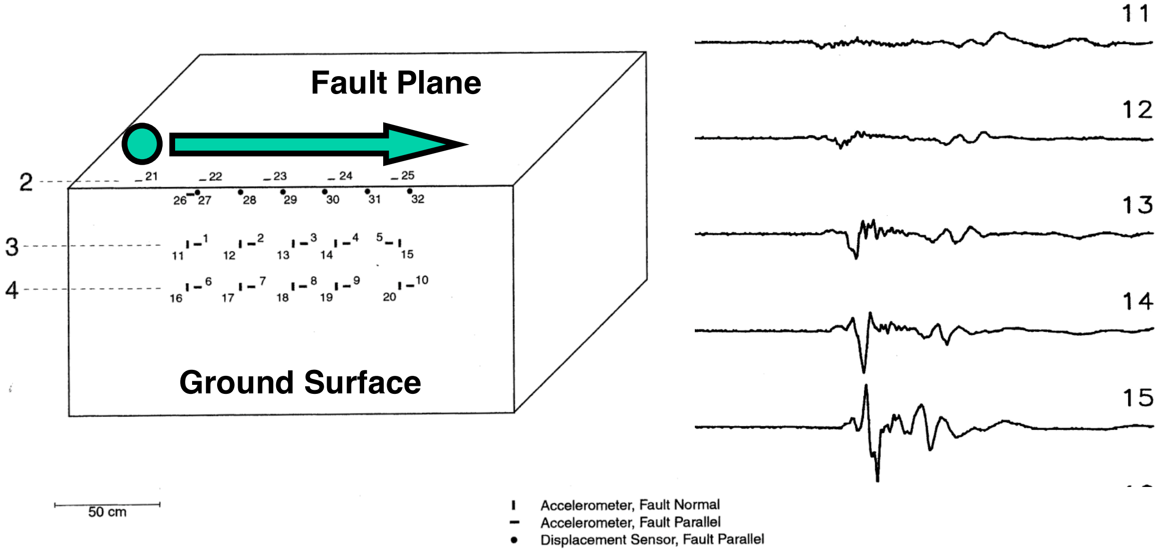


Figure 6. Foamquake model and example forward directivity pulse data (Anooshehpoor, 2002 [11])

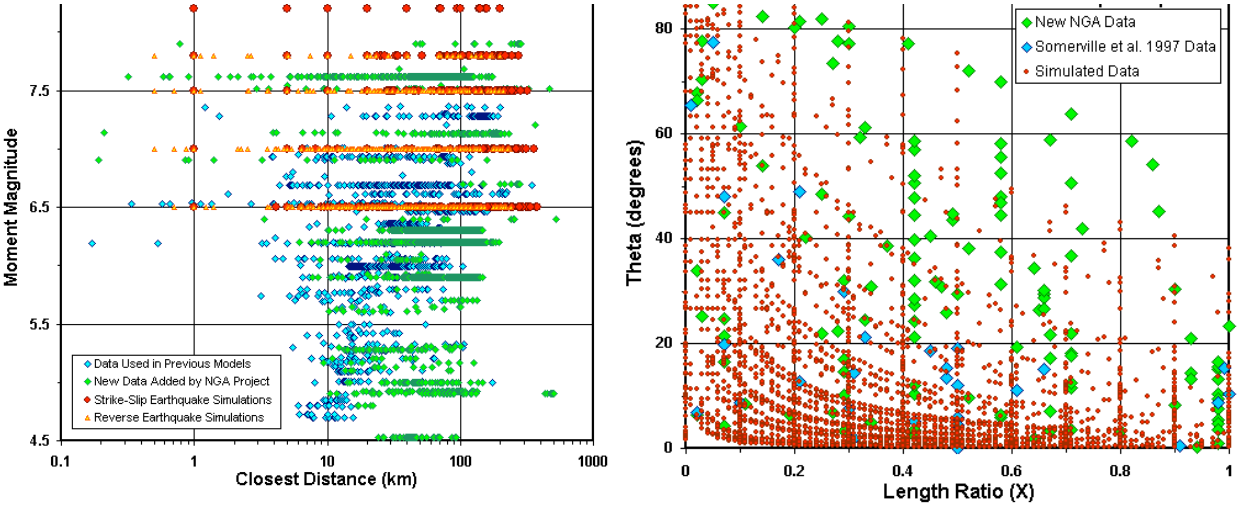


Figure 7. Combined distribution of empirical and simulated data being made available to NGA model developers shown in terms of magnitude-distance for all faulting types (left) and directivity parameters (right) for strike-slip earthquakes. (Chiou, 2003 [13])

Figure 7 shows the combined distribution of both empirical data and 1-D simulations (3-D simulation not shown) from two perspectives. The plot on the left shows the data in traditional magnitude-distance parameter space, while that on the right shows the distribution of strike-slip data in terms of Somerville et. al. [14] directivity parameters. In both figures, the blue symbols correspond to the empirical data distributions used for previous attenuation relations; the green symbols correspond to 'new' empirical data added by the NGA project; and the red and yellow symbols correspond to "data" provided by new 1-D simulations. The new data and simulations represent significant enhancements that provide important new constraints both at large magnitude and within the near-source region.

2.1.4.4 NGA Fling Step Models

Another key element of the NGA program is the development and evaluation of "fling step" displacement models. Fling step is that component of fault-parallel ground motion that is associated with irreversible, or static, fault offset. Ground motion very near a fault is composed of a combination of fling step and dynamic shaking components. To date, attenuation models have treated these components in combination. However, some in the seismological research community believe it is important to isolate the components because fling step motion attenuates much more rapidly with distance from the causative fault than does dynamic motion, an effect that is difficult to capture in attenuation models applied over the full distance range. Norm Abrahamson [15] has proposed a methodology to separate fling step from vibratory motions for strike slip earthquakes as illustrated in Fig. 8. Rob Graves [16] worked with Norm Abrahamson to refine and extend fling-step models for both strike-slip and reverse faulting for the NGA program. To be utilized for attenuation model development, the fling step component must be removed from near-fault recordings in a consistent manner. This issue is somewhat challenging due to the non-uniqueness of possible solutions. A NGA working group will be making a recommendation to developers on this issue, though the decision to incorporate a separate fling-step model is being left to each developer. To accommodate both approaches, the NGA database will include two versions of near-field recordings, those with and without fling step.

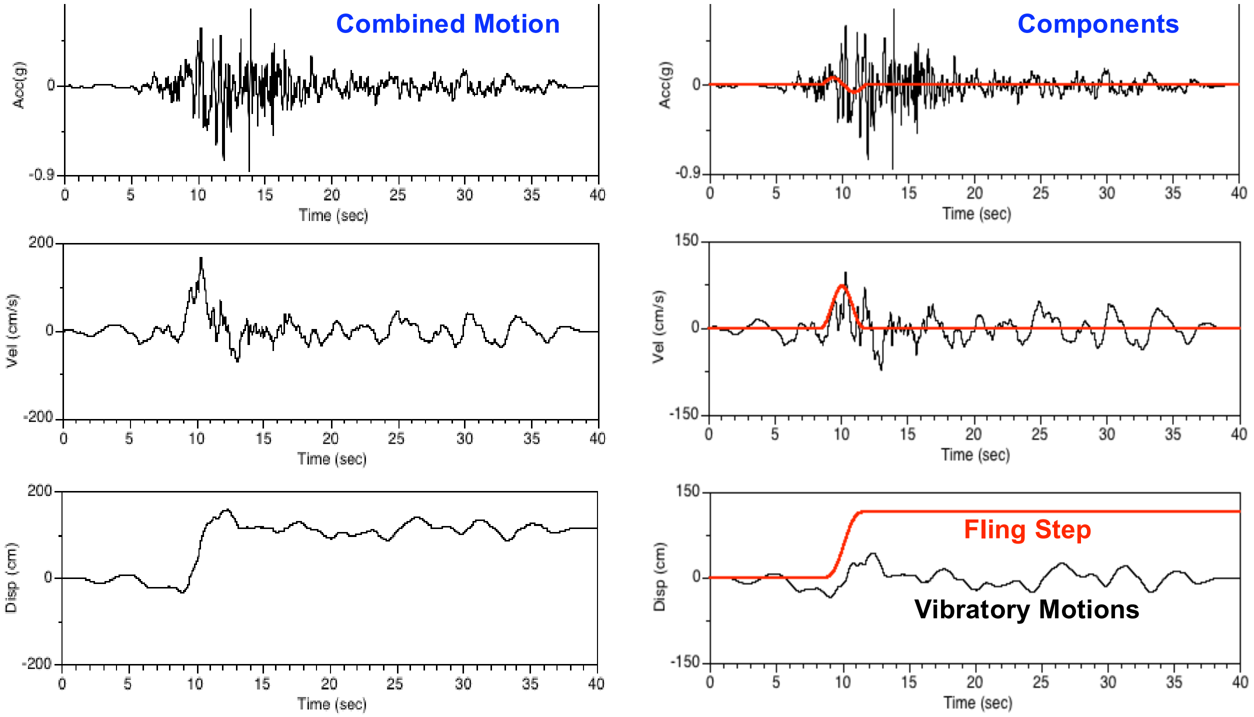


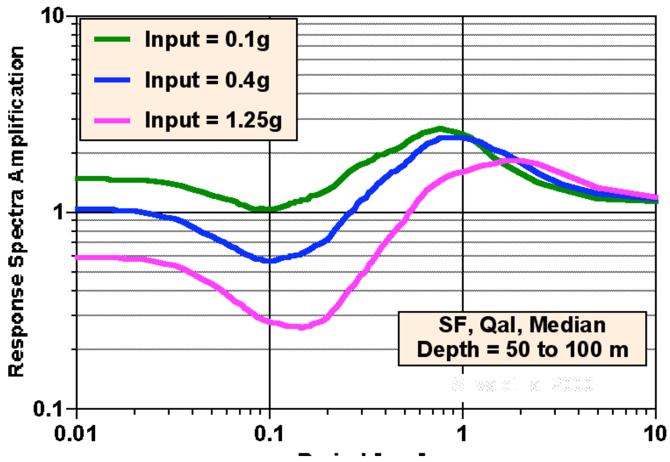
Figure 8. Example separation of irreversible "fling step" displacement from "vibratory motions" in a near-field fault-parallel recording. (Abrahamson, 2002 [15])

2.1.4.5 NGA Site Amplification Effects Modeling

The last key element of the NGA program involved research in support of consistent modeling of site amplification effects. Current attenuation models account for site amplification effects differently. Sites are classified according to several different schemes, and the soil amplification effects produced by the different attenuation models vary significantly and are not fully consistent with results provided by geotechnical site-response analyses. The NGA program used site-amplification modeling to achieve two objectives:

1) Establish expected trends in site amplification as a function of input-motion amplitude or magnitude and distance for each site classification scheme used by the NGA developers;
2) Establish a mechanism to efficiently translate attenuation-model results between the different site classification schemes so that users of the different schemes can apply all models.

To analyze site effects, the NGA project used a random-vibration-theory (RVT) based equivalent-linear formulation developed by Silva [17]. This stochastic framework provides smooth median amplification functions as well as an ability to track uncertainties associated with both subsurface and material-properties variations. Figure 9 shows an example of median 'site amps' produced by Silva et. al. [18] for three different levels of input motion for sites having 50-m to 100-m of quaternary alluvium overlying Franciscan bedrock commonly found in the San Francisco Bay area. The general shape of the amplification function is governed by the impedance contrast between the rock and near-surface soil, and resonance associated with the depth and stiffness of the soil profile. The decrease in amplification at short period with increased level of input motion is caused by soil non-linearity.



The stochastic RVT method was used to develop site amplification functions for each of the various site classification schemes. The site categories used previously by attenuation-model developers include:

1. 'Rock' and 'soil';
2. 'Hard rock', 'soft rock', 'soil' and 'soft soil';

3. Various surface-geology (age and grain-size based) schemes;
4. Average shear-wave velocity of the top 30 m at a site (Vs_{30});
5. NEHRP categories based on (Vs_{30}).

The NGA model developers were encouraged to adopt a more uniform approach for site classification, though final decisions have yet to be made. There seems to be broad consensus toward adding a 'depth' term for site classification. However, a consensus definition that satisfies the varied needs of different regional geologies and for which data can be obtained has yet to be established. Where available, depths to shear-wave isosurfaces of 1 km/s and 2.5 km/s were captured in the NGA database. This depth value was also be used as a proxy for engineering modeling of 3-D basin effects.

The site-amplification functions developed under the NGA program will not be used directly in attenuation models. Rather, the results were made available to all NGA developers as a resource to help guide their judgment in the selection of functional forms for site effects. Final NGA models will also be compared for consistency with the site-amp models.

2.1.4.6 NGA Schedule

The NGA database and simulation results were delivered to the developers in August 2004. NGA-E models incorporating average horizontal components are to be completed by each development team by November 2004. The final NGA-E model, incorporating fault normal and fault parallel components, will be completed by March 2005. Advanced efforts toward a NGA-H model will follow pending availability of funding.

2.2 Probabilistic Hazard Code Validation

Probabilistic seismic hazard analysis (PSHA) is a methodology for establishing design ground-motion hazard level that is an alternative to the deterministic, or scenario-based, methodology. Advantages of PSHA include that it provides a consistent framework to incorporate contributions to hazard arising from multiple earthquake sources, poorly defined sources, and from a variety of uncertainties in hazard estimation ranging from variability in attenuation relationships to the likelihood of occurrence of a particular earthquake magnitude. Both national and California earthquake hazard maps used for building codes are based on PSHA. PSHA is also used to evaluate site-specific hazard for critical facilities such as power plants and dams, and is also used widely for risk analyses and loss estimation.

2.2.1 Technical Issues and Goals

PSHA is a relatively sophisticated analysis, and a number of computer codes have been developed by a variety of organizations to implement the analysis. Design experience has shown that results of PSHA can vary widely depending upon both the analyst and the code employed. Differences in results can be attributed to:

1. Input errors (operator error due to ignorance or mistakes);
2. Numerical coding errors (e.g. poor integration scheme, code 'bugs', etc.);
3. Errors in coding related to misinterpretation of component models (e.g. how to properly specify the region to receive 'hanging wall' correction for dip slip events);
4. Differing approaches used for computational details (e.g. how to treat the distribution of uniform slip near fault edges, handling curved faults, etc.).

The overall research goal for this project was to improve the consistency and transparency of results by assuring that computer codes are numerically correct, that consensus is established among code developers regarding the most appropriate implementation of component models and computational details, and that clear guidelines are available regarding proper usage and limitations of codes.

2.2.2 Program Approach

Under the management of Ivan Wong and Patricia Thomas [19] of URS Corp, the project established an unprecedented working group of PSHA model developers representing various agencies in both the federal and California state government, and consultants for the engineering, insurance and loss-estimation practices (see 'working group' in next section). This working group brought together 10 independently developed PSHA codes into a single joint verification exercise. Public domain codes included those used for national and California hazard maps. Representatives for three commercial codes were invited to participate in the verification process, and two elected to participate. The third commercial code was not configured to easily accommodate the verification exercises.

The approach adopted for consensus building involved a series of workshops focused on critical examination of results of 10 PSHA codes for a series of test cases. The test cases were designed to test basic aspects of standard PSHA and cover the wide variety of fault and site geometries encountered in practice. The joint verification program was structured to progress from extremely simple test cases to very sophisticated ones that tested all key aspects of the codes. The simplest cases had closed-form solutions for comparison and were used to isolate potential fundamental coding errors in the numerics. The more advanced test cases were used to illuminate discrepancies between approaches as a means to both to illustrate consequences of certain code-implementation decisions as well as to focus workshop discussion on establishing consensus definitions and methodologies.

The overall process involved establishment of two sets of test cases by the project leaders in consultation with the working group. PSHA results were then prepared and submitted by each of the code developers, with the project leaders providing results for the commercial codes. Results were compiled and plotted anonymously for distribution back to the developers and discussion at the workshop. Workshops focused on possible reasons for discrepancies, and each modeler was invited to make code and/or input modifications and resubmit results for subsequent comparison. This process was repeated until discrepancies between solutions were considered insignificant or that remaining discrepancies were technically justified and documented.

2.2.3 Research Team (alphabetical order)

Task PI's:	Ivan Wong
Co-PI's:	Patricia Thomas
Working Group:	Norm Abrahamson, Tianqing Cao, Brian Chiou, Ned Field, Roland LaForge, Robin McGuire, Andres Mendez, Badie Rowshandel, Jean Savy, Mark Stirling, Phalkun Tan, Gabe Toro, Bob Youngs

2.2.4 Selected Accomplishments

The working group completed a total of 18 test cases. Figure 10 illustrates fault and site geometries for the first test case. Figure 11 shows an example of the progression of results for a test case involving a site located 10 km perpendicular to the midpoint on the hanging wall side of a dip slip fault. The difference in originally submitted results illustrates the type of discrepancies that were viewed as problematic by users of PSHA. Differences of 100% in ground motion or a factor of 10 in occurrence are seen. The convergence of results obtained with subsequent iterations primarily represents growing consensus regarding appropriate code implementation for use of hanging-wall correction terms used for dip-slip faults. The remaining discrepancies shown in the “final” plot on the right are considered to be insignificant for design purposes.

The primary product of this project is a comprehensive set of 18 validation test cases (multiple sites for each test case) with benchmark solution ranges. Users of PSHA analyses can use the test set as example problems to confirm correct implementation. Users of PSHA results can use these test cases as qualification criteria for accepting results from a consultant. Developers of new PSHA codes can use the results to confirm that their implementation is correct. The complete set of test cases and benchmark solutions is made publicly available on the PEER web site.

Figure 10. Example test-problem fault and site geometries used for the PEER-LL joint verification of PSHA computer codes. (Wong et.al. [19])

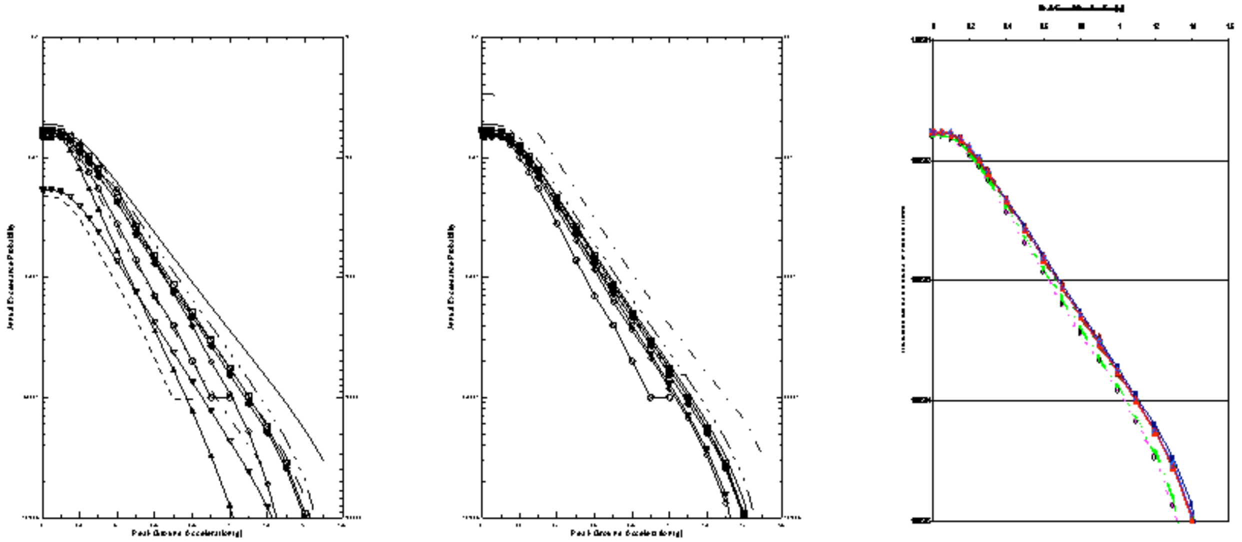


Figure 11. **Example results from 1st, 2nd, and final iteration of consensus-building working group process used for joint verification of PSHA codes. (Thomas, 2003 [20])**

3.0 IMPROVED METHODS FOR EQ TIME HISTORY SELECTION AND SCALING

Non-linear time domain structural analyses are relatively advanced methodologies required to assess the post-yield behavior of inelastic structures subjected to strong seismic loading. Although design application of non-linear structural analyses is still in its infancy, routine usage is expected to increase, especially for cases involving near-fault locations, unusual structural geometries, or for those involving special details including energy dissipation devices. These analyses are particularly useful where designers are seeking to more closely approximate detailed structural behavior. When high seismic demands are expected or where higher performance standards are to be adopted, nonlinear analysis is becoming common.

Earthquake time histories are a fundamental input to non-linear structural analyses. Unfortunately, two time histories having the same elastic response spectrum can lead to very different non-linear structural response. One input motion may indicate a safe design while the other illuminates key vulnerabilities. Figure 12 illustrates this issue by showing two sets of displacement time histories for a simple single-degree-of-freedom oscillator having four different levels of inelastic behavior. The black, red, green and blue traces correspond to a structure having a strength reduction factor ('R') of 1 (or elastic), 2, 4, and 8, respectively. The two input motions, used for the results on the left and right, have

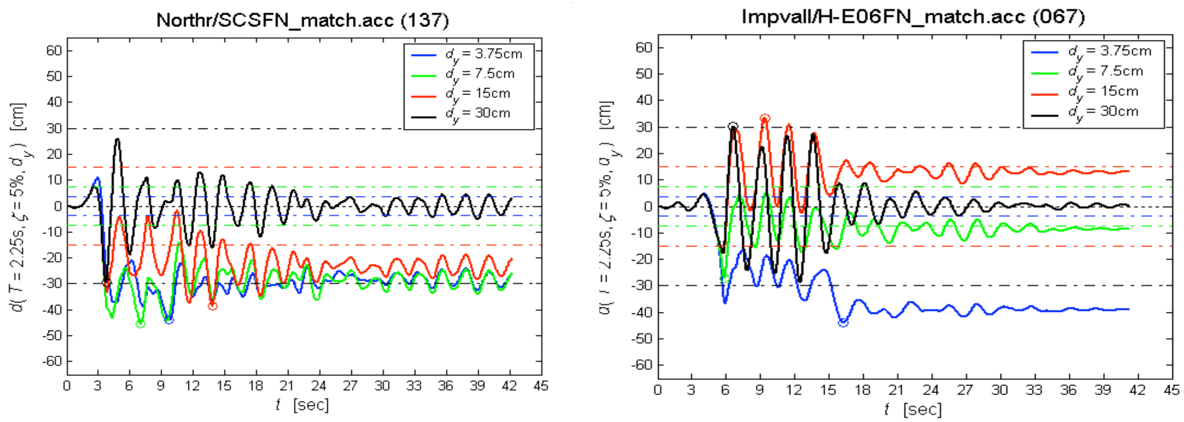


Figure 12. **Illustration of the effect of 2 different input time histories on displacement of inelastic SDOF systems (d_y=30cm) having R of 2, 4, and 8. (Luco and Bazzurro, 2003 [21])**

both been spectrally matched to have the same elastic response spectrum and therefore have the same maximum elastic displacement (black line). However, the inelastic, or permanent, displacement can be seen to vary not only because of different 'R' values, but also as a result of the different input motions. Furthermore, a systematic trend cannot be established with increased 'R'. For the motion on the left, permanent displacement for all three inelastic systems is similar. However, for the motion on the right, the displacement for R=2 and R=8 are relatively large, but that for the R=4 case is small. Another input motion would yield yet different results.

Comprehensive characterization of non-linear structural behavior may require that large sets (tens) of motions be considered and that the range of possible responses be characterized in terms of median behavior and an uncertainty band. Ideally, the large sets of motions would be selected from recordings having similar seismological conditions (magnitude, distance, directivity, basin location, soil type, etc.) as the design site. Unfortunately, there simply are not sufficient recordings for many of the most important design cases. For these cases, the only alternatives to address the seismological data gap are either to use simulated motions or to scale up weaker recorded motions to higher design hazard levels. Unresolved issues remain for both of these practices.

Overall, designers need a standard, comprehensive, and defensible approach for selection and scaling of seismological input in order to advance the effective use of non-linear structural analysis procedures.

3.1 Design Ground Motion Library (DGML) *(PEER-LL, CGS-CSMIP Collaboration)*

Although several high-quality databases of strong motion recordings are currently available, selection of the most appropriate subset of motions for a specific design application remains a challenge. Time-domain motions meeting similar spectral-hazard criteria can be selected, intentionally or inadvertently, that drive a structure toward extreme ends of its range in performance. Designers need a convenient, transparent, and standard mechanism to select record sets that will produce the level of seismic demand intended for the specific design assessment. Such an assessment could seek to define 'representative' demand, say median with uncertainty, or seek to identify the most challenging cases. Designers need a time-history selection process that recognizes the needs of different structure types and seismological conditions. They also need clear guidance on how to properly scale the selected motions to meet design-level hazard.

To address these needs, the PEER-LL program established a joint research project with the California Strong Motion Instrumentation Program (CSMIP) to develop an electronic "Design Ground Motion Library (DGML)". The DGML will contain recommended sets of motions, and scaling rules for adjusting these motions, for all ranges of seismological conditions used for seismic design of California bridges and other critical infrastructure components.

3.1.1 Technical Issues and Goals

The DGML project aims to develop a convenient electronic database for the selection and download of recommended sets of motions and their metadata. The DGML is being pursued in two phases. The 1st phase focused on general library development and populating the library for shallow crustal earthquakes using only recorded data. Substantial data gaps were identified during this phase. The 2nd phase of the project will address the data gaps by adding supplemental motions generated using a variety of simulation techniques. The second phase will also add records and simulations for subduction events. The central technical challenges in creating the DGML are: 1) defining an appropriate 'bin structure' for organizing the records, and 2) identifying the most relevant subsets of 'recommended records' to populate the bins.

The DGML bin structure must cover a wide range of seismological conditions including fault type, magnitude, distance, directivity, basin location, and soil type. The bin structure also needs to recognize the sensitivity of different types of structures to different time-domain features of motions. For example, some long-period structures may be especially sensitive to near-field directivity pulse characteristics, while other facilities are more sensitive to the duration of motion. Accommodating these considerations tend to increase the number of bins. However, the lack of recorded earthquake data makes it desirable to minimize the number of bins so that each bin is well populated. Establishing the proper balance requires careful consideration of the effects of record scaling. If large scaling factors are allowed, fewer bins are required and more recordings are available to populate each bin. Research addressing the issue of acceptable scaling is discussed in section 3.2.

Establishing consensus regarding record selection for each bin is perhaps the single most important facet that distinguishes the DGML 'design library' concept from a conventional database. Practicing design engineers rarely perform non-linear analyses using more than a handful of records due to time and cost. Typically, 1 to 3 sets of motions are considered where each motion is scaled using spectrum-matching methods. On rare occasion, simple scaling is used with suites of as many as 10 to 15 motions. Therefore, providing clear guidance on how to wisely select records is a critical goal of the DGML project.

3.1.2 Program Approach

Maury Power of Geomatrix Consultant [22, 23] is managing the DGML project team for PEER-LL and CSMIP. The project team includes experienced engineers having expertise in the design of highway bridges, utilities, buildings, base-isolated structures, and concrete and earthen dams as well as selected engineering seismologists and academics familiar with issues of time-history analysis (see project team). Consensus recommendations from this working group are being used as the basis for establishing both the DGML bin framework and the 'recommended sets' of time histories.

3.1.3 Research Team (alphabetical order)

Task PI's:	Maury Power
Co-PI's:	Allin Cornell, Roupen Donikian, Yusof Ghanaat, Ron Hamburger, Steve Mahin, Faiz Makdisi, Ron Mayes, Ignatius Po Lam, Walt Silva, Paul Somerville, Bob Youngs
Review:	Abbas Abghari, Norm Abrahamson, Fadel Alameddine, Brian Chiou, Moh Huang, Cliff Roblee, Vladimir Graizer, Tony Shakal.

3.1.4 Selected Accomplishments

The DGML is being configured as a searchable electronic database that will allow customized searches on a number of ground-motion intensity measures and supporting information. The list of intensity measures being considered for quantification for records in the library include those parameters currently used in routine design, as well as those being proposed by PEER and other researchers for vector-based hazard assessments within the performance-based earthquake engineering framework. The list includes:

- Peak values for acceleration, velocity and displacement (PGA, PGV, PGD);
- Elastic and inelastic response spectra;
- Various other intensity measures including duration, cumulative absolute velocity (CAV), energy, damage indices, Arias intensity, Housner spectrum intensity
- Near-source characteristics including pulse velocity, pulse period, and number of pulses.

Supporting information for each record will include parameters used for attenuation models such as fault type, earthquake magnitude, source-to-site distance, site classifications and parameters, hanging wall or footwall designation, near-source directivity parameters, and basin parameters.

The research team has established a preliminary bin structure for the DGML. Table 3 presents the current proposal for primary bins to account for seismological hazard effects. The near-source distance ranges will be further subdivided into spatial regions around a fault to account for directivity parameters and hanging wall designation. Records for each of these magnitude-distance bins will be subdivided for each of the other seismological parameters such as fault type, site class, and basin parameters.

Table 3 - Preliminary Hazard Bin Ranges Being Considered for DGML (Power, et. al. 2003, [22, 23])

Moment Magnitude	Closest Source-to-Site Distance (km)
5.0 to 5.9	0-10, 10-25, 25-50
6.0 to 6.4	0-10, 10-25, 25-50
6.5 to 7.0	0-10, 10-25, 25-50, 50-100
6.9 to 7.9	0-10, 10-25, 25-50, 50-100

Studies by PEER and PEER-LL have indicated a strong correlation between structure damageability and elastic response spectral characteristics over a period range. Therefore, the project team has recommended that the response spectral shape of a recorded time history over a period range of interest be part of the time history selection criteria. The period range of interest would depend on factors such as the estimated fundamental elastic period of the structure and its uncertainty, the anticipated lengthening of the fundamental period due to inelastic response (structure softening) and its uncertainty, and the contributions of higher-mode (shorter-period) effects on structure response. The period range of interest may also reflect a designer's preference for using time histories having broad-banded or narrow banded spectral content.

The project team has defined a preliminary set of overlapping period ranges defined to encompass period ranges of significance to response for a wide range of structures and designer preferences for narrow- or broad-banded spectral content. The preliminary period ranges are shown in Table 4 [24]. These period ranges would be used to sub-bin time history records within each hazard bin. Some records may be assigned to several of these sub-bins due to the overlapping period ranges. Within each sub-bin, records would be selected having spectrum shapes over the period range that have a better fit to the median spectrum shape ("target" shape) for the magnitude and distance range for the respective hazard bins, based on current attenuation relationships. For a given structure, the design engineer would evaluate a period range of interest, and would then select time histories from the sub-bin approximately corresponding to that period range. Table 4 also illustrates typical types of facilities that may correspond to the proposed period sub-bins. These types, and the period range limits, should be viewed only as a preliminary proposal and are subject to more detailed evaluation and definition.

Table 4 - Preliminary Sub-Bin Period Ranges Being Considered for DGML (Power, 2003 [24])

Category	Period (sec)	Typical Facility Types
Short	0.1 to 0.5	Stiff Low-Rise Buildings, Small Bridges, Concrete Dams, Low Earth Dams
Intermediate	0.1 to 1.0	Mid-Rise Buildings with Higher Mode Effects, Midsize Bridges with Varying Span Lengths, Mid-Height Earth Dams
	0.5 to 1.5	
Narrow-Banded Long	1.0 to 3.0	High-Rise Steel and Concrete Buildings and High Bridges (Not Cable Supported) Governed by Fundamental Mode, Base-Isolated Structures
	2.0 to 4.0	
Broad-Banded	0.2 to 4.0	High-Rise Buildings with Multi-Mode Effects, Large Bridges (Not Cable Supported) with Multiple Span Lengths, Structures Requiring Broad-Band Excitation
	0.5 to 4.0	

Another proposed element of the DGML is a 'selection tool' to help a designer narrow the selection of recordings for those cases where the number of recordings are plentiful. The proposed selection tool will rank motions based on the fit of the recording to a target spectral shape over the specified sub-bin period range, where the target shape would be defined by an attenuation relationship. The selection tool is being configured to support two alternative selection strategies. The first strategy would identify those records that most closely fit the target spectra, and is intended to provide a good estimate of typical structural performance. Figure 13 shows an example of seven best-fit spectra relative to a target having specified period range, magnitude, and distance. Different records would be identified for different target criteria. The second selection strategy would provide a random selection of records that meet inclusion criteria. This random selection may be more appropriate when the designer aims to identify the full range

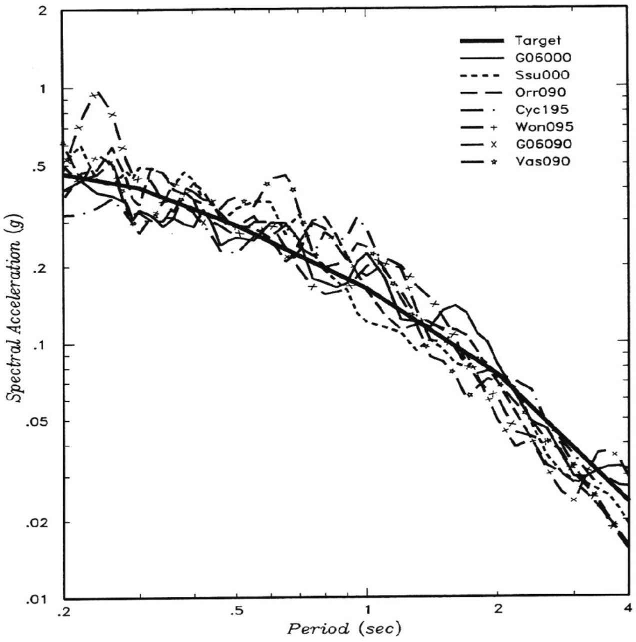


Figure 13. Example of best-fit spectra for one design sub-bin (Power, 2003 [23])

of possible structural performance for a specified hazard level.

The final elements of the DGML project are utilization guidelines. These guidelines are intended to serve as a tutorial for proper usage of the DGML, and also identify any limits and deficiencies. Specific advice will be provided regarding record scaling using both a simple (constant factor) approach and alternative spectrum-matching approaches. The guidelines will also address the number of records needed to obtain a stable estimate of inelastic structural performance. These recommendations will be based on research described in the following section.

3.1.5 DGML Schedule

The DGML framework was completed in May 2004. Population of DGML database has not yet begun, and is pending delivery of rotated (to fault normal and fault parallel orientations) earthquake time-histories from the NGA program. DGML is expected to be completed in Spring 2005.

3.2 Damage Indicators and Scaling Impacts

As described in the previous section, development of an effective bin structure and record-selection criteria for the DGML is closely intertwined with issues of record scaling and the ability to identify additional indicators of how damaging a particular time history is to a structure. Selection of appropriate recordings would be aided significantly by an improved ability to identify those “non-stationary” characteristics within a time history that are most damaging to structures. A priori knowledge of these characteristics would allow the seismologist to select a smaller set of motions for analysis.

Additionally, scaling by different approaches also affects the number of recordings needed to establish a stable estimate of the average non-linear structural performance. The most common scaling options include ‘simple scaling’ by a constant factor, and ‘spectrum-compatible scaling’ that, in effect, applies different factors to each frequency. Simple scaling allows a ground-motion record to match a specified target response spectrum at a minimum of one period. The period most often selected for matching is the fundamental period of the structure being designed, though scaling to PGA has also been selected. Spectrum compatible scaling allows the recording to be matched to a specified target spectrum across the entire period range. Spectrum compatible scaling can be achieved using either time-domain or frequency-domain techniques.

3.2.1 Technical Issues and Goals

Seismologists are frequently asked by structural engineers to provide a small set of “representative” time histories for a specified hazard level. Engineers are frequently surprised by the variability observed in non-linear structural performance; one motion will prove highly challenging while another is relatively benign. This situation can lead to unproductive debate, unnecessary re-examination of modeling results, and arbitrary decisions. Additional analyses with supplementary motions are often required leading to project delivery delays and cost overruns.

Logically addressing this issue requires that designers: 1) consider a larger number of motions, or 2) that better ways are found to select a limited set of motions that will yield representative structural performance for a specified hazard level. If the first path is pursued, designers need to know how many motions are sufficient. For the second path to work, seismologists must identify additional parameters within the time history that will be indicative of structural damage.

There is also controversy in the seismological field regarding the acceptable limits of scaling. Because of the lack of recorded data, scaling factors as large as 10 may be required for design. This practice is considered acceptable by some engineering seismologists; however, others believe scaling should be limited to a factor in the range of 2. Designers need this issue to be resolved.

Designers typically prefer use of spectrum-compatible motions to simply scaled motions. This practice is broadly believed to reduce the required number of motions needed to establish stable estimates of typical non-linear structural response. However, little quantitative information is available regarding the number of simply scaled or spectrum-compatible scaled motions needed to achieve a specific level of uncertainty in the average non-linear structural performance. Further, there are widely varying opinions as to whether spectrum-compatible motions are biased, and if such a bias is ‘conservative’ or ‘unconservative’. Overall, designers need specific guidance on acceptable levels of scaling and whether scaling introduces bias or additional uncertainty into non-linear assessments of structural performance.

3.2.2 Program Approach

Paolo Bazzurro and Nicolas Luco [25] of AIR Worldwide Corporation have investigated: 1) improved time-domain predictors of structural damage, and 2) several fundamental issues related to time-history scaling. This work was performed in close coordination with DGML project leaders so that results can be reflected within the binning structure and selection criteria for the DGML.

To characterize non-linear structural performance, these studies utilized the displacement of idealized inelastic single-degree-of-freedom (SDOF) systems of varying period and strength reduction factors ('R') of 1, 2, 4, and 8. To confirm key findings from the SDOF model, additional studies were performed using a multi-degree-of-freedom (MDOF) model of a 9-story building developed for the SAC Joint Venture project.

For input motions, these studies have focused exclusively on actual recordings (rather than including consideration of synthetic time-histories) to assure that recognized and potentially unrecognized time-domain features of real earthquakes are properly represented. While it would have been desirable to explore scaling issues using typical design-level earthquake scenarios (say magnitude 7 to 8 in the near field), the lack of recordings forced this study to adopt somewhat lower motions. The majority of analyses were performed using a bin of 31 near-field, forward rupture-directivity recordings from 6 shallow crustal earthquakes, both strike-slip and reverse, having magnitudes between 6.4 and 6.8 and fault-to-site distance of up to 16 km.

3.2.3 Research Team (alphabetical order)

Task PI's:	Paolo Bazzurro
Co-PI's:	Nicolas Luco
Review:	Norm Abrahamson, Brian Chiou, DGML Project Team

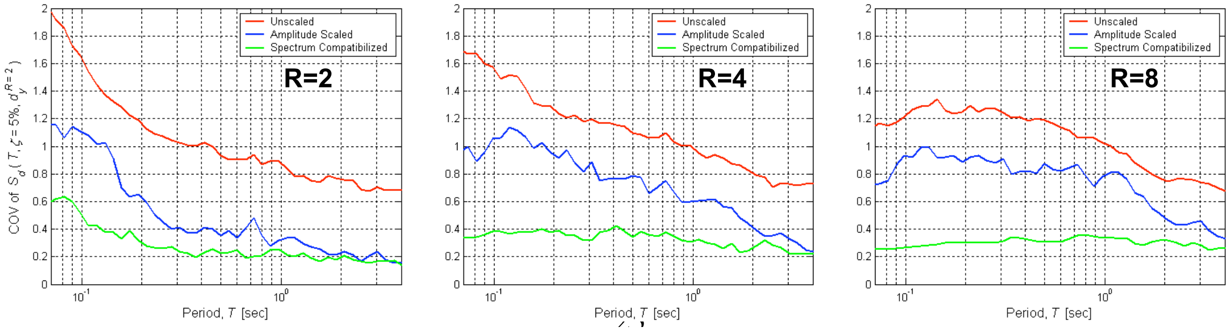
3.2.4 Selected Accomplishments

A primary objective of the studies by Bazzurro and Luco was to identify "damaging features" in ground motion recordings that would allow a designer to analyze fewer motions to converge on stable estimates of structural performance. First, the benefits of scaling, both simple and spectrum compatible, were investigated. Figure 14 shows that the variability in inelastic structural response is a function of structural period and the degree of inelastic behavior, as reflected by R. The figure also shows a significant reduction in variability associated with scaling of motions using either method, but that spectrum-compatible motions yield the greatest reduction in variability. Table 5 summarizes values of dispersion in inelastic response for spectrum-compatible records for different periods and strength values. It also lists (in parentheses) the number of recordings needed to achieve only 10% uncertainty in the median inelastic response. Note that the number of records needed increases with decreasing period and with decreasing structural strength (increasing R).

The next step in their study was to look for additional parameters beyond the elastic response spectrum that might correlate well with damage, thus allow further reduction in the number of recordings needed for analysis. Initial emphasis was placed on parameterizing near-field directivity pulse characteristics and duration as these were intuitively thought to be particularly damaging characteristics. Specifically, they examined:

- Pulse period
- Pulse amplitude (in velocity)
- Number of pulses
- Duration (Trifunac and Brady definition)

Somewhat surprisingly, none of these parameters of the spectrum-compatible motions were found to be well correlated with damage as measured by inelastic displacement. However, investigation



additional ground-motion parameters revealed that the "first significant peak elastic displacement" of a spectrum-compatible record did correlate reasonably well and was viewed as a proxy for inelastic spectral displacement. When this factor is considered, the number of records can be reduced significantly as shown in Table 5. However, for application to design, a target intensity level for this additional parameter would need to be specified using a yet-to-be-developed attenuation model.

Table 5 - Dispersion and Number of Records for 10% Uncertainty (Bazzurro and Luco, 2003 [25])

Given	Dispersion of $S_d^I(T, \zeta=5\%, d_y^R)$		
	$R=2$	$R=4$	$R=8$
$T = 1.0$ sec			
Elastic Response Spectrum (Spectrum Compatibles)	0.27 (7)	0.30 (9)	0.34 (11)
+ First (in time) Significant Peak Elastic Displacement	0.18 (3)	0.25 (6)	0.29 (8)
$T = 2.25$ sec			
Elastic Response Spectrum (Spectrum Compatibles)	0.19 (4)	0.31 (9)	0.31 (9)
+ First (in time) Significant Peak Elastic Displacement	0.11 (1)	0.21 (4)	0.27 (8)
$T = 4.0$ sec			
Elastic Response Spectrum (Spectrum Compatibles)	0.14 (2)	0.23 (5)	0.26 (7)
+ First (in time) Significant Peak Elastic Displacement	0.10 (1)	0.19 (3)	0.20 (4)

(In parantheses): Number of seismograms necessary to estimate median S_d^I with 10% uncertainty.

The other issue addressed by Bazzurro and Luco is whether scaled motions produce inelastic displacement values that are biased as a result of the scaling process. Figures 15 and 16 present highlights of their findings. Figure 15 shows that some bias is indeed introduced by both scaling procedures and that the bias can be significant for short periods (say below 0.3 seconds). At longer periods, the bias is approximately 20% or less, with spectrum compatible motions being biased low and simply scaled motions being biased high. Note that the scale factors used to obtain this result were set to target the median elastic spectral response of the records in the bin. Different results may be obtained if the target was the mean or some other number.

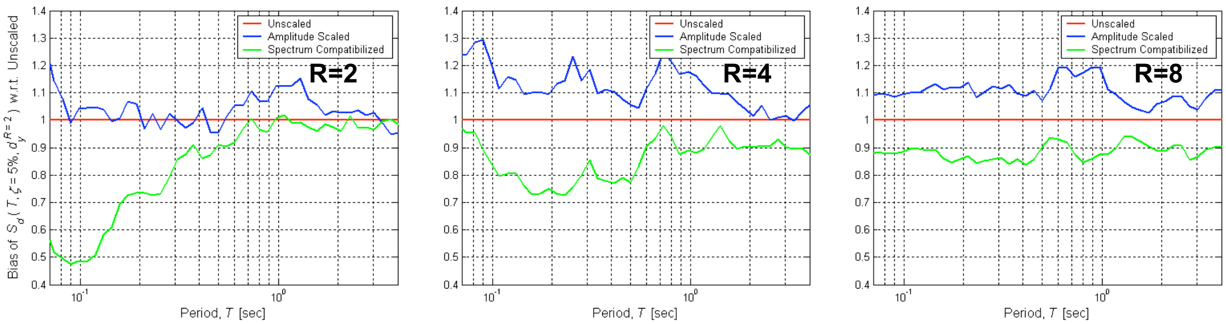


Figure 15. Bias in inelastic structural response for simply-scaled and spectrum-compatible motions scaled to median of unscaled records. (Bazzurro and Luco, 2003 [25])

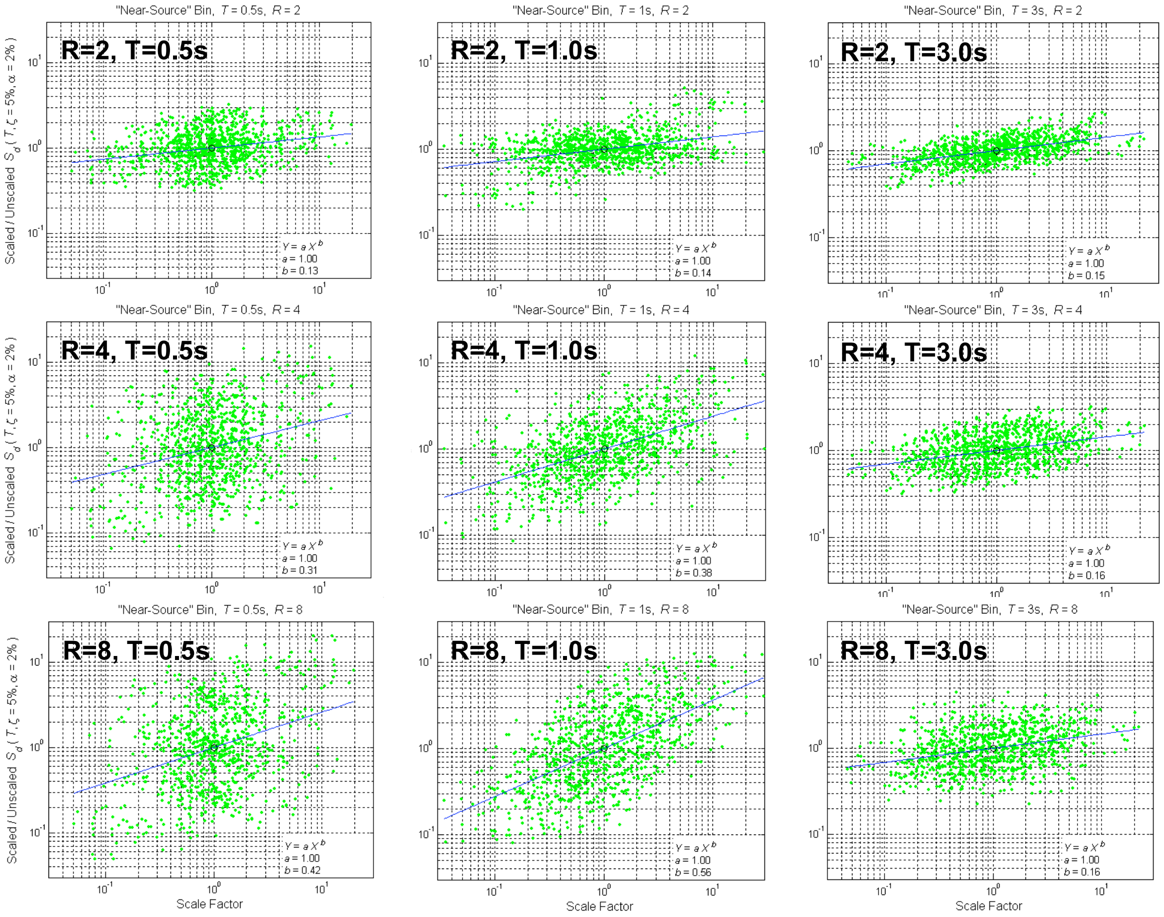


Figure 16. Bias in scaled-to-unscaled inelastic spectral displacements as a function of scale factor for 31 simply-scaled near-field forward-directivity motions. (Luco, 2003 [26])

Figure 16 illustrates trends in bias as a function of the amplitude of the simple-scaling factor. The 'cloud' of points was obtained using each of 31 records as a target and scaling all other records to the spectral acceleration of that target at the specified period. Each point represents the ratio of inelastic response of the scaled record to that of the target record. Results clearly indicate a positive correlation between scale factor and bias level. The increase in bias is more pronounced for short period and weaker structures (i.e. larger R's). For 3-second structures, the bias is less than 20% for a range in scale factors up to 10. For the same range in scale factors, response of a 1-second structure can be biased from 25% to 100% with the larger numbers associated with weaker structures. In all cases, the record-to-record variability is much larger than the bias.

4.0 IMPROVED MODELING OF GEOTECHNICAL SITE EFFECTS

Geotechnical site effects are a period-dependent amplification or de-amplification of earthquake motions caused by near-surface sediments (including soft rock). These effects depend upon the stiffness and damping of the sediments, which in turn are a non-linear function of the amplitude of the motions. The non-linearity in site effects is associated with the inelastic material behavior of the sediments, which become less stiff and more energy absorbing with increased levels of strain.

Geotechnical site effects enter the design process through any of several mechanisms. Attenuation models take a purely empirical approach that simply identifies different site categories, and then regresses different model coefficients for each site category. As described in section 2.1.4.5, a variety of site classification schemes are employed. A more fundamentally sound approach is to use wave propagation theory to evaluate site effects. Vertically propagating shear waves are assumed to dominate the wave field, and therefore 1-D models are employed. All wave-propagation models require input of a shear-wave velocity (Vs) profile to represent the low-strain stiffness of the soil. To account for non-linear material behavior at higher strain, either 'equivalent linear' or any of several 'fully nonlinear' computation schemes are employed. Both approaches require material models that reduce stiffness and increase damping of the sediments at larger strain levels. The material models are generally derived from laboratory experimental data on both natural and reconstituted soil samples.

Wave-equation-based methods can enter the design process either through use of generic amplification factors or through a site-specific assessment of site effects. The site-specific approach assigns a velocity profile and material properties representative of sediments beneath a specific facility. The generic amplification-factor approach considers the typical (median and uncertainty) site response for a variety of velocity profiles and material properties that are representative of a particular site category for a particular site classification scheme. Figure 9 and section 2.1.4.5 described one such generic approach. The seismic design of major infrastructure projects (e.g. highway bridges, major buildings, dams and power plants) typically employs the site-specific approach to assessment of site effects. However, seismic hazard maps used for planning and preliminary project design are based on either generic amplification factors or use various attenuation models based on site classification.

Data about subsurface conditions are needed for some site classification schemes and all analytically based site amplification calculations. Only the direct empirical attenuation approach does not require subsurface data if the classification scheme relies on visual and/or surface geology characteristics. Subsurface data needed for all other site effects assessments are developed through a combination of geological, geotechnical and geophysical exploration techniques. Geological and geotechnical programs typically involve drilling and logging of exploratory boreholes, performing various in-situ tests, and obtaining samples for subsequent laboratory testing. Geophysical testing is frequently performed within an exploratory borehole, but some effective surface-based techniques are available. Site-specific calculations of site effects use information local to the site, while increasingly generic approaches (e.g. surface geology or "rock vs. soil") use broader averages of information.

This section outlines PEER-LL efforts to develop, synthesize, and disseminate basic subsurface characterization information that address key data gaps needed to improve ground motion hazard planning and design procedures.

4.1 Characterization of SMR Sites ***(Collaborations w/ USGS, SCEC, NCREE, Kajima Corp., NSF)***

Accurate assessment of geotechnical site effects hinges on the availability of high-quality subsurface data. However, there remain very significant data gaps in subsurface information at strong-motion recording (SMR) sites, the data from which form the basis for all ground-motion estimation procedures. Over 1700 sites are in the current NGA database, but only a small fraction (less than 20%) of these have been thoroughly characterized. Approximately half of the sites investigated had been previously misclassified using one or more schemes used for assessment of site effects. Where data is absent, correlations and extrapolations need to be employed, resulting in possible misclassification and unnecessary scatter and bias in attenuation relationships used for design.

I4.1.1 Technical Issues and Goals

Comprehensive subsurface characterization of SMR sites is costly, so program planning must be selective in scoping the tasks to be performed so as to optimize benefits for design applications. Drilling and sampling costs typically comprise the largest single expense, with unit costs increasing at greater borehole depths. An often overlooked and sometimes significant component of the cost is the time needed to coordinate permits and the effort required for disposal of drill cuttings and site restoration. Laboratory testing to determine non-linear material properties of sediment samples is also very expensive. Therefore, these tests are performed on only a very limited number of samples that must be carefully selected to be representative of site conditions. The remaining costs of site characterization involve geological, geotechnical, and geophysical logging, the performance of routine index tests on soil samples, and miscellaneous costs associated with information synthesis and dissemination.

The technical goals of the overall SMR site characterization program are varied and continue to evolve. The recent PEER-LL activity in the area of SMR site characterization is largely an outgrowth and significant extension of the earlier ROSRINE program [27]. The initial phases of the ROSRINE program focused on thoroughly characterizing several key near-field recording sites from the 1994 Northridge earthquake. Borings were typically drilled to 100-m or more, soil samples were collected for non-linear material properties testing, and multiple geophysical testing methods were used on many of the sites. This program emphasized thoroughness over quantity of sites and provided key data needed to test the efficacy of alternative geophysical logging techniques, and established typical velocity profiles and material properties for analysis of site response effects from Northridge recordings. As part of the emphasis on thoroughness, the ROSRINE program adopted the 100-m target characterization depth for soil sites to provide a basis for meaningful analysis of site effects to periods beyond 1 second. The sample collection and laboratory-testing program for non-linear properties was focused on extending existing design models for application to larger strains and greater depths as discussed in section 4.2.

As the program has evolved, the technical goals have increasingly stressed cost-effectiveness as a means to extend the breadth of site coverage. Surface-wave testing methods have been adopted to eliminate drilling costs, but are more limited in depth range and provide no samples for strata logging or materials testing. Limited drilling programs have been pursued where deeper velocity profiles or samples were needed. The objectives of these less-extensive characterization efforts were to develop data needed to both clarify the classification of sites having anomalous motions and to enhance site-classification correlations to regional mapped quantities such as surface geology. Emphasis was placed on coverage of broader ranges of site types and new regions having limited data availability. For example, data for “rock” sites (that typically have a soil layer on top) is quite sparse, and critical new recordings in Turkey and Taiwan were classified using local schemes for which little velocity profile data was available. Improved correlations developed as a result of these new investigations have reduced the number of misclassified sites used in the development of NGA attenuation relationships.

4.1.2 Program Approach

Because of the high cost of site characterization, initiatives in this area have sought to leverage related activities through partnerships and use of “holes of opportunity” as they arise. Since its inception, the ROSRINE project has worked closely with related and sustained efforts by the USGS. ROSRINE also worked in collaboration with SCEC’s borehole initiative that installed downhole and surface SMR pairs at key reference sites around the Los Angeles region. Very deep 300-meter monitoring wells drilled by the Los Angeles Water Reclamation District are excellent examples of “holes of opportunity” that provided tremendous new geophysical data sets at no added drilling cost.

More recent partnerships include: 1) a collaboration with Kajima Corporation of Japan to share results from characterization of a US SMR site, 2) a project co-funded with NSF to characterize SMR and aftershock sites that recorded the 1999 M7.4 Kocaeli and M7.1 Duzce earthquakes in Turkey, and 3) two joint projects with NCREE of Taiwan to characterize sites that recorded the 1999 M7.6 Chi Chi earthquake.

4.1.3 Research Team (alphabetical order)

PI’s:	Bob Nigbor, Ellen Rathje, Ken Stokoe
Co-PI’s:	Ali Asghari, Leo Brown, Ming-Hung Chen, Ding-Shing Cheng, John Diehl, Jim Gibbs, Shin-Kae Huang, Jagrut Jathal, Yin-Cheng Lin, Sheng-Huoo (Tony) Ni, Dan Ponti, Brent Rosenblad, Rob Steller, Jennifer Swift, John Tinsley
Review:	Don Anderson, Dave Boore, Roger Borcherdt, Brian Chiou, Mustafa Erdik, Ugar Kuran, Chin-Hsiung Loh, I.M. Idriss, Ron Porcella, Bob Pyke, Cliff Roblee, John Schneider, Walt Silva, Jon Stewart, Kuo-Liang Wen, Chris Wills

4.1.4 Selected Accomplishments

The primary accomplishment of the site characterization research team has been a significant expansion of the fundamental knowledge base for key SMR sites. Table 6 summarizes specific data-collection achievements under both the ROSRINE and PEER-LL partnered projects. Together, these projects will have generated subsurface velocity profiles for 104 sites in the US [27, 28], 17 sites in Turkey [29], and 59 sites in Taiwan [30, 31]. Additionally, the collaboration with NCREE has led to common site characterization standards, and has provided researchers early access to data for over 150 additional sites in Taiwan [31].

Detailed site characterization data from the ROSRINE program is posted on a publicly accessible web site (http://geoinfo.usc.edu/rosrine/) [32] as illustrated in Fig. 17. More recent SASW data from US sites have also been added to the ROSRINE web site. Figure 18 illustrates how individual

Table 6 - Summary of ROSRINE and PEER-LL SMR Site Characterization Data

Program	No. & Type of Sites	Location
ROSRINE [27]		
- CSMIP Deep Arrays	2 Multi-Borehole SMR Arrays	I-10 Los Angeles & I-8 El Centro, CA
- CSMIP Shallow Array	1 Downhole-Surface SMR Pair	Tarzana Site in Los Angeles, CA
- SCEC/UCSB Arrays	5 Downhole-Surface SMR Pairs	Greater Los Angeles Region, CA
- LAWRD/USGS	3 Very Deep Boreholes	Central Los Angeles Basin, CA
- ROS-Northridge	11 Boreholes at SMR Sites	Los Angeles (Northridge Region), CA
- ROS-USGS Northridge	18 Boreholes at SMR Sites	Los Angeles (Northridge Region), CA
- ROS-Kajima Holes	13 Boreholes at SMR Sites	Various Regions in N. and S. CA
- Potrero Special Study	2 Boreholes at Aftershock Sites	Potrero Valley N. of Los Angeles, CA
PEER-LL 2C01 [28]		
- Imperial Valley Sites	30 SASW Profiles at SMR Sites	Greater Imperial Valley Region, CA
- Los Angeles Sites	19 SASW Profiles at SMR Sites	Greater Los Angeles Region, CA
PEER-LL 2A02a [29]		
- Permanent Sites	12 SASW Profiles at SMR Sites	Kocaeli EQ in Izmit, Turkey
- Lamont Temp. Sites	5 SASW Profiles at Aftershock Sites	Duzce EQ West of Izmit Bay, Turkey
PEER-LL 2A02c [30]		
- UT Testing	~26 SASW Profiles at SMR Sites	Chi Chi EQ Region in Central Taiwan
- NCKU Testing	~15 SASW Profiles at SMR Sites	tbd, Taiwan
- CCIT Testing	~15 SASW Profiles at SMR Sites	tbd, Taiwan
PEER-LL 2A02d [31]		
- 2000 NCREE	29 Boreholes w/ Vs Log at SMR Sites	Taipei and Ilan Regions, Taiwan
- 2001 NCREE	75 Boreholes w/ Vs Log at SMR Sites	Ilan and Chia Yi Regions, Taiwan
- 2002 NCREE	48 Boreholes w/ Vs Log at SMR Sites	24 near Chi Chi EQ Region, Taiwan
- 2002 Enhancement	3 Deep Boreholes at SMR Sites	Chi Chi EQ Region, Taiwan

profiles can be synthesized to develop region-specific or surface-geology-specific representative velocity models. These models are used to extend results from a limited number of well-characterized sites to a much broader range of uncharacterized sites on the basis of site classification parameters. Researchers use these generalized models to develop site amplification functions, and design engineers can use either the site-specific data or generalized models to guide judgment regarding typical profiles and test results. ROSRINE and related data were used in the development of generalized velocity models for various geologic units in the Los Angeles region that were, in turn, used by SCEC to update the near-surface portion of their "community 3-D velocity model" used for ground-motion simulations. Preliminary

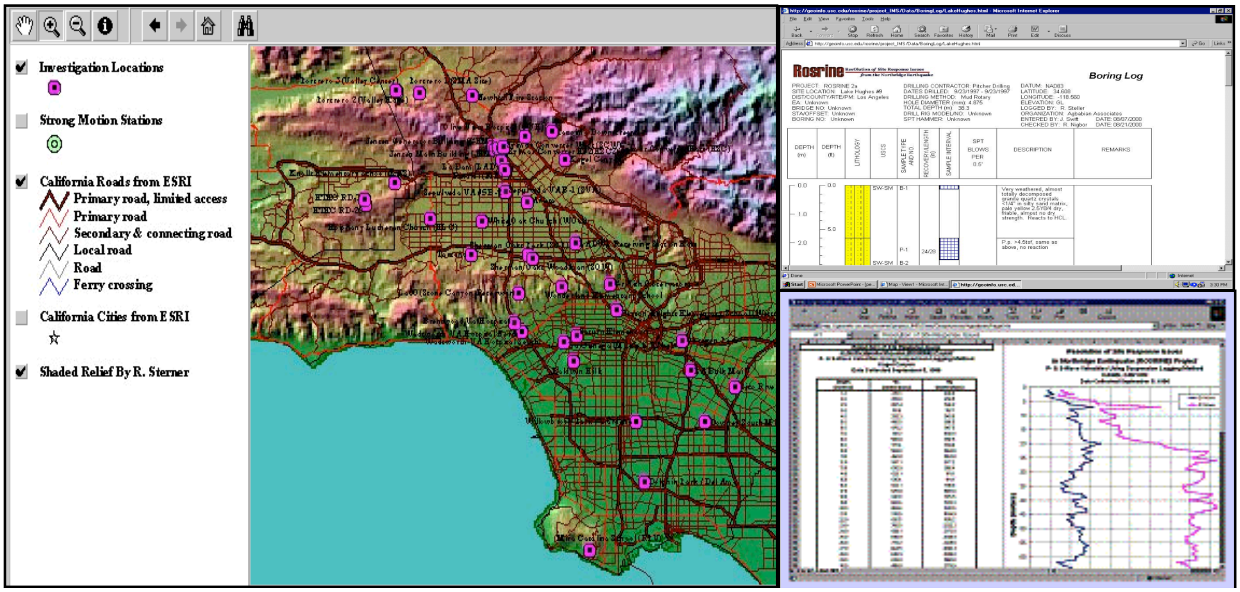


Figure 17. Illustration of ROSRINE GIS-based web interface and sample data logs used for dissemination of geotechnical site characterization data. (Nigbor et. al., 2001 [32])

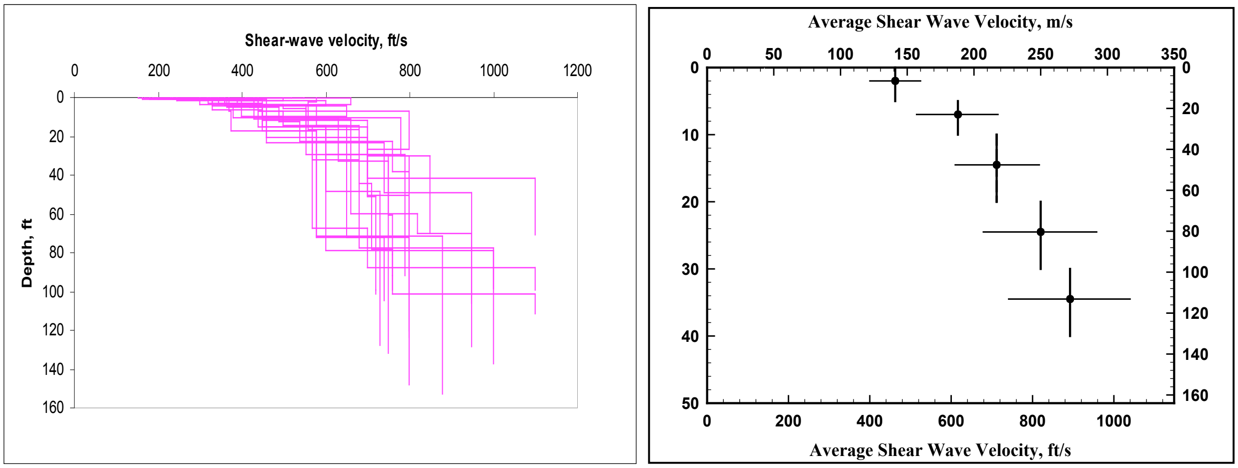


Figure 18. Individual SASW shear-wave velocity profiles (left) and composite averages with standard deviation (right) for Imperial Valley sediments. (Stokoe et. al., 2003 [28])

results from the SASW testing program in Taiwan suggest that the classification system used there may be biased toward lower site categories relative to systems used in the US.

A parallel research thrust, emphasized during the early phases of the site characterization programs, has been an effort to systematically investigate alternative geophysical testing techniques. The techniques most commonly employed in boreholes are the ‘PS-logging’ and the ‘downhole’ methods, while the ‘SASW’ method is a popular surface-wave technique that does not require boreholes. Each of the techniques has its proponents, and a systematic program was needed to objectively identify strengths and critical limitations of each approach. Multiple methods were employed for a selection of sites tested in each program initiative. Figure 19 presents example results [33] from the La Cienega array site where the most extensive comparisons were made. Figure 20 presents example results for 14 sites where both PS-logging and downhole testing was performed. Additional comparisons have been between the SASW tests and the borehole methods and for other phases of the testing programs.

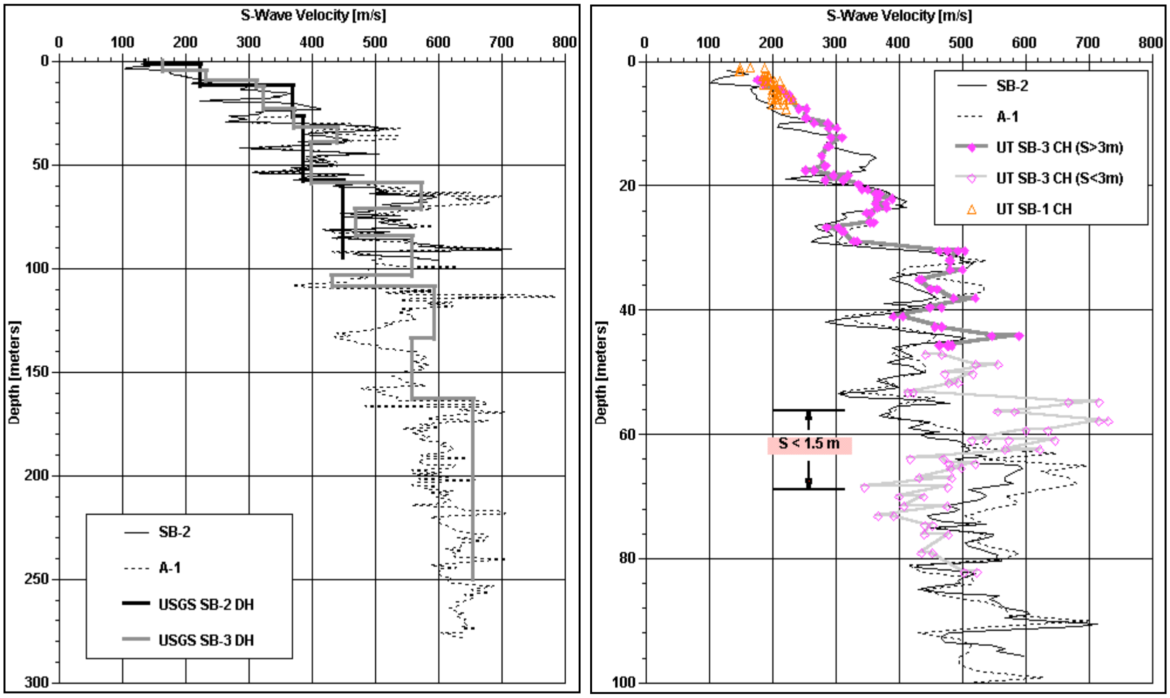


Figure 19. Comparison of Vs profiles obtained at the I-10 La Cienega Array site in Los Angeles using alternative geophysical techniques including PS-logging, downhole, and crosshole techniques. (Owen and Roblee, 2000 [33])

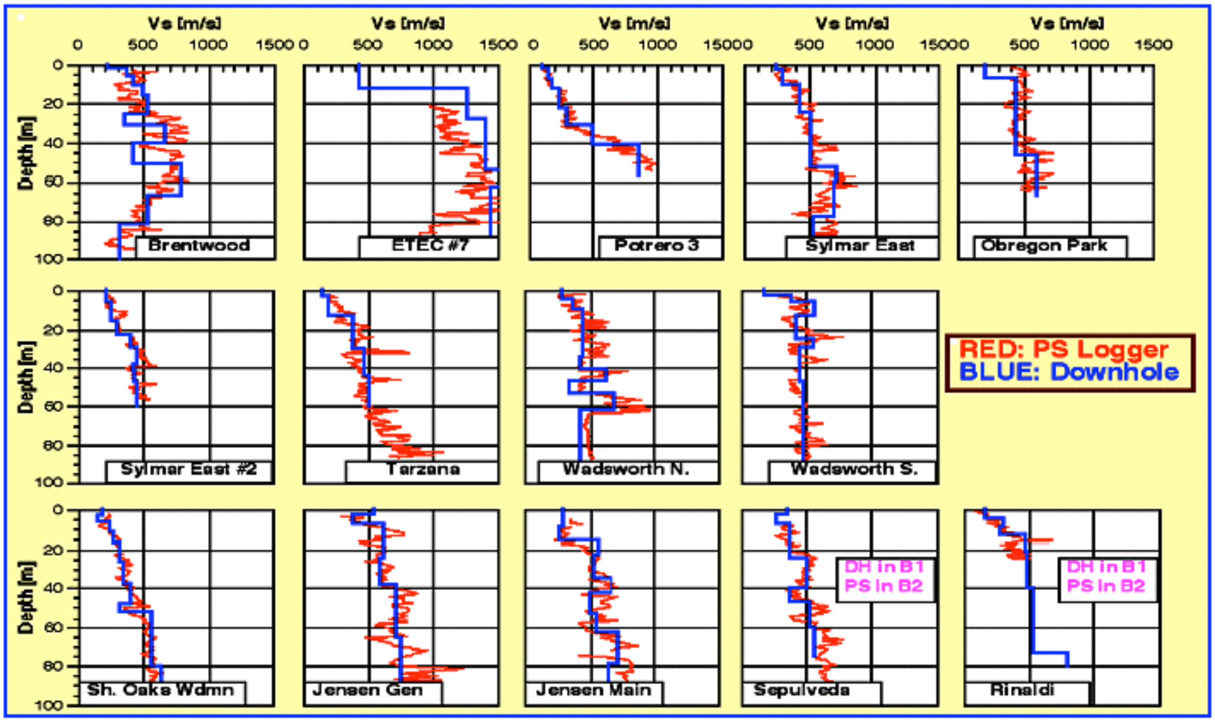


Figure 20. Comparison of Vs profiles independently obtained using PS-logging and downhole techniques at 14 Northridge SMR sites. (Roblee, 2002 [34])

Overall, all three methods described here were found to provide reasonably consistent results that are wholly sufficient for design applications. Particular strengths and limitations are summarized in Table 7. An alternative surface wave technique, called the CXW method that has been applied to many SMR sites throughout the Los Angeles region, was found to have an unacceptable bias beyond a depth of approximately 10 meters. Another geophysical method comparison utilizing data from the Turkey site investigations is illustrated in Fig. 21. Here, the SASW surface-wave method is compared with results

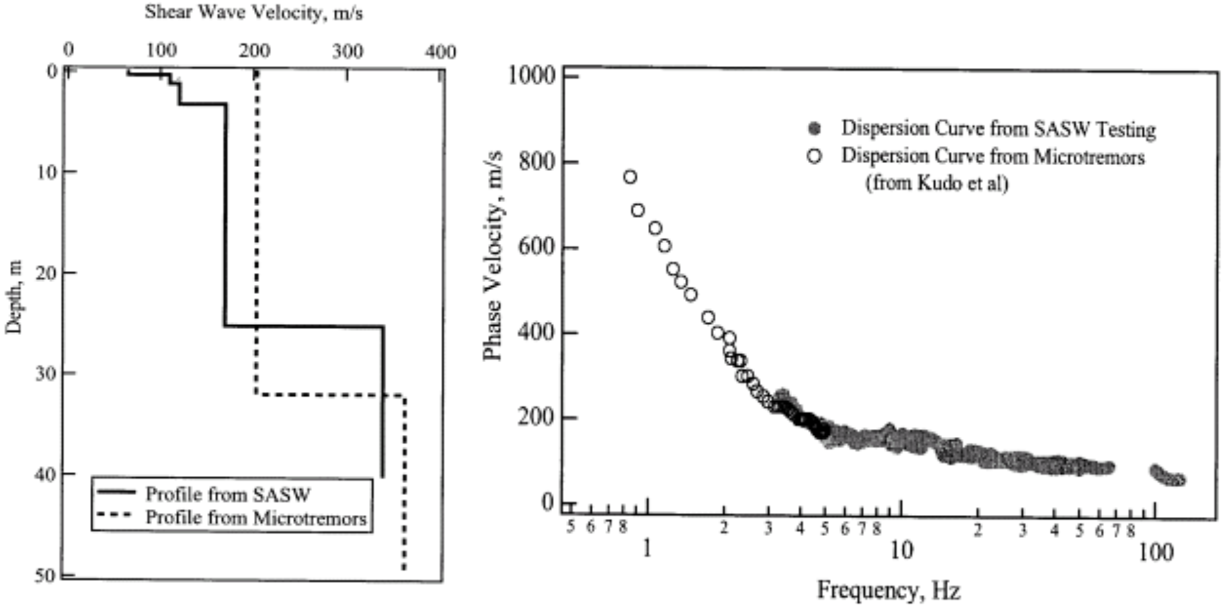


Figure 21 Example comparison of near-surface Vs profiles and dispersion curves from SASW and microtremor array testing at the Ambarli, Turkey site. (Rosenblad et. al, 2001 [29])

obtained by Kudo et. al. (2001) [35] using an 'array microtremor inversion' technique. Like SASW, the array microtremor approach is also a surface-wave technique. However, where the SASW uses two receivers and an active surface source, the microtremor array technique deploys multiple receivers in a wide array to passively record microtremors as a source. The microtremor approach appears to offer capability to develop profiles to much greater depths than the SASW technique, while the SASW technique offers higher profile resolution near surface. These limited comparisons point toward a possible hybrid surface-wave approach that might provide excellent depth range without the need for boreholes. Additional research is needed to fully evaluate the potential of this approach.

Table 7 - Comparison of Alternative Geophysical Techniques Used for Velocity Profiling

PS Suspension Logging (Uncased Fluid-Filled Borehole)

- Good Agreement w/ Other Methods, But Better Resolution
- Measured Local Variability Is Repeatable (… w/ Good Data!)
- Problems with Fractured Rock, Steel Casing, and V. Near Surface
- Poor P-Wave Data Above GWT

Downhole Logging (Cased Borehole)

- Reliable Average Velocities to Large Depth (… w/ Good Data!)
- Better than PS for P-Wave Data Above GWT
- Problems Very Near Surface

SASW Profiling (Surface-Wave Technique, No Boreholes)

- Very High Resolution Very Near Surface (… w/ Good Data!)
- Resolution Decreases w/ Depth .. OK for EQ
- Problems with ID Bottom of Reliable Inversion (w/o GWT info)

4.2 Laboratory Testing for Non-Linear Material Properties *(Collaborations w/ Kajima Corp., NSF)*

In addition to the velocity profile, the other essential input required for quantitative analysis of geotechnical site effects is a non-linear material model for the sediments. The most common of these models involve families of two strain-dependent parameters: modulus reduction (G/G_{max}) and hysteretic damping (D) that are commonly presented as curves on a semi-log plot. Two alternative models developed in the early 1990's that are commonly used in design are shown in Fig. 22. These models are derived from statistical analysis of results from sophisticated, and expensive, laboratory tests on soil samples. Unfortunately, only a very limited data set of (a few hundred) lab-test results have been available for model development. This data set is insufficient to clearly separate trends with standard geotechnical parameters such as depth, soil plasticity, and grain size.

4.2.1 Technical Issues and Goals

Prior to the ROSRINE and PEER-LL programs, non-linear material models were based on a limited set of test results for samples taken from relatively shallow depths (say 10-20 m). Fundamental research on reconstituted soils identified the need for a stress-dependent (or depth-dependent) model, but there was insufficient laboratory data to adequately constrain such a model. Furthermore, test results that were available extended over only a limited strain range, so models had to be extrapolated to higher strain for use in design. New data were needed to constrain material behavior at high stress and over wide strain ranges. New unified models were needed to merge these new constraints with existing knowledge, and more clearly track uncertainties.

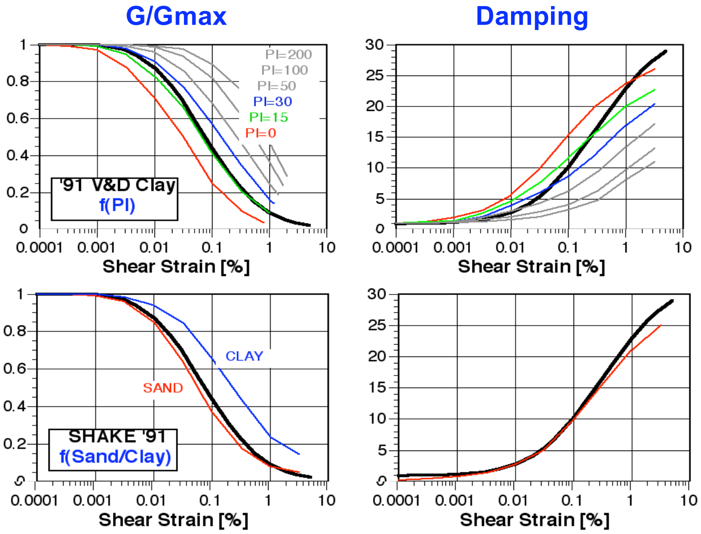


Figure 22. Example non-linear material models for site response analysis. (Roblee, 2002 [34])

Finally, a perennial problem within the geotechnical field is the issue of sample “disturbance”. Removal of a soil sample from its in situ environment can involve large reductions in stress and variable levels of strain. The stress reduction is associated with bringing the sample to the surface after it had been under the load of the overlying soil. Larger stress reductions are associated with greater sampling depths. The mechanical process of sampling itself imparts a significant strain field on the soil sample. Various techniques using thin-walled samplers and over-coring can reduce this impact. These combined effects of stress and strain caused by the sampling process are known to lead to irreversible changes in material behavior. The extent to which these changes are significant remains an open issue. A goal of the material-model program was to shed light on this issue to the extent possible.

4.2.2 Program Approach

The laboratory-testing program has been closely linked to the ROSRINE (drilling) component of the SMR site characterization program described in section 4.1. Samples for testing were acquired exclusively at US SMR sites. Don Anderson of CH2Mhill of Seattle [36] coordinated the lab-testing program, and all lab tests were performed under the guidance of either Ken Stokoe at the University of Texas (UT) [37] or Mladen Vucetic at the University of California at Los Angeles (UCLA) [38]. This testing program involved partnerships with both NSF and Kajima Corp. of Japan. Kajima contributed test results from the UT and UCLA labs for samples taken from six US SMR sites. NSF was a major sponsor of the 1st phase of the ROSRINE program, and sponsored a research workshop to review new models and remaining issues pertaining to laboratory testing for non-linear material models. UT and UCLA have also contributed additional test results for development of new material models.

The technical strategy adopted by the program was to use only natural field samples in testing as there are questions regarding the ability of reconstituted samples to replicate field behavior. Next, the unique capabilities of two testing labs, UT’s and UCLA’s, was used to extend the range of data to cover design needs. The UT lab makes use of resonant-column/torsional shear (RC/TS) equipment that has been configured for application to very high pressures. This allowed field stresses to be replicated in the lab for samples acquired at depths of as much as 300 meters, thus providing constraints on depth-dependent models. The RC/TS device is capable of measuring properties for strains ranging from <0.0001% to around 0.1%. Strain measurements below approximately 0.001% are required to establish the value of elastic stiffness (G_{max}) that is used to normalize the modulus reduction curve. The high end of the measurable strain range is below that needed for design. While reasonable extrapolations have been made in the past, the program sought new constraints at high strain. The UCLA lab recently developed a dual-specimen direct simple shear device (DSDSS) that has unique capabilities to test specimens over the strain range of <0.001% to over 3%, thus allowing non-linear models to be extended for a full range of design applications. Finally, the use of two labs also allowed independent tests to be performed on a subset of samples to check the overall consistency of lab testing.

4.2.3 Research Team (alphabetical order)

PI’s:	Don Anderson, Ellen Rathje, Ken Stokoe, Mladen Vucetic
Co-PI’s:	Mehmet Darendelli, Macan Doroudian, Chu-Chung Hsu, Farn-Yuh Menq, Kentaro Tabata
Review:	I.M. Idriss, Bob Pyke, Mike Riemer, Cliff Roblee, Walt Silva, Jon Stewart, and DESM Workshop participants.

4.2.4 Selected Accomplishments

Similar to the SMR site characterization program, the primary accomplishment of the lab-testing program has been a major expansion and extension of the fundamental database used to develop material properties models. As presented in Table 8, the expansion includes new test results for 126 samples taken from 22 SMR locations and 2 deep vertical SMR arrays. Results were obtained from 48 coarse-grained soils and 78 fine-grained samples having plasticity index values ranging from 0 to 46. The extension toward greater confining stress includes results for 44 samples taken at depths greater than 30 meters including 11 samples taken from depths beyond 100 meters. The extension toward greater strain is provided through 48 DSDSS tests. These test results have been made publicly available on the ROSRINE web site.

The new data created under this testing program have been used in combination with additional data sources to develop new engineering models for non-linear material behavior. The new models can be used directly in equivalent-linear site response analyses or as constraints for more complex non-linear

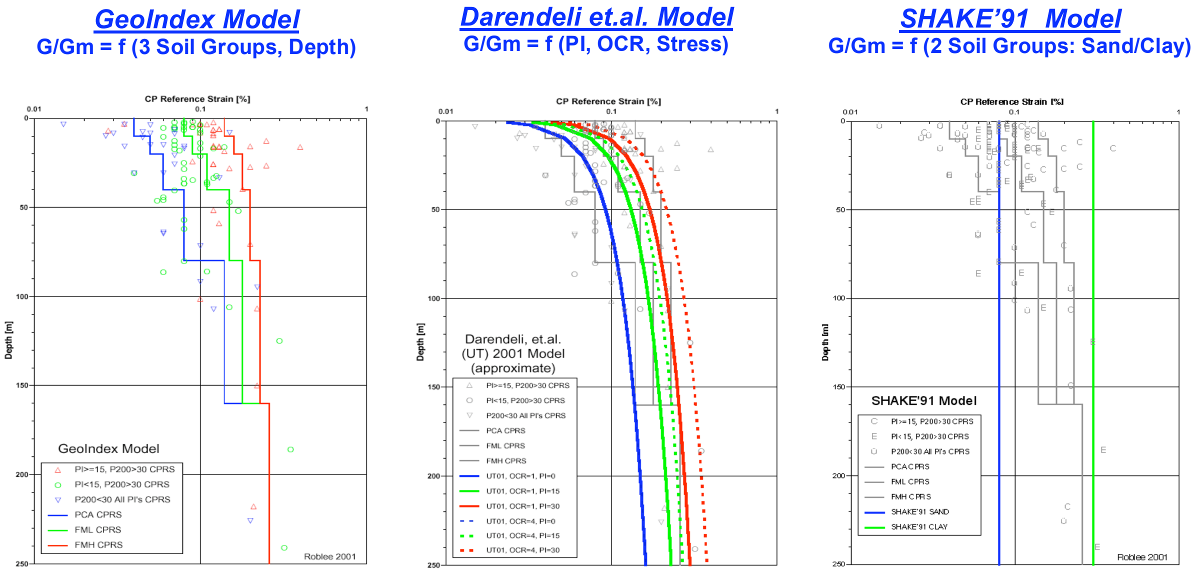
Table 8 - Summary of ROSRINE & PEER-LL Lab Test Data for Non-Linear Material Properties

Program and Sites	RC/TS Tests at UT	DSDSS Tests at UCLA
ROSRINE, Phases 1&2	Total Samples Tested = 42	Total Samples Tested = 25
- 11 Northridge EQ SMR Sites	D = 92 m, C=14, F=11	D = 17 m, C=4, F=14
- I-10 La Cienega Deep SMR Array	D = 240 m, C=4, F=9	D = 8 m, C=0, F=3
- Laval Samples at La Cienega	D = 8 m, C=1, F=3	D = 34 m, C=2, F=2
ROSRINE, Phase 5a (by Kajima)	Total Samples Tested = 11	Total Samples Tested = 8
- 6 CA SMR Sites	D = 102 m, C=8, F=3	D = 69 m, C=5, F=3
PEER-LL 2B01/02 [36]	Total Samples Tested = 25	Total Samples Tested = 15
- 5 CA SMR Sites	D = 52 m, C=7, F=11	D = 29 m, C=2, F=9
- I-8 Meloland Deep SMR Array	D = 134 m, C=0, F=7	D = 31 m, C=0, F=4

D = Maximum Sample Depth, F= # of Fine-Grained Samples, C = # of Coarse-Grained Samples

material models. These models clearly identify a depth (or stress) dependency of G/G_{max}. The two left-hand charts in Fig. 23 illustrate how two new alternative material models account for depth dependency relative to the new data. The right-hand chart shows how an earlier depth-independent model, which was developed from tests on shallow samples, does not account for behavior of deep sediments. Whereas the older models should only be applied to site profiles ranging from 15 to 80 meters, the new models can be applied to depths beyond 200 meters, which is sufficient to cover the full range of depths for which non-linear material behavior thought to be important.

Another insight derived from the lab data is an improved understanding of how sample disturbance may affect laboratory-measured material behavior. Nicola Chiara [39] made a systematic comparison using international data sets of the ratio of low-strain stiffness measured in the lab to that measured in the field using geophysical techniques. This ratio was expressed in terms of shear-modulus ratio ($G_{m,\ lab}$ / $G_{m,\ field}$). Ratio values close to unity are inferred to reflect low levels of sample disturbance, while lower values are indicative of higher levels of disturbance. The data were examined for trends with respect to sampling technique, depth of sampling, soil type, and soil stiffness as well as other parameters. Higher quality sampling techniques were found to produce higher ratio values. However, the most revealing finding, illustrated in Fig. 24, is that stiffer soils, as reflected by field modulus, typically had lower ratio values regardless of whether the sample was obtained at great depth or near the surface. This observation is interpreted to indicate that stiffer soils are "de-structured" by the sampling process more than softer soils. This may be associated with breakage of weak cements and rearrangement of inter-particle contacts caused by the strain field imposed by sampling. Regardless of the cause, the key issue is how to adjust material models to account for these effects. Alternative correction schemes have been


GeoIndex Model
G/Gm = f (3 Soil Groups, Depth)

Darendeli et.al. Model
G/Gm = f (PI, OCR, Stress)

SHAKE'91 Model
G/Gm = f (2 Soil Groups: Sand/Clay)

Figure 23. Alternative new models (left, center) that account for depth-dependency of non-linear material properties and an older depth-independent model (right). (Roblee, 2002 [34])

proposed, and the seismological modeling has been applied to investigate the issue from a complementary perspective.

Finally, comparisons between RC/TS and DSDSS results were performed on several split samples to establish any systematic differences between devices. These results show that normalized modulus (G/G_{max}) and damping (D) results from the two devices are comparable. However, the absolute modulus (G) measurements differ by as much as a factor of two (even when corrected to a common mean stress), with the DSDSS device invariably yielding the smaller value. This finding may be indicative of additional sample disturbance associated with strains caused by seating of the samples against the lateral restraining system. Overall, any bias in G/G_{max} or D data between the two devices appears to be small relative to inherent variability of properties.

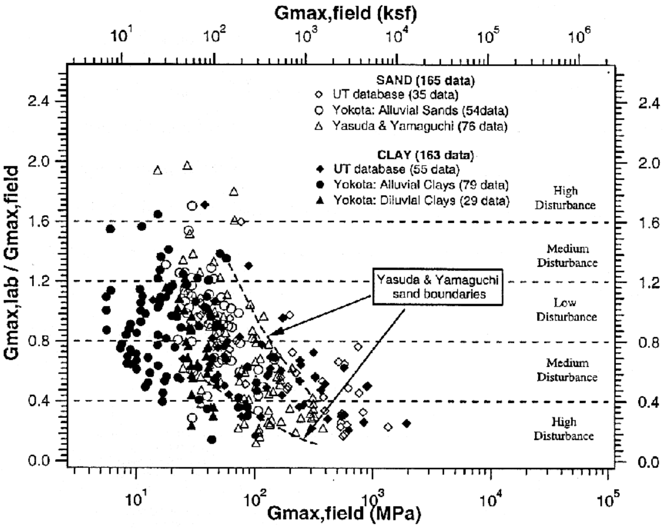


Figure 24. Soil disturbance as inferred by ratio of lab-to-field low-strain shear modulus. (Chiara, 2001 [39])

4.3 Geotechnical Virtual Data Center

(Collaborations w/ CGS, USGS, POSC, Caltrans, PG&E)

Tremendous amounts of geotechnical exploratory data have been, and continue to be, generated for characterization of subsurface conditions and materials. For example, data sets for the Los Angeles region used by CGS for seismic hazard mapping exceed 12,500 borings. Hundreds of new borings are generated statewide each year by Caltrans alone. Other sources of data include a variety of state and federal agencies as well as private consulting firms.

These data sets have tremendous untapped potential for project designers, especially for early site reconnaissance phases of project development. Information from nearby borings can be used to establish general subsurface conditions and identify problematic strata that could affect the new project site. Having this information a priori can help to tailor a drilling program to assure good coverage of problematic zones or layers. This, in turn, will lead to better subsurface characterization with fewer surprises and reduced drilling costs. Each boring that does not need to be drilled results in a savings on the order of several thousands to tens of thousands of dollars.

Access is the primary impediment to realizing the full potential of utilizing available subsurface data. The major barriers to access are: 1) simple lack of knowledge regarding data availability, 2) differing and incompatible methods, both paper and electronic, for archiving the data, and 3) institutional barriers that restrict the sharing and dissemination of data.

4.3.1 Technical Issues and Goals

Emerging information technologies are now making it possible to overcome key data-access barriers using the concept of a “virtual data center” (VDC). A VDC allows multiple data providers to make their data available through a uniform web interface, while each provider retains possession and control of the data itself. Figure 25 illustrates the general intent of the VDC [40], which is to provide a data user with access to information from multiple organizations through a single web resource, and to be able to view and/or download data from each organization in a uniform file format. For example, a VDC user at PG&E might wish to access and download boring logs being held at CGS, USGS, and Caltrans that are near to a new PG&E project site.

Technologically, the VDC itself is essentially a GIS-based web interface coupled with a database, data translators, and data harvesters. The VDC database does not contain the actual boring logs, but rather serves as an index or catalog to available data from participating data providers, with descriptive information about the borehole (e.g. date drilled, total depth, types of test information available, etc.). The GIS map interface allows the user to effectively search the database by location or a specified region of interest. Additional search criteria would be used to narrow the data selection (e.g. only boreholes with

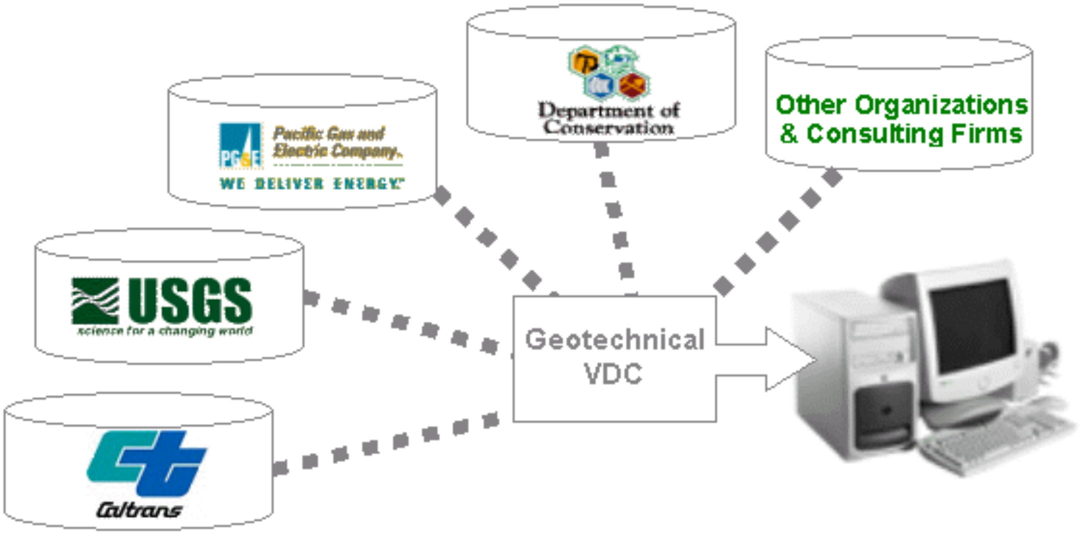


Figure 25. General concept for a geotechnical virtual data center for cross-institutional sharing of subsurface characterization and laboratory testing data (Swift, 2003 [40])

SPT data that are more than 10-m deep). Once the desired data is identified, the VDC server would retrieve the data from the server of the appropriate agency and use its data translators to deliver the data to the end user in a standardized format.

To make a geotechnical VDC a reality, certain institutional and technical hurdles must be overcome. On the institutional side, organizations having an interest in sharing data must agree on a framework for coordination. This includes finding acceptable mechanisms to assure data provider's adequate control over their data and a mechanism to assure appropriate attribution to the source of the data served by the VDC. On the technical side, an IT system architecture needs to be specified, a standard data dictionary needs to be defined, standard file formats and protocols need to be developed, and data translators need to be written.

4.3.2 Program Approach

The PEER-LL program first recognized the merits of a standard system for electronic archive and exchange of geotechnical data through its experience with the ROSRINE web site. However, during subsequent efforts to coordinate results of other programs of field investigations, it proved difficult to identify a common format for data archive that met all organizations' needs. About the same time, an NSF-sponsored workshop on geotechnical data management, hosted by J.P. Bardet in April 1998 [41], provided a broader perspective that these same issues and interests were shared by a much wider variety of infrastructure owners including PEER-LL sponsors, CGS, USGS and others. The intent to jointly investigate feasibility and develop a pilot VDC for geotechnical data exchange had been established.

Execution of the VDC concept required both technical expertise and an intimate knowledge of the sensitivities of various data-provider and stakeholder organizations. The PEER-LL program selected COSMOS (Consortium of Organizations for Strong-Motion Observational Systems) to lead the VDC development effort. COSMOS is a non-profit organization that includes both CGS and USGS as founding organizations. Under the leadership of Carl Stepp, COSMOS had successfully coordinated a broad array of organizations to develop a similar VDC for exchange of strong-motion data. To lead the technical development, COSMOS subcontracted with Jennifer Swift of USC who has extensive experience with the development of the ROSRINE web site.

The approach adopted by COSMOS to move this collaborative VDC-development effort forward has been to hold a series of consensus-building workshops and to assign technical tasks to specific working groups. Special efforts have been made to build upon the experience of the Petroleum Organizations Standards Committee (POSC), the National Geotechnical Experimental Sites (NGES) program, the information technology component of the Network for Experimental Earthquake Simulation (NEESgrid), the Association of Geotechnical and Geoenvironmental Specialists (AGS), the American Society for Testing and Materials (ASTM), the Federal Highway Administration (FHWA), and recent initiatives of the US Army Corps of Engineers (USCOE) and various state Departments of Transportation (DOT's).

Three working groups have been established. The "User Scenario Work Group (USWG)" represents end user interests, the "Data Dictionary Work Group (DDWG)" addresses issues related to data specification, and the "Virtual Data Center Working Group (VDCWG)" addresses information technology issues. Working group chairs, key technical contributors, and sponsor/partner representatives serve on the organizing committee. Organizing committee members from Caltrans, CGS, PG&E, POSC and USGS are contributing a very significant portion of the technical work at no cost to the project. Other working group members include a wide variety of technical experts and stakeholders from government and industry who have provided needed input and review.

4.3.3 Research Team (alphabetical order)

PI's:	Carl Stepp, Jennifer Swift
Organizing:	Jean Benoit, John Bobbitt, Joe Futrelle, Paul Grimes, Dan Ponti, Chuck Real, Cliff Roblee, Woody Savage, Joseph Sun, Loren Turner
1-USWG:	Michael Brown, Dave Chambers, Craig Davis, John Diehl, Chris Hitchcock, Tom Holzer, Bob Nigbor, Stu Nishenko, Cliff Plumb, Mike Riemer, Jamie Steidl, John Tinsley, Diane Vaughn
2-DDWG:	Salvatore Corona, David Jang, Allen Marr, Terilee McGuire, Scott Shimel, David Towsey
3-VDCWG:	J.P. Bardet, Debra Bartling, Keith Farnsworth, Bob Moscovitz, Raghu Satyanarayana, Mindy Squibb, Scott Weaver

4.3.4 Selected Accomplishments

The project has two phases: 1) a completed feasibility study, and 2) the current development of a pilot VDC. The feasibility investigation culminated in a workshop [42] where user needs were discussed, alternative development case histories were presented, and both technical and institutional issues were examined. Workshop proceedings can be viewed at (http://geoinfo.usc.edu/gvdc/home.htm). The general conclusion of the workshop was that development of a geotechnical VDC is indeed timely and feasible from both technical and institutional perspectives. Key issues identified to move forward with a pilot VDC were a clearer definition of users and use scenarios, the need for a standard "data dictionary" and associated data structures, and an IT architecture that meet technical and institutional constraints. The three working groups described above were formed to address these needs.

The second phase of the project, recently completed, developed a pilot geotechnical VDC capable of serving selected data sets from CGS, USGS, Caltrans, and PG&E. The mixture of public and private entities participating in the pilot is thought to mirror the range of organizations that would ultimately serve as data providers and provide a realistic test case to assure that the functional requirements of the system can meet the expectations of diverse users.

The geotechnical VDC could be configured in many ways to handle diverse clients and data needs. The strategy adopted for the pilot system was to focus initial development on those data types and functionality features that would be of immediate use to practice, and to provide the VDC with the flexibility to expand with time. To capture a realistic picture of the needs of practice, an on-line user survey was developed by Loren Turner and Paul Grimes of Caltrans [43] with assistance from the USWG. The survey link was distributed through both research and practice channels nationwide, and approximately 200 responses were obtained from organizations in 38 states.

The survey results painted a relatively clear picture of initial user needs. Interestingly, the typical responder was a licensed professional that was relatively new to practice (2 to 5 years) and had an advanced education (Masters degree or above). These tech-savvy users wanted a simple web-based interface that allowed spatial searches by coordinates and/or street address; the ability to search and sort by additional criteria such as types of information available for a boring; both text and graphical preview functionality, a "shopping cart" approach to file selection; and downloadable files in common formats such as spreadsheets and text files. Fig. 26 shows example survey results for the types of information most frequently used by the respondents. Information such as this was used to guide initial priorities for the pilot VDC system that are listed in Table 9. Finally, the survey also provided insight into the level of detail that users wish to access for experimental data. Generally, users typically want access to "interpreted data" (derived quantities) and "primary data" (basic data in terms of engineering units), but are not as interested in "raw data" (transducer voltages).

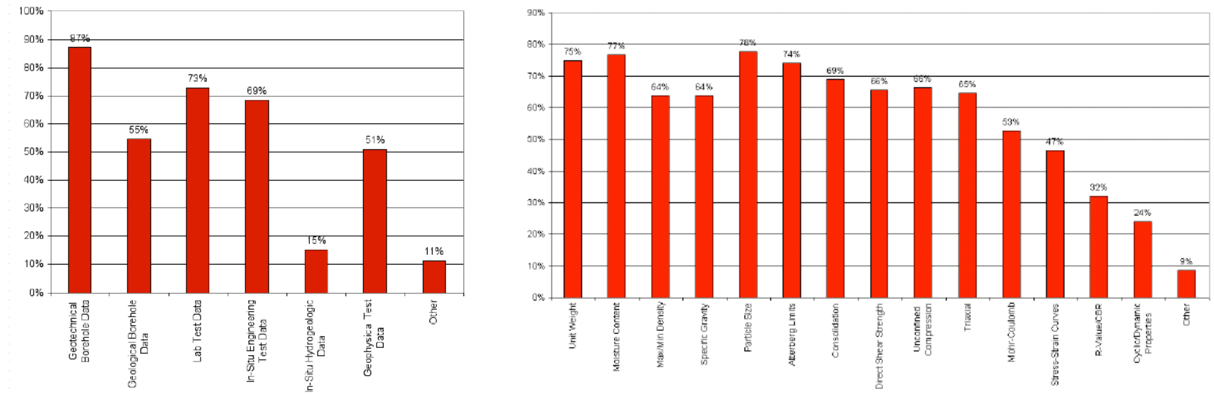


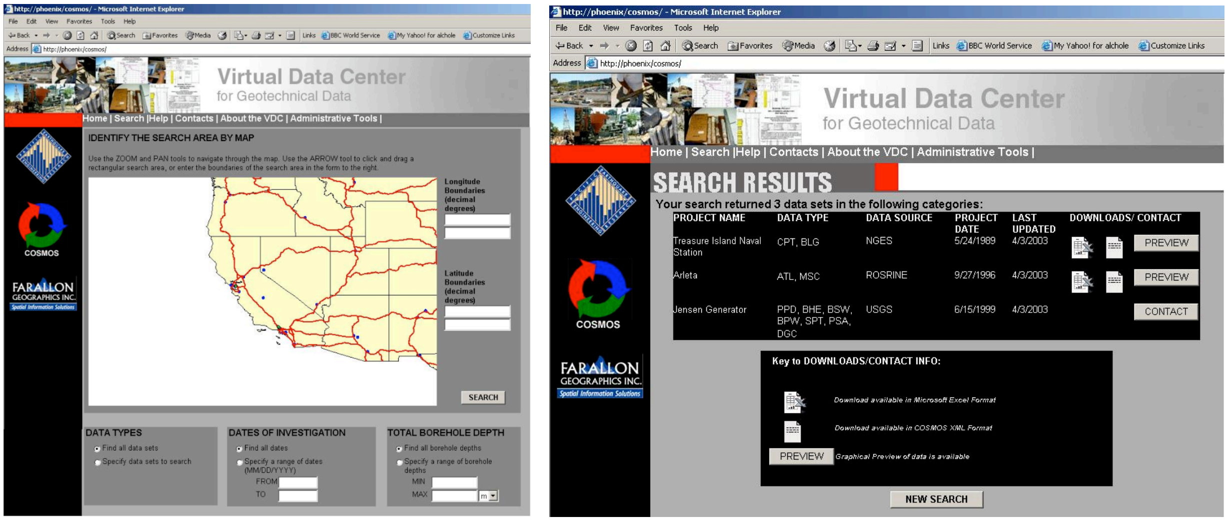
Figure 26. Example on-line user survey results for desired content of the geotechnical VDC. Results show percentage of respondents who use various types of boring log information (left) and laboratory test information (right). (Turner & Grimes, 2003 [43])

Establishment of the "data dictionary" and associated data structures are at the very core of the VDC concept and create its ability to deliver uniformly formatted data from a number of different providers. The data dictionary provides an unambiguous standard definition of each parameter needed to characterize a particular test result, and specifies the relationships between parameters. The data structures adopted for the geotechnical VDC are being written as "XML schema" which provides a very flexible and extensible file structure that is ideal for exchange of data between organizations having different archive formats. Development of the data dictionary and XML schema for the VDC is a complex task requiring expertise in both geosciences and information technology. This aspect of the project was led by three individuals: Jean Benoit of University of New Hampshire who was instrumental in developing the geotechnical data structures for the NGES database; John Bobbitt of POSC who has extensive experience in developing a similar system for the petroleum industry; and Dan Ponti of USGS-Menlo Park who has extensive geologic experience as well as detailed knowledge of electronic data exchange systems. Their development work is being reviewed by the larger DDWG.

Table 9 – Example Data Types Being Incorporated Into the Pilot Geotechnical VDC

Borehole Identification • Site Information (Project, Location, Owner, Purpose, Contacts, etc.) • Hole Information (ID, Driller, Logger, Datum, Location, Date Drilled, Total Depth, Surface Geology, etc)
Logging Information • Layer Information (Geologic Layers, Thickness, Classification System, Grain Size, Bedding, etc.) • Component Information (Features/Conditions Within or Crossing Layers) • Core Information (ID, Core Interval, Sampling Method, Recovery, etc.)
Sample Information • Specimen Information (Location within Core, Tests Performed, etc.)
Laboratory Test Results • Moisture Content & Atterberg Limits (Liquid/Plastic Limits, Methods) • Grain Size Distribution (Percent Passing, D_{10}, D_{50}, P_{200}, Uniformity, etc.)
Field Test Results • Standard Penetration Test (N-Value, Hammer Type, Efficiency, etc.) • Cone Penetration Test (Tip/Sleeve Resistance, Saturation Method, etc.)

The final, and most complex, component of the geotechnical VDC is the development of the information technology itself. Jennifer Swift from USC led this effort with special assistance provided by Joe Futrelle of the NEES consortium. There were several key components to the IT architecture developed: 1) the user interface for specifying data searches based on location and content, 2) a relational database containing the metadata for all borings served by the VDC, 3) data translators that convert data from the original source to the standard XML file format, and 4) administrative functions that



IDENTIFY THE SEARCH AREA BY MAP

Use the ZOOM and PAN tools to navigate through the map. Use the ARROW tool to click and drag a rectangular search area, or enter the boundaries of the search area in the form to the right.

DATA TYPES
● Find all data sets
○ Specify data sets to search

DATES OF INVESTIGATION
● Find all dates
○ Specify a range of dates (MM/DD/YYYY)
FROM
TO

TOTAL BOREHOLE DEPTH
● Find all borehole depths
○ Specify a range of borehole depths
MIN
MAX m

Your search returned 3 data sets in the following categories:

PROJECT NAME	DATA TYPE	DATA SOURCE	PROJECT DATE	LAST UPDATED	DOWNLOADS/ CONTACT
Treasure Island Naval Station	CPT, BLG	NGES	5/24/1989	4/3/2003	PREVIEW
Arleta	ATL, MSC	ROSRINE	9/27/1996	4/3/2003	PREVIEW
Jensen Generator	PPD, BHE, BSW, BPW, SPT, PSA, DGC	USGS	6/15/1999	4/3/2003	CONTACT

Key to DOWNLOADS/CONTACT INFO:

Download available in Microsoft Excel Format

Download available in COSMOS XML Format

PREVIEW *Graphical Preview of data is available*

Figure 27. Mock up of recommended functionality features of the geotechnical VDC web interface. (Turner, 2003 [44])

allow the data providers to interface with the VDC and control the data to be made available. Detailed treatment of these issues is discussed in Swift [40].

Figure 27 illustrates the user experience recommended by the USWG for the pilot geotechnical VDC [44]. A user would use a browser to access the VDC web site. A GIS interface, with standard pan and zoom features, would be used to select a search region. Additional search criteria ranging from simple (e.g. depth of borehole, dates of investigation) to complex (particular data types) would be used to narrow the search result. Based on these search criteria, the user would be presented with search results as a list of borings with descriptors indicating boring contents. The logs for any particular boring could be previewed using an on-the-fly graphics program, and the search further narrowed. The final list of desired logs would be downloadable in either text or spreadsheet formats.

Finally, it is worth noting that the potential impact of this pilot VDC project may be significantly greater than its immediate application for data exchange. The data dictionary will define all the parameters needed to provide a high-quality site characterization measurement. Although some of these data fields may not be available for legacy data, the contents of the data dictionary are expected to set a de facto standard for future high-quality site investigations. This, in turn, will help to raise the standard of practice for a process where data quality is known to vary widely. Furthermore, the development of a standard interchange format is expected to facilitate software and technology advancements both for the display of data and for on-site electronic data entry. These advancements will have a lasting impact on the geotechnical field that will serve to streamline and standardize site characterization procedures.

5.0 IMPROVED MODELS FOR GROUND DEFORMATION HAZARD ESTIMATION

Ground failure mechanisms include fault surface rupture, liquefaction, and earthquake-induced landslides. Fault surface rupture can result in large relative displacements of the ground surface across the fault. These displacements are largely a function of magnitude and can be as large as 5 to 10 meters for a large magnitude event. Liquefaction is the phenomena whereby saturated sediments soften due to pore-pressure buildup caused by shaking-induced strains. Foundations bearing in liquefied soils will experience a dramatic loss of capacity. Liquefaction also causes settlement of the ground surface that can severely distress at-grade facilities. Notably, liquefied ground can also displace laterally large distances on very gentle slopes, a phenomenon known as "lateral spread". This lateral ground movement can impose large loads on buried facilities such as bridge foundations and utility pipelines. Quantitative modeling of the load-transfer mechanism of displacing liquefied ground is an important element of a class of problems called "soil-foundation-structure interaction (SFSI)". Lastly, earthquake shaking can trigger any of a number of landslide types ranging from rockslides to earth flows. Though important, earthquake-induced landslide hazards have not been addressed in the PEER-LL program. This section presents

PEER-LL efforts to develop improved tools for prediction of fault surface rupture and various liquefaction-related phenomena.

5.1 Fault Surface Rupture Model *(Collaborations w/ USGS, CGS)*

Ground offsets caused by fault surface rupture can cause collapse of bridges or rupture of pipelines. This behavior has been demonstrated repeatedly in recent earthquakes in Turkey and Taiwan. To address this critical issue, new displacement-tolerant design strategies and details are being developed. However, effective use of these new strategies also requires development of improved seismological tools for estimating design values of fault offset.

5.1.1 Technical Issues and Goals

Conventional methods for estimating fault surface rupture offset primarily involve correlations between magnitude and offset. Median offset along with statistical uncertainty is provided, but no information is provided regarding the likely width over which the offset is likely to occur relative to the mapped fault. Furthermore, conventional methods fail to address these additional issues: (1) variations of offset that occur along the fault strike, (2) errors in mapping of the primary fault trace, (3) additional distributed offsets that occur on adjacent secondary faults, or (4) lack of a systematic process to account for increased risk of crossing an offset as the facility footprint size becomes larger.

The research objective of the Fault Surface Rupture Model is to develop a design-oriented estimation tool that addresses each of the issues described above in a manner that can be applied within either a deterministic or probabilistic framework. The estimation tool will be useful both for the design of specific transportation projects that cross faults, and will also serve to supplement planning information now provided by Alquist-Priolo maps.

5.1.2 Program Approach

The PEER-LL program has established a project-specific partnership with the USGS and CGS to synthesize available fault-rupture offset data, develop statistical models for that data, develop a preliminary design tool (software), and apply this tool to selected test cases. This process and results are being performed under the guidance and periodic review of an expert panel. This initiative is currently focused on strike-slip faulting only, but may be extended to reverse faulting if warranted. Chris Wills of CGS is coordinating the overall effort, with fault data development being headed by Dave Schwartz of USGS-Menlo Park, and model coding being led by Mark Petersen of USGS-Golden.

5.1.3 Research Team (alphabetical order)

Task PI's:	Mark Petersen, David Schwartz, Chris Wills
Co-PI's:	Bill Bryant, Tianqing Cao, Tim Dawson, Badie Rowshandel
Review:	Norm Abrahamson, Clarence Allen, Jon Bray, Brian Chiou, Lloyd Cluff, Kevin Coppersmith, Bill Lettis, Mahmoud Khojasteh, Martha Merriam, Cliff Roblee, Tom Rockwell, Donald Wells, Bob Youngs

5.1.4 Selected Accomplishments

A major accomplishment of the research team has been the systematic organization of available fault surface-rupture data into a series of digital GIS files. Heretofore, digitization of rupture offsets had been sporadic, and no central resource existed. Tim Dawson and Dave Schwartz of USGS [45] have led this effort to organize available data and perform the spatial GIS analyses needed to develop a new engineering model. Figure 28 shows seven of the digitized fault maps used for analysis of strike slip earthquakes. As can be seen, the complexity of real fault surface-rupture patterns is not always straightforward and can include splays, step-overs, junctions, and distributed faulting. All digitized fault-surface rupture data used in the development of the engineering model will be made publicly available as GIS files to facilitate future research investigations.

Figures 29 and 30 illustrate how the newly digitized data are being used to develop component models for use in the new design tool. Figure 29 shows a portion of actual 1999 Hector Mine rupture trace (red) and the pre-earthquake mapping of fault trace (blue). Data such as these are being used to establish probability density functions (pdf's) for mapping error. Understanding how much error is involved in mapping is important for designers since they must estimate hazard from mapped traces before an earthquake occurs. As shown in Fig. 29, mapping accuracy is quite good for the straight

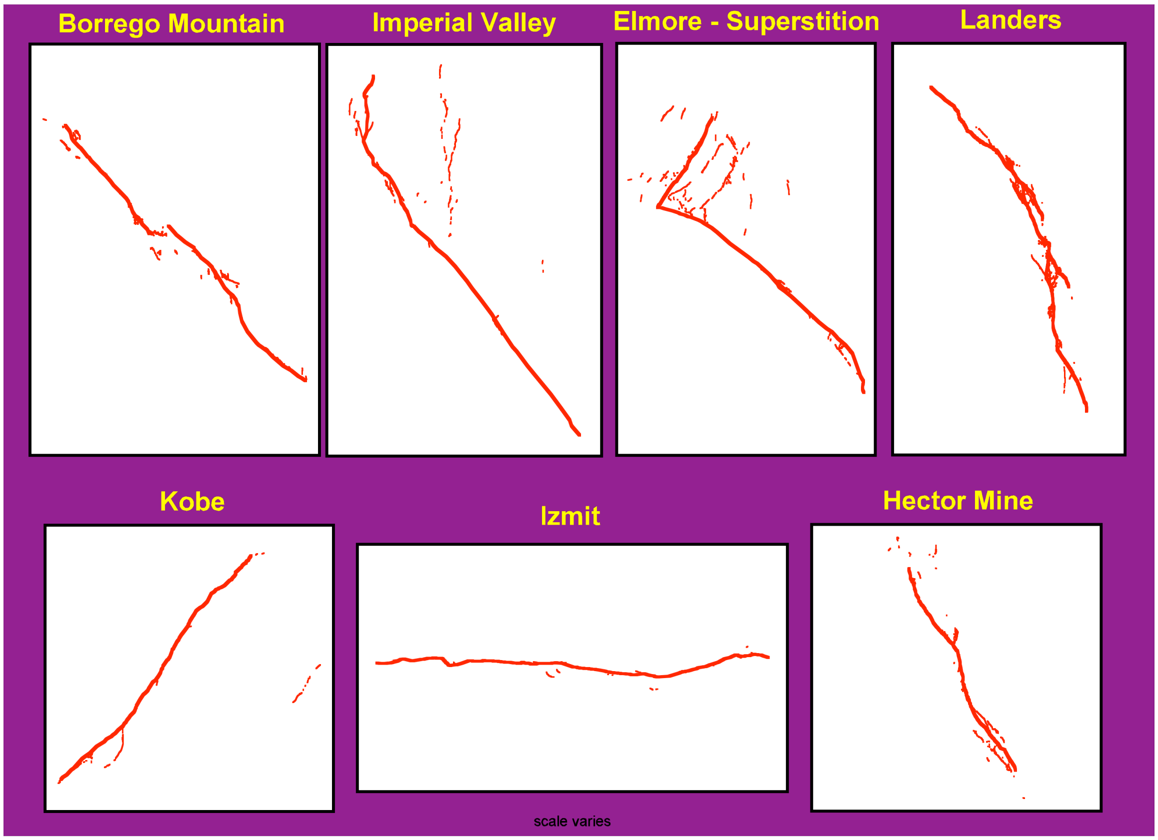


Figure 28. **Digitized fault surface-rupture traces for seven strike slip earthquakes used in the development of the fault surface-rupture model. (Dawson, 2003 [45])**

portions of the fault trace toward the bottom, but become less accurate near complex intersection zone. To account for this behavior, the fault model will develop separate pdf's for simple and complex regions of the fault trace. The accuracy of the mapping (i.e. whether a fault is well located, approximately located, concealed, or inferred) will also be considered so as to be consistent with current fault mapping practices.

Figure 30 illustrates another key element of the new model; that of characterizing the variability of fault displacement along strike. Prior models have not considered this issue even though observations have indicated that displacement values tend to decrease near the ends of the fault. As described by Wills et. al. [46], Fig. 30 shows offset data for 10 digitized faults where the offsets are normalized to the largest measured displacement on the fault. The offset values are presented as a function of normalized position along fault strike where the fault has been 'folded over' its midpoint so that values on the left represent near the end of the fault and values on the right are for the midpoint of the fault. These data show several interesting trends. First, median offset is typically on the

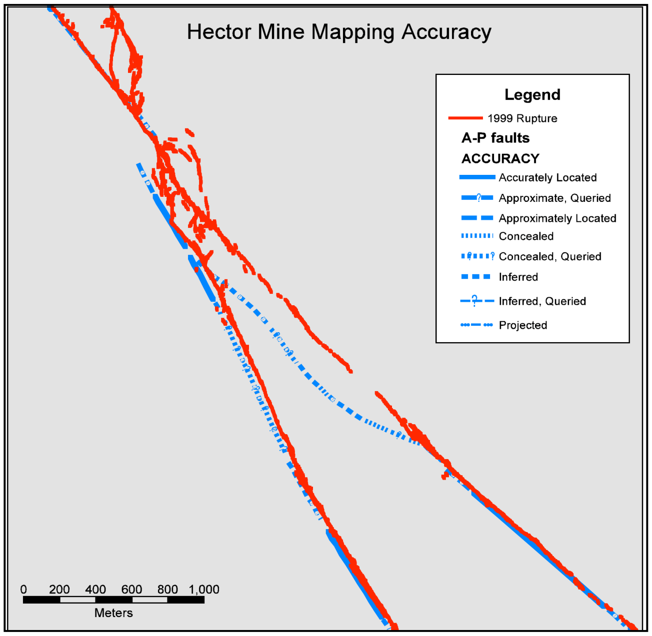


Figure 29. Example of complex faulting region comparing pre-EQ mapping (blue) vs actual (red) rupture trace for 1999 Hector Mine EQ. (Dawson, 2003 [45])

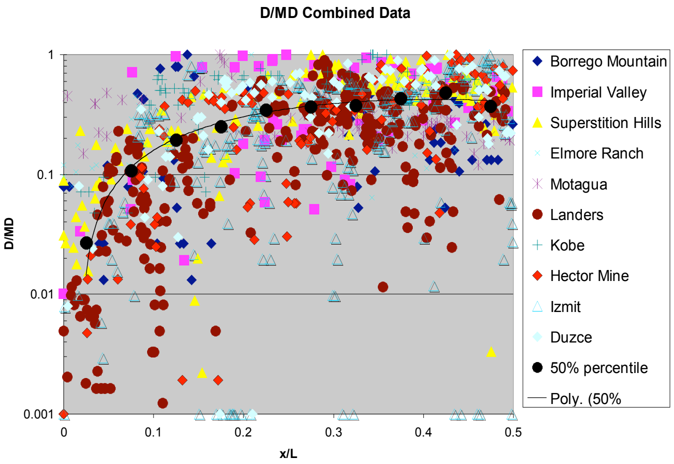


Figure 30. Normalized displacement as a function of normalized distance for 10 strike-slip EQ's. (Wills et. al., 2003 [46])

order of half of the maximum displacement. Second, there is a clear decrease in median surface slip near the end of the fault with offset values within 10% of the fault length dropping below about 25% of median displacement near the middle of the fault. Finally, these results clearly show a large dispersion of data that must be considered when establishing acceptable risk for a particular design.

Other components of the new fault surface-rupture model include establishing both the likelihood and amplitude of secondary faulting as a function of distance from the main fault trace. The likelihood of encountering a surface-rupture offset is also considered as a function of the footprint size of a facility. Larger extended facilities are more likely to cross an offset than a smaller compact facility.

Results from these GIS analyses of the digitized fault data are being used to construct a design model for estimating fault surface-rupture displacement. Mark Petersen of USGS-Golden and Tianqing Cao of CGS in Sacramento are heading model development. Model formulation and trial applications are being reviewed by a panel of experts having familiarity with geologic, modeling, and end-user aspects of the problem. A preliminary model has been formulated, and the review panel is now providing input on how it can be improved to better reflect field realities and be more effective for use in design.

Figure 31 illustrates preliminary sample output from the new fault surface-rupture design tool [47]. The figure shows several distributions of fault displacement as a function of perpendicular distance from the mapped trace. These particular idealized results are for a location near the middle of a fault having a characteristic magnitude of 7.25 and an annual recurrence rate of 0.006. Two different parameters are varied in the figure. The family of blue curves has the same 1-sigma mapping-uncertainty values of 10 meters and represent, from lowest to highest, fault displacement values having a 10%, 5%, and 2% chance of exceedance in 50 years. Lower offset values would be determined near the ends of the fault. For this idealized example, a bridge designer using the 5%-in-50-year results (shown in the solid blue line) would need to accommodate an offset of approximately 2.8 meters if crossing the fault. For this level of mapping uncertainty, a bridge would need to be sited no closer than 25 meters from the mapped fault to limit fault rupture offsets to less than 1 meter or have a setback of approximately 40 meters to encounter negligible fault displacement. If fault mapping were more uncertain, the computed distribution of offset would widen. This is illustrated by the purple and red curves that are for 5%-in-50-year having 1-sigma mapping-uncertainty values of 30 and 100 meters, respectively. The completed design tool will be configured as a flexible PC-based computer program that will provide these types of results as well as accommodate other types of design-oriented queries.

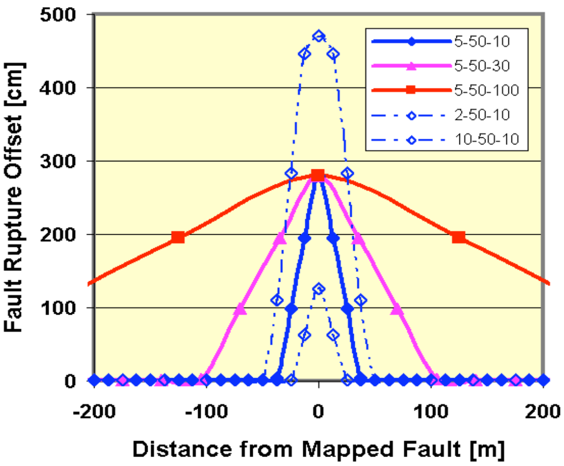


Figure 31. Example preliminary results from new fault surface-rupture design tool. (Cao, 2003 [47])

5.1.4 Project Status and Schedule

Digitization, conversion to GIS formatting, and evaluation of surface rupture maps is largely complete. Scope was expanded mid-project to take advantage of new data stemming from the Denali earthquake in Alaska. This has led to modest delay in the finalization of probability density functions and the software design tool. Expected project completion date is March 2005.

5.2 Liquefaction Triggering *(Collaborations w/ USGS, NSF in U.S; ZETAS, Sakarya University, and Middle East Technical University in Turkey; NCREE, National Chung-Hsing University, National Cheng-Kung University, and National Chi-Nan University in Taiwan)*

Liquefaction triggering assessment is the process of determining whether liquefaction is likely to occur at a particular site. It is the first step in a comprehensive liquefaction hazard assessment, and possible consequences are assessed only if liquefaction triggering is considered likely. In its simplest form, liquefaction triggering assessment is determined by comparison of the expected levels of ground shaking, expressed as a cyclic stress ratio (CSR), against various measures of the soils capacity to withstand shaking, expressed as a cyclic resistance ratio (CRR). Thresholds of liquefaction susceptibility are determined through empirical regression of observed behavior using worldwide case studies. The threshold is a function of the soil type and earthquake magnitude (i.e. as a proxy for duration or number of large strain cycles). The baseline threshold curve is normally expressed for clean sandy soils and a magnitude of 7.5. Adjustments to CSR are made to account for duration effects associated with different earthquake magnitude. Threshold boundaries are adjusted for different soil types, with increasing fines contents leading to lower likelihood of liquefaction.

5.2.1 Technical Issues and Goals

There are a number of technical issues affecting designers faced with liquefaction triggering assessments. Early assessment tools developed since the 1960's presented liquefaction hazard as a binary process; a site was considered to be either definitely susceptible, or not, to liquefaction. Many design cases involve soils near the borderline, and uncertainties in both CSR and CRR made decisions regarding liquefaction mitigation both difficult and somewhat arbitrary. Compounding this issue, mitigation measures used to stabilize the ground from liquefaction tend to be expensive, thus imposing a large cost penalty for adopting a conservative design strategy. The inherent uncertainty in the evaluation process led researchers to develop probabilistic approaches starting in the late 1980's. However, until very recently, there have been an insufficient number of high-quality case histories to constrain these approaches, and the resulting models would indicate unreasonably wide bands of uncertainty that provided little useful guidance. Thus, significant enhancements to the case history database were required to put liquefaction triggering assessment on a useful probabilistic footing, especially for higher levels of CSR (say >0.25) that are important for designs in highly seismic regions.

Another troublesome issue for designers is that different techniques for site characterization could lead to different conclusions regarding liquefaction triggering. The in situ testing techniques used to establish CRR include, from earliest to most recent, the standard penetration test (SPT), the cone penetration test (CPT), and the shear-wave velocity test (Vs). Each method offers advantages; the SPT provides soil samples for measurement of fines content, the CPT provides a more continuous profile that can identify thin layers, and the Vs method provides a lateral-average measure and can also be used at gravelly sites where the other methods prove difficult. Designers would like to have procedures for all methods to yield consistent conclusions regarding liquefaction triggering risk.

Lastly, fine-grained soils, those having silt and clay-sized particles, have often presented problems for assessment of liquefaction triggering. There is significant controversy regarding the soil classification criteria that best reflects potentially liquefiable soils. Until recently, resolution of this issue was hampered by lack of high-quality case histories. Designers seek consensus recommendations regarding criteria for identification of potentially liquefiable fine-grained soils.

5.2.2 Program Approach

The PEER-LL program has supported activities of a group of investigators aimed at systematically advancing practices for liquefaction triggering assessment. A major component of these activities has centered on significantly extending the number of high-quality case histories. These new case histories include sites that did and did not liquefy, and focused on sites that experienced high levels of CSR that are critical to design assessments in California. The need for "no liquefaction" case histories has been to assure the statistics used to establish liquefaction thresholds are not biased conservatively. Many new cases in Turkey and Taiwan were thoroughly investigated, but older case histories were also significantly improved through the addition of critical new subsurface data involving new drilling and/or geophysical testing.

Site exploration and case history development activity has been highly leveraged through a number of international partnerships. PEER-LL directly matched NSF funding for characterization of key sites in Turkey. These U.S.-sponsored activities were also supported with extensive in-kind services provided by a variety of researchers in Turkey. In a similar arrangement, PEER-LL supported U.S. investigators to collaborate and exchange data with a number of researchers in Taiwan. Finally, PEER-LL has provided key operational support for a USGS-funded team to gather previously unavailable shear-wave velocity data from key case history sites worldwide.

Finally, researchers from, or closely affiliated with, UC-Berkeley have guided development of much of the liquefaction-triggering models sponsored by PEER-LL. This work has been clearly focused on design issues. However, the topic of liquefaction involves fundamental and sometimes contentious issues. Therefore, a review panel reflecting a less regional perspective was established to provide review and comment on this body of work to PEER-LL sponsors with particular emphasis on ways to enhance these efforts for design applications.

5.2.3 Research Team (alphabetical order)

Task PI's:	J.P. Bardet, Jim Bay, Jon Bray, Rob Kayan, Ray Seed, Jon Stewart, Les Youd
Co-PI's:	Onder Cetin, Daniel Chu, Brady Cox, H. Durgunoglu, Allison Faris, Ann Kammerer, Rob Moss, A. Onalp, J. Pestana, Rodolfo Sancio, Daniel Whang
Review:	I.M. Idriss, Goeff Martin, Mike Riemer, Tom Shantz, Les Youd

5.2.4 Selected Accomplishments

A major achievement of the PEER-LL program has been the significant extension of the number of high-quality liquefaction case histories. A team led by Jon Bray of UC-Berkeley, Jon Stewart of UC-Los Angeles, and Les Youd of Brigham Young University [48] characterized key liquefaction and lateral spread sites from the two 1999 Turkey earthquakes. These investigations were complemented by SASW shear-wave measurements obtained by Jim Bay of the University of Utah [49] and by aerial photo interpretation studies provided by J.P. Bardet of University of Southern California. Important contributions from these case histories include new insights into liquefaction phenomena for fine-grained (silty/clayey) soil sites. All of these new case-history data including photos and sketches of damage observations and SPT and CPT subsurface logs are publicly accessible via web (http://peer.berkeley.edu/turkey/adapazari/). Another team led by Jon Stewart of UC-Los Angeles [50], in collaboration with several Taiwanese counterparts, focused on characterizing key liquefaction and lateral spread sites from the 1999 Chi Chi, Taiwan earthquake. These investigations focused on cases in the Wufeng, Nantou, and Yuanlin regions that underwent high levels of motion. These data are currently available at (http://cee.ea.ucla.edu/faculty/Taiwanwebpage/Main.htm), and at the PEER-LL web site. Jon Stewart has also collected needed CPT data for several liquefaction sites in the Imperial Valley. Finally, Rob Kayen of the USGS [51] has spearheaded a major effort to collect shear-wave velocity data using the SASW method. His team has measured velocity profiles at over 300 recent and historic liquefaction sites from worldwide earthquakes extending from 1948-2003. These velocity profile data enhance other penetration-testing information previously available for these sites, thus allowing the Vs method to be developed to its full extent.

The newly expanded database of case histories, plus new knowledge gained from fundamental research have made it possible to develop improved design tools for assessment of liquefaction triggering. Ray Seed along with his colleagues from UC-Berkeley has led a series of investigations [52, 53, 54, 55] that have resulted in several significant advancements. A complete review of these advancements is summarized in a recent extended article by Seed, et.al. [56]. Figure 32 illustrates that the primary outcome of these investigations is a pair of new probabilistic-based liquefaction triggering procedures using either SPT or CPT test methods. The key advancement is a greatly reduced level of uncertainty in the probabilistic triggering bounds. This was achieved through: 1) use of more selective screening criteria for case histories where only very well constrained cases are used, 2) the use of a Bayesian statistical approach that allows for separation of components of uncertainty, 3) new understanding of ground motions, 4) new understanding and treatment of SPT and CPT data, and 5) improved methods for assessing the CSR. The chart on the right in Fig 32 separates out "new data" as circle symbols, and shows that these data comprise about half of the high-quality case histories, and nearly all of the case histories for high values of CSR. These new design charts can now be applied to routine practice. These studies are also contributing to resolution of other corollary issues including

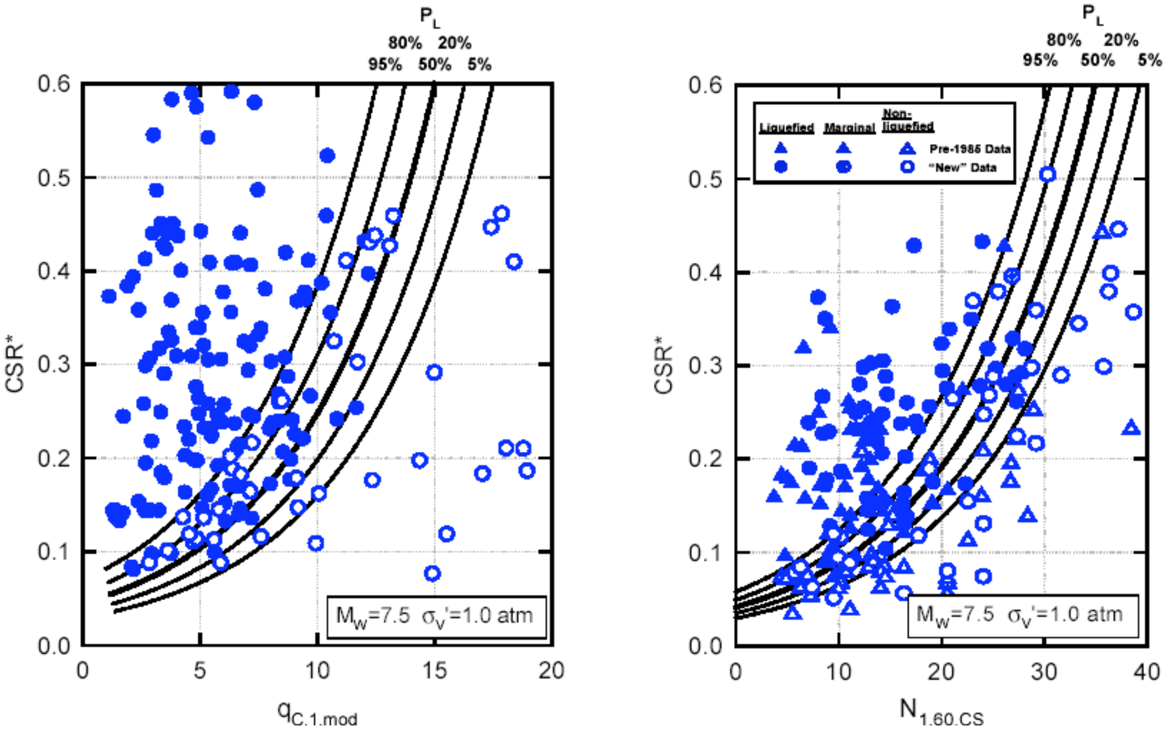


Figure 32. **Proposed probabilistic liquefaction triggering boundaries using both CPT and SPT criteria. (Seed et. al., 2003 [56])**

magnitude-correlated duration weighting factors, adjustments for fines, and corrections for overburden stress.

Figure 33 shows recent results using the newest approach for liquefaction triggering assessment, normalized shear-wave velocity. Rob Kayen of USGS [51], who has spearheaded the collection of new worldwide velocity data, is also working on the development of probabilistic Vs-based triggering boundaries. This work is being closely coordinated with the UC-Berkeley group who developed the new

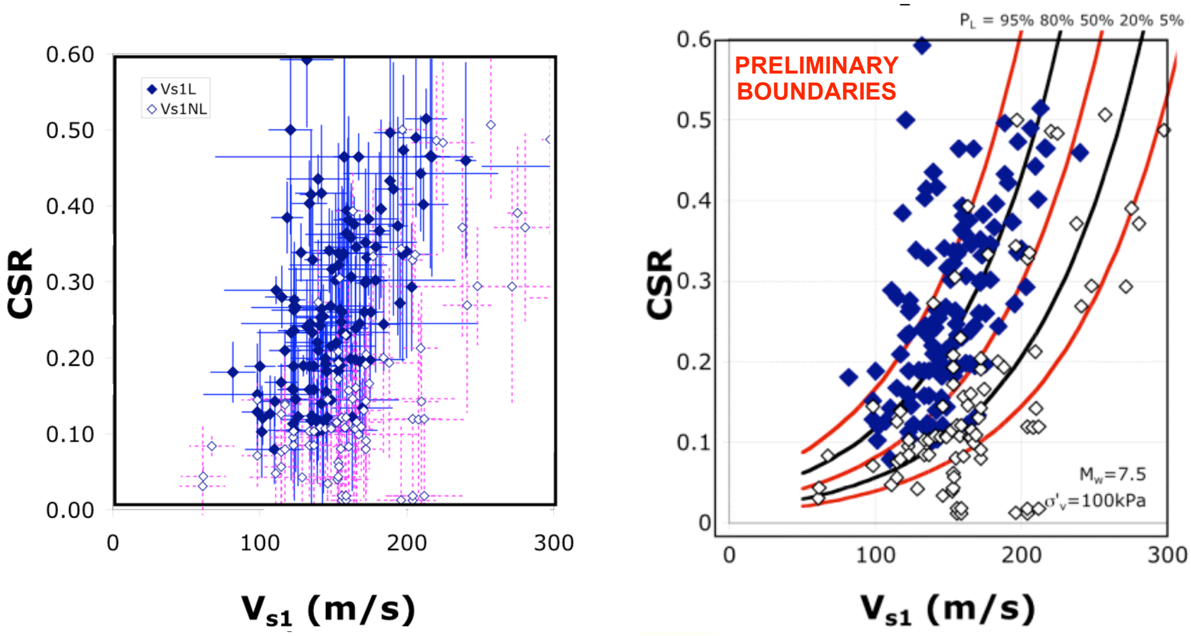


Figure 33. **Liquefaction triggering data and preliminary probabilistic boundaries using normalized-shear-wave velocity criteria. (Kayen, 2003 [51])**

SPT and CPT design charts shown in Fig. 32, thus assuring that consistent methodologies are employed. Figure 33 shows the vastly expanded data set of velocity-based case histories and preliminary Vs-based boundaries. These boundaries are very preliminary and should not yet be used for design until review and refinement has been completed. Final recommendations are expected in 2004.

5.3 Lateral Spread Case Histories *(Collaborations w/ NSF, LADWP, and both Waseda University and Kobe University of Japan)*

Lateral spread is the phenomena where liquefied ground can displace laterally large distances on very gentle slopes. Lateral spread can impose extremely large loads on underground facilities including bridge foundations and buried utilities. Although the fundamental mechanics of lateral spread are reasonably well understood, analytical calculation of the amount of spread is not well constrained. Currently, designers typically rely on empirical approaches derived from examination of case histories. Advancements in numerical simulation capabilities will also rely on calibration against well-documented case histories.

5.3.1 Technical Issues and Goals

The collection and organization of case history data for analysis of lateral spread phenomena is a very laborious and time-consuming process. As with liquefaction triggering assessment or site-response analysis, soils beneath a site must be characterized using any of several imperfect in situ and laboratory testing techniques. The quality of testing has evolved over the years with improved standards, but practices can differ between countries having important case histories. Therefore, most of the data must be interpreted carefully within the context of the time when the measurements were taken and the standards of practice used during that time and at that location. Documentation of lateral-spread case histories adds several dimensions of complexity. Detailed knowledge of site topography is needed to establish the shallow slopes and free faces that drive lateral spread. Knowledge of subsurface water conditions at the time of the spread is also needed. Finally, displacement vectors documenting the amount and direction of movement are needed. In the field, each of these parameters involves a 3-dimensional spatial distribution, though many case histories are idealized to a 2-D problem. Documentation also needs to describe damage to cultural features associated with the spreading ground.

Researchers and practitioners alike have sought a single definitive resource of lateral spread case histories. Such a resource would minimize duplication of effort and provide a common baseline for comparison of results from different modeling techniques. This resource needs to provide: 1) consistent interpretation of the subsurface characterization data in light of the time and location of the spread event, 2) a consistent spatial perspective for the various types of data, and 3) access to original source documentation so that differing interpretations can be developed over time as new knowledge is gained or if different researchers have alternative interpretations of the data.

5.3.2 Program Approach

The PEER-LL program contracted with J.P. Bardet of University of Southern California to lead development of a unified archive framework for comprehensive documentation of lateral spread case histories, and to enter data for an initial set of cases coming from US and Japan. This work builds upon previous work by Bardet to develop simplified regression models for lateral spread prediction [57]. The US case histories were developed through collaboration with the Los Angeles Department of Water and Power (LADWP). The Japanese case histories were developed through the NSF-sponsored US-Japan collaborative research framework and through direct contributions from Professor Masanori Hamada of Waseda University and Professor Tanaka of Kobe University.

5.3.3 Research Team (alphabetical order)

Task PI's:	J.P. Bardet
Co-PI's:	Jianping Hu, Jennifer Swift, Tetsuo Tobita
Collaborators:	Craig Davis, Prof. Masanori Hamada, Prof. Tanaka.
Review:	I.M. Idriss, Mike Riemer, Tom Shantz

5.3.4 Selected Accomplishments

Bardet et. al. [58] have developed a lateral spread case history archive framed around a relational database management system (RDBMS) and a geographic information system (GIS) interface. The

RDBMS provides a means to structure, screen, and organize files. The GIS interface provides a consistent spatial framework for display and analysis of the data. Care has been taken to assure that novice users having no RDBMS knowledge can access all data. Archive outputs have been published as organized file systems in formats including Microsoft Excel spreadsheets, jpeg and gif files for photos and scanned documents, ASCII digital elevation models (DEM's), and GIS shapefiles. Freeware including an Excel viewer for viewing spreadsheets, and ArcExplorer for viewing shapefiles is included in the published data CD's.

Filling the archive with initial case history data sets has provided the wide range of experience needed to identify and rectify glitches in the archive framework. The data, which originated from different sources in the US and Japan, have been combined and archived. Legacy data, including hardcopy reports on displacement vectors and soil SPT and CPT soundings have been converted to digital format. All hardcopy source documents have been scanned and archived. Aerial photos, DEM's, and other basemaps have been organized for viewing within the GIS framework. Table 10 summarizes highlights of the case histories that are currently included in the archive. Overall, the database includes over 16,000 displacement vectors, nearly 150 aerial photos, and over 5000 borings. Figure 34 illustrates typical capabilities of the archive.

Table 10 - Initial lateral-spread case histories incorporated into database (Bardet, 2002 [58]).

Earthquake	Coverage	Aerial Photos	Displ. Vectors	DEM's	SPT	CPT
1964 Niigata, Japan	Niigata City	20	2498	4	645	0
1971 San Fernando, CA	Jensen Filtration Plant	67*	864	1 text	257*	153*
1983 Noshiro, Japan	Noshiro City	4	2954	4	71	0
1989 Loma Prieta, CA	Marina District	1	0	2	0	9
1994 Northridge, CA	Van Norman Complex	67*	1011	2	257*	153*
1995 Kobe, Japan	Kobe City	59	8894	8	4002	0

* Jensen Filtration Plant and Van Norman Complex use same aerial photos, SPT and CPT data

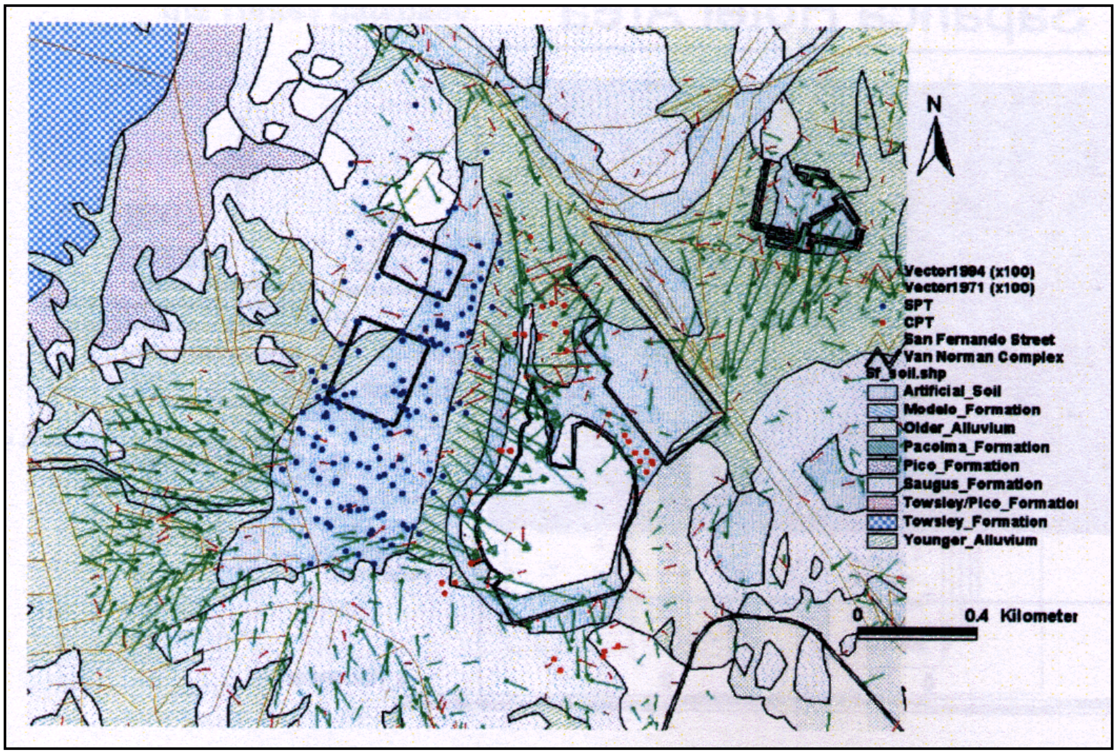


Figure 34. Typical GIS output from lateral spread case history database showing spread displacement vectors and boring locations. (Bardet, 2002 [58])

With feasibility demonstrated and the archive framework in place, the population of lateral spread case histories is positioned to be significantly expanded to include newly documented sites Turkey and Taiwan as well as key legacy cases in the U.S and elsewhere. However, even with the limited set of cases now in the archive, designers and researchers alike have a powerful new resource. Designers can look to these case histories for guidance on projects. Researchers can extract simplified 2-D profiles from these cases to serve as a common reference set for comparison of different modeling techniques. A new project by Faris et. al. [59] is now using case histories from this database to aid development of a new "strain potential" method for improved estimation of lateral spread.

5.4 Regional Liquefaction Deformation Hazard Mapping *(Collaboration w/ CGS)*

Liquefaction hazards exist over large areas, such as many urban regions of California, that have a combination of young saturated sediments and high shaking hazard. Identification of whether a site may be subject to liquefaction hazard is needed for facility planning and a first screening step for design. In California, liquefaction hazards are being mapped by the California Geological Survey (CGS) under authority of the Seismic Hazards Mapping Act of 1990. The zone maps classify a site on a binary basis as either within or outside of a zone that is potentially susceptible to liquefaction hazards. No gradation is provided to identify relative hazard within the zones that are considered susceptible. Therefore, planners and designers use these maps primarily to identify where they *do not* have a liquefaction hazard, and site-specific assessments are required for all other locations. Another resource for identification of liquefaction hazards is "liquefaction susceptibility" maps produced by USGS. These maps do identify different levels of hazard, but the differentiation is based strictly on geologic criteria so all sites within the same surface geology unit are assigned the same hazard level. This approach provides valuable insight, but does not account for different seismic hazards or important variations within units, and does not incorporate knowledge of basic engineering principles driving the liquefaction process.

A significant step forward would be to develop a new generation of liquefaction hazard maps that identify relative hazard of potentially liquefaction-susceptible sites directly in terms of potential for facility damage. Facility damage from liquefaction can be best correlated with the extent of lateral ground displacement and vertical ground settlement. Lateral spread is related to lateral strain of liquefiable layers, and settlement to volumetric strain. Both of these engineering parameters can be estimated using physically based models. Therefore, if feasible, liquefaction hazard mapping on the basis of ground deformation offers several practical advantages: 1) it would identify relative hazard on the basis of parameters used in engineering design that correlate to damage, 2) because the mapped quantity has engineering significance, different thresholds of tolerable displacements could be set for different facility types and design strategies, and 3) assuming that some displacement level can be tolerated by most facilities, the size of the hazard zones could be significantly reduced, thus appropriately focusing resources on the most critical cases.

5.4.1 Technical Issues and Goals

The primary technical issue in the development of deformation-based liquefaction hazard maps is whether the concept is feasible given the extensive data requirements that are anticipated. Even the simplest engineering models for prediction of settlement or spread require significant knowledge of subsurface conditions. While these types of information are routinely collected on specific projects, hazard mapping requires compilation and synthesis of such data on a regional scale. More sophisticated models require additional information, so a primary challenge in this project is to establish realistic and achievable requirements for data and match these to compatible levels of model sophistication.

The fundamental goals of this initiative were to: 1) investigate the overall feasibility of a deformation-based liquefaction hazard mapping, 2) to identify appropriate engineering models for use in prediction of deformation at a regional scale, 3) to assess the level of effort required to assemble the needed data sets, 4) to evaluate whether readily accessible data is capable of supporting the proposed engineering models, and 5) to evaluate alternative map presentation formats that might be most effective for planning and engineering applications.

5.4.2 Program Approach

The PEER-LL program established a collaborative project with CGS to explore the feasibility of deformation-based liquefaction hazard maps. CGS was uniquely positioned to lead this project as they routinely collect and synthesize subsurface data on a regional scale as part of their existing hazard mapping program. To evaluate the feasibility and potential of the deformation-based approach, CGS developed information for a region near San Jose that can be simultaneously applied to produce traditional Hazard Mapping Act zone maps and prototype deformation-based maps. Keith Knudsen and Anne Rosinski of CGS led the subsurface data synthesis, GIS analysis and map development aspects of the project. Engineering modeling aspects of the project were guided by Ray Seed at UC-Berkeley with key model developments provided by his student Jiaer Wu. The engineering models were developed within a consistent framework of the liquefaction triggering models discussed in section 5.2.

5.4.3 Research Team (alphabetical order)

Task PI's:	Keith Knudsen, Ray Seed
Co-PI's:	Anne Rosinski, Jiaer Wu
Review:	I.M. Idriss, Rob Kayen, Cliff Roblee, Tom Shantz, Woody Savage

5.4.4 Selected Accomplishments

The research team [60] selected a study region of the Northern Santa Clara Valley near San Jose as depicted by the green border in Fig. 35. The region includes over 700 borings and has locations of historic ground failure. Each boring log was classified according to surface geology and ground motion hazard, interpreted for thickness of saturated sediment with liquefiable textures, and analyzed using alternative models for settlement and horizontal displacement. Geologic cross-sections were developed to interpolate the Holocene era deposits and layering across the region and on identification of the Pleistocene isosurface below which liquefaction susceptibility is greatly reduced.

Figure 36 shows an example of a preliminary pilot deformation-based map and the hazard zone map that is currently available. The pilot map shown is for 10%-in-50-year probabilistic ground motions using historic high groundwater levels to be consistent with current hazard zone maps. This particular pilot map is color-coded for earthquake-induced settlement using the Wu and Seed (2002) procedure. Alternative deformation maps were also produced and evaluated.

This preliminary pilot map clearly illustrates the broader conclusion that deformation-based liquefaction hazard mapping is indeed feasible and useful. These particular results clearly identify the most hazardous zones for settlements are located along the stream banks and adjacent levee deposits, a result that is consistent with experience. From the applications perspective, these maps show a much reduced hazard area for facility designs that are more tolerant to settlements, thus providing useful information for planning and engineering assessments.

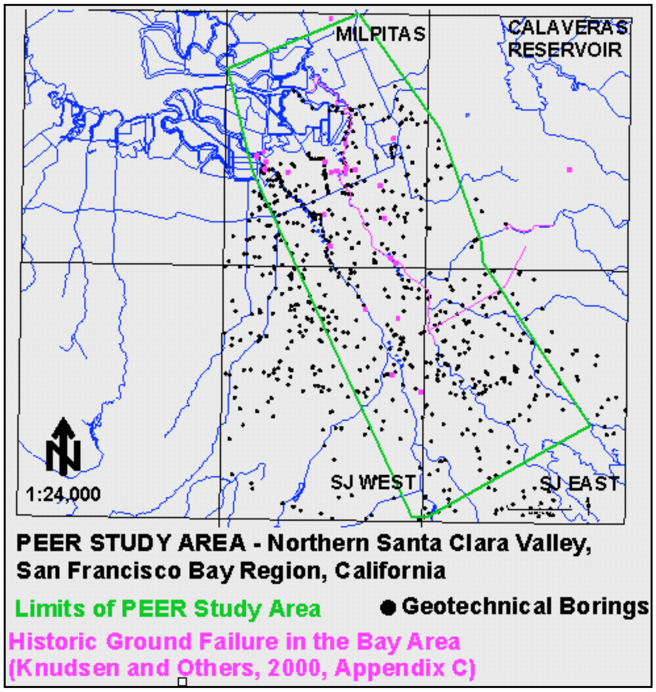
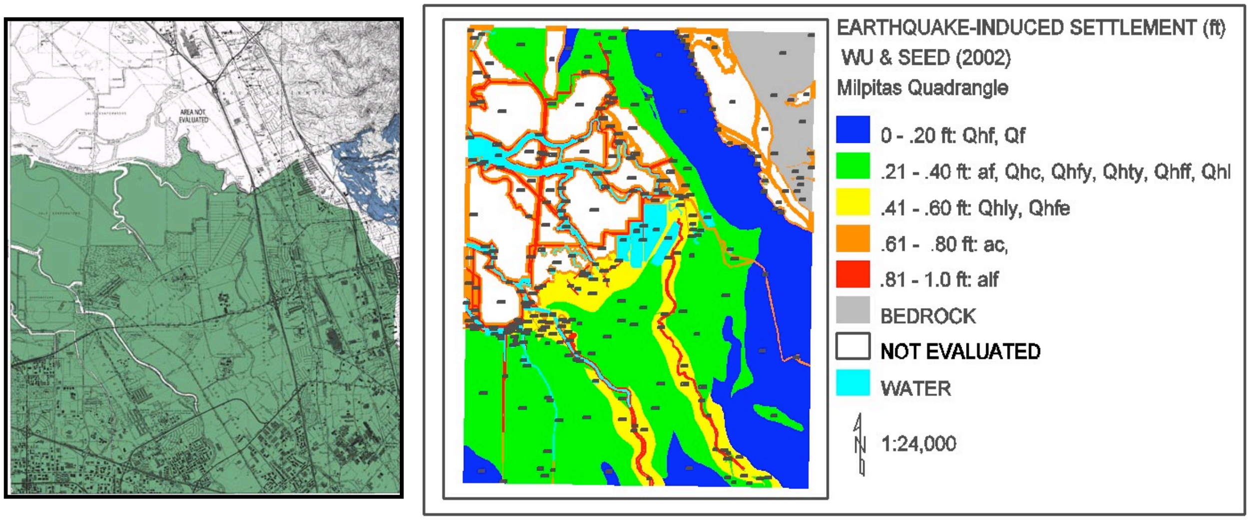


Figure 35. Study area for liquefaction deformation map. (Knudsen et. al., 2003 [60])

A key component of this pilot project has been to assess the compatibility of existing ground-deformation models with the types and quantity of data that is available at a regional scale. The research team concludes that the data needed for implementation of the alternative models for volumetric strain, shear strain, and settlement are readily available. However, the process of establishing subsurface layering is demanding, and there remains significant uncertainty in the mapped deformation values. This uncertainty is primarily associated with variability in the quality of subsurface data, thus reinforcing the need for subsurface boring-log data standards (discussed in section 4.3). An improved method of relating soil material properties to geologic units that can be mapped on a regional scale remains a central challenge to reducing uncertainty. Nevertheless, as an incremental step toward a deformation-based



a) Existing Zone Map **b) Preliminary Pilot Deformation Map**

Figure 36. Comparison of current zone and a preliminary pilot deformation-based liquefaction hazard maps for the Milpitas quadrangle. (Knudsen et. al., 2003 [60])

approach, the research team concludes that the information demands required for this pilot mapping process are indeed feasible and could be readily incorporated into existing mapping programs.

The remaining feasibility question is whether lateral spread maps can be developed. In addition to subsurface data, these models also require specification of surface topography including very shallow slopes and "free faces" such as river channels. Various data sources have been investigated. Thus far, USGS digital elevation models (DEM's) have been found to provide reasonably good constraints on regional slopes, but are insufficient for defining free faces. Radar and LIDAR methods have also been investigated, but the DEM's produced by these techniques have thus far been noisy and subject to yielding false topography. Hybrid methods using photogrammetric break lines are now being investigated. If an acceptable procedure can be established, a complete deformation-based mapping methodology will have been demonstrated.

5.5 Soil-Foundation-Structure Interaction

(Collaborations w/ Caltrans, PEER-Core, FHWA, NSF, and PARI, CERI, NIED, TSR, TIT, Waseda University and University of Tokyo, Japan)

Once a site has been identified as susceptible to liquefaction-induced ground displacement, a designer can elect to either remove or improve the poor soils, or design the facility to withstand the additional loads imposed by the ground displacement. The latter strategy requires use of engineering models that account for the interaction of the displacing soil with the foundation and, ideally, also with inertial loads caused by the earthquake-induced vibratory motions of the structure. This general problem is called "soil-foundation-structure interaction (SFSI)", and the special case of liquefaction-induced soil loads is a particularly important SFSI problem that seriously impacts the design of buried utilities and bridge foundations.

5.5.1 Technical Issues and Goals

Engineering modeling of SFSI for liquefied ground is a major technical challenge that must simultaneously account for the material complexities of liquefied soil, poorly constrained load-transfer mechanics, complex geometric effects, and a dynamic loading environment. In simplest terms, a successful model must: 1) predict displacement demands for both the liquefied ground and any non-liquefied soil layers above the liquefied zone; 2) capture the load-transfer behavior between the displacing soil and the pipeline or foundation system, and 3) include the contribution from inertial loads caused by excitation of any foundation-supported structure. Challenges in predicting displacement demand include a wide range of possible soil behavior in response to dynamic cyclic loading and elevated pore pressure. This range of behavior affects both the magnitude of overall displacement and the distribution of displacement with depth. While relatively straightforward models exist for the load-transfer behavior between stable soil and pipelines (or piles), load-transfer models that account for elevated pore pressure and liquefaction are just beginning to emerge and are only partially constrained. The load-transfer mechanics are further complicated by geometric affects. For the example of pile-foundation systems, the SFSI model must account for "pile cap effects", where the pile cap typically attracts a greater portion of soil load than the piles, and "pile group effects" where leading piles in a group typically attract a larger proportion of load than trailing piles. Lastly, the contribution from structural inertial forces is complicated by both the nonlinear response of the structure and the inherent randomness associated with earthquake loading.

Recognizing that the SFSI problem for liquefied ground is a technically challenging problem, there are two basic and inter-related issues of concern to designers: 1) the level of model sophistication required to capture essential elements of the problem, and 2) establishing adequate constraints on the model to allow meaningful design application. On the issue of required model sophistication, many models have been proposed ranging from very simple modifications to standard load-displacement, or "p-y curves" used for stable ground, to very sophisticated 3-D finite element procedures involving advanced material models. Generally, the simple models are recognized as not accounting for important known behavior, but it remains to be seen whether they can be modified to achieve an acceptable level of performance. At the other extreme, the most advanced models provide a mechanism to account for all understood behavior, however, the level of sophistication is beyond typical capabilities of practicing engineers and the models themselves are very poorly constrained.

The issue of developing model constraints is quite challenging since it requires detailed knowledge of time-dependent subsurface behavior during an earthquake. Field case histories of failures have provided general qualitative guidance into the key mechanisms involved. However, the lack of instrumentation makes it impossible to extract the quantitative information needed to constrain engineering models. Another option is to create well-instrumented laboratory models that can be shaken using testing equipment including shake-tables and centrifuges. This approach allows detailed instrumentation and input of realistic earthquake motions. However, laboratory models must be performed at a reduced scale, thus introducing scaling effects. Shake table models can be built to a larger size, but typically not large enough to replicate field conditions. Centrifuge testing can reproduce field stress conditions, but must be performed on very small-scale specimens. Both laboratory strategies involve use of reconstituted soils that, while well controlled, do not necessarily reflect typical field conditions. One strategy is to perform full-scale tests in the field, thus allowing for use of realistic materials and construction details, and natural soil variability. The challenge in this approach is to induce liquefaction. A relatively new approach has been to use controlled blasting to elevate pore-water pressure in the ground to the point where liquefaction and static displacement occurs. However, this approach does not replicate realistic cyclic shear motions that are produced in an actual earthquake. Therefore, no single testing strategy provides a completely realistic reproduction of earthquake-induced lateral spreading phenomena.

The over-riding goal of SFSI research into laterally spreading ground is to develop practical design-oriented tools that sufficiently quantify the key phenomena affecting load transfer so that alternative design strategies and mitigation measures can be meaningfully evaluated.

5.5.2 Program Approach

The overall research strategy on the topic of SFSI for liquefied ground is to develop both the fundamental understanding and quantitative constraints needed to calibrate realistically comprehensive analytic models, and then to exercise these advanced models to guide development of simplified design-oriented approaches. Since no single testing strategy provides a completely realistic representation of actual field conditions during earthquakes, a variety of laboratory and field-testing approaches are being pursued within an overall coordinated strategy.

Collaboration opportunities on this topic have been actively pursued since both the laboratory and field tests needed to constrain these models are very expensive. Several inter-related projects have been funded recently using a variety of mechanisms. Caltrans, the FHWA, and several state DOT's co-sponsored a "Federal Pooled Fund" investigation called the "Treasure Island Liquefaction Test (TILT)" where full-scale lateral load tests were performed on single piles and pile groups within blast-induced liquefied ground. Caltrans separately funded a detailed program of centrifuge experiments at UC-Davis where single piles and pile groups were subjected to shaking-induced lateral spreading for a controlled suite of soil densities and crusts. The PEER-LL program was a major co-sponsor of a collaborative full-scale liquefaction-testing program performed in 2002 at a hydraulic-fill harbor site in Tokachi, Japan. In that series of tests, buried pipelines and both single piles and pile groups of the same configuration as used in the UCD centrifuge tests were subjected to lateral spreads initiated through blast-induced liquefaction. The PEER-Core program has sponsored follow-up work by researchers at UCSD to analytically model the Tokachi experiments using both sophisticated and simplified SFSI models. The PEER-LL program has also recently entered into a major US-Japan collaboration with NSF involving a coordinated series of centrifuge tests at RPI, moderate-scale shaking table tests at UCSD, and near-full-scale shaking table tests at the NIED facility in Japan. Finally, the PEER-Core program has initiated planning for a synthesis workshop where consensus recommendations and remaining issues can be reviewed.

5.5.3 Research Team (alphabetical order)

Task PI's: Scott Ashford, Ross Boulanger, Ahmed Elgamal

Co-PI's: Tarek Abdoun, Scott Brandenberg, Dongdong Chang, Ricardo Dobry, Teerawut Juirnarongrit, Bruce Kutter, Kyle Rollins, Priyanshu Singh

Japan Co-PI's: Akio Abe (TSR), Masanori Hamada (Waseda), Masayoshi Sato (NIED), Takehiro Sugano (PARI), Kohji Tokimatsu (TIT)

Review: Abbas Abghari, Liam Finn, Kenji Ishihara, Mahmoud Khojasteh, Tom O'Rourke, Angel Perez-Cobo, Tom Shantz

5.5.4 Selected Accomplishments

Within the overall context of the strategy to develop improved design-oriented models, activities in this area have thus far primarily focused on data development. Nevertheless, many important tests have been completed that offer new understanding and constraints for engineering models. Comprehensive, or even cursory, treatment of these results is beyond the scope of this overview paper. Therefore, only a small representative selection of highlights will be discussed here.

One relatively mature outcome of the various testing programs is that conventional p-y models typically used in design for analysis of lateral loads do not capture key features of the load-deformation relationship in liquefied conditions. Figure 37 illustrates this observation using centrifuge testing results developed by a team of UC-Davis researchers headed by Ross Boulanger and Bruce Kutter. These results compare measured behavior (black) at various depths within a pair of soil profiles against standard design models (red) appropriate for that depth. The results on the left for loose sand shown that little load (p) can be developed over the entire displacement range at any depth within the profile. In contrast, the results on the right for medium-dense sand show that "banana-shaped" loops develop with increased cycles (and displacement). These unusual loop shapes are the result of complex material behavior whereby the sand dilates at high strain reducing pore pressures and increasing strength and stiffness. Similar behavior is observed from the full-scale lateral load tests performed under the TILT project headed by Scott Ashford of UC-San Diego and Kyle Rollins of Brigham Young University. As shown in Fig. 38, increasing numbers of load cycles lead to decreased load capacity for the same deformation, and increasingly banana-shaped loops. This same behavior is observed in other tests as well. Although standard p-y load deformation models clearly do not capture this complex behavior of liquefied soil, it remains to be seen whether simple design models can be satisfactorily modified and/or applied with appropriate guidance.

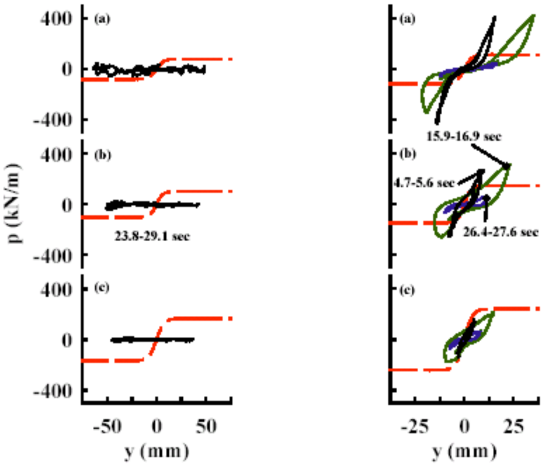


Fig. 2-6. p-y loops in liquefying loose sand ($D_r \approx 40\%$) at depths (a) 2-D, (b) 3-D, and (c) 4-D (D = 0.67 m). Dashed lines per API (1993). (Wilson et al. 2000)

Fig. 2-7. p-y loops for liquefying med. sand ($D_r \approx 55\%$) at depths (a) 2-D, (b) 3-D, and (c) 4-D (D = 0.67 m). Dashed lines per API (1993). (Wilson et al. 2000)

Figure 37. Illustration of p-y behavior for liquefied ground. (Boulanger et. al. 2003 [61])

Another fundamental liquefied soil behavior observed in the UC-Davis centrifuge tests is the strong localization of strain at the boundary between the liquefied soil and the overlying impermeable crust. Figure 39 illustrates this observation for the case of a clay crust overlying liquefiable loose sand. This phenomenon is explained as void ratio redistribution that occurs during and after shaking where excess pore pressure causes pore fluid to migrate and accumulate beneath the impermeable boundary, thus reducing effective stress and allowing large strains. This pattern of strain distribution would impose very high loads on a pile foundation near the interface of these strata. Recognition of the potential for this pattern of displacements, and the conditions under which it might occur, is an important design consideration.

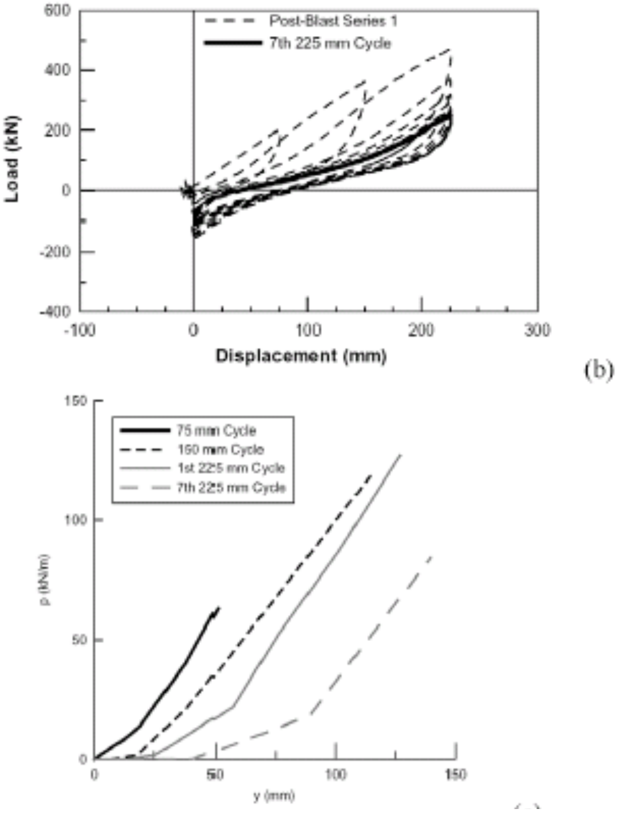


Figure 38. Load-displacement and p-y curves from TILT. (Ashford & Rollins, 2001 [62])

The Tokachi, Japan full-scale blast-induced liquefaction experiment provided an unprecedented opportunity to leverage international liquefaction research. The Port and Harbor Research Institute (PARI) of Japan originally developed the site to test a new seismically resistant quay wall design for use in liquefaction-susceptible seaports. The test site was configured to include a large region behind a conventionally designed quay wall that was expected to undergo significant lateral displacement. The remainder of the site was expected to liquefy, but not undergo significant lateral movements. PARI offered to make the site available to other researchers at the marginal cost of installing their experiment. This offer was accepted by several organizations listed in Table 11, and a number of independent but coordinated research experiments were performed at this site in late 2002. The major experiments examined the behavior of quay walls, pile foundations, pipeline/conduit systems, tank tie-down systems, and soil improvement techniques. Numerous additional site characterization tools and measurement technologies were also evaluated at the site.

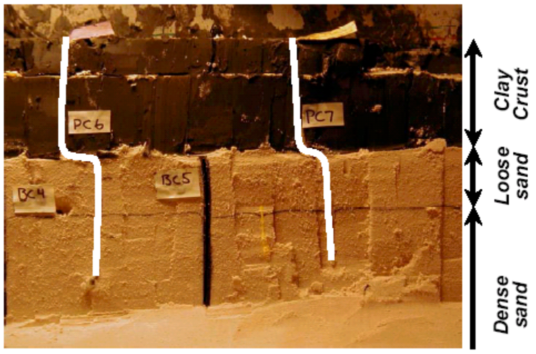


Figure 3-15: Excavation of SJB02 showing the strong localized deformation at the interface between the loose sand and overlying clay layer (paper markers highlighted for clarity). Note that the clay is dark and the horizontal black seam in the sand is a colored marker separating the loose and dense layers.

Figure 39. Example of localized deformation beneath a clay crust (Boulanger et. al. 2003 [61])

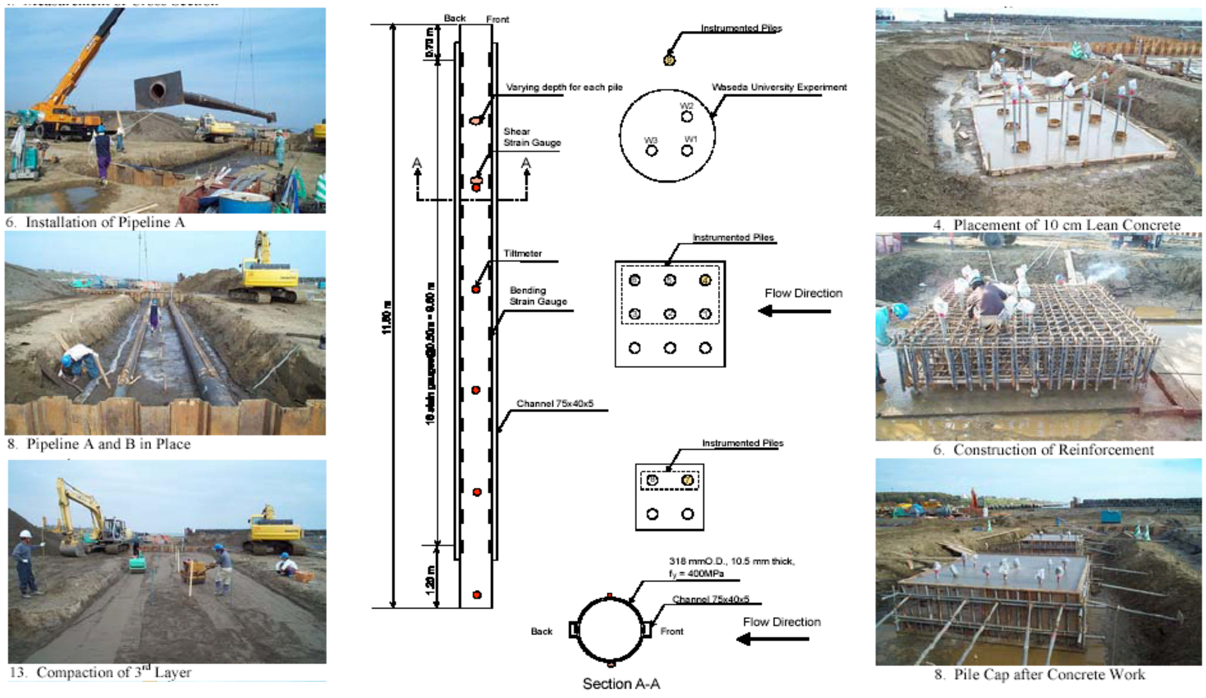
The PEER-LL program elected to support a proposal by Scott Ashford to install full-scale foundations and pipeline/conduit systems within the lateral spreading side of the site. The foundation systems included a single pile, a 4-pile group, and a 9-pile group. All piles were steel pipe, and pile caps were constructed per standard Caltrans specifications. Instrumentation was configured to allow measurement of pile load-transfer behavior throughout the profile as well as pile group effects and loading of the pile cap. The pipeline/conduit systems were installed in both transverse and parallel to soil flow using standard backfill practices. These pipes were instrumented to capture load-transfer behavior long their length.

Table 11 - Participating Organizations in the Tokachi, Japan Blast-Induced Liquefaction Experiment (Ashford & Juirnarongrit, 2002 [63])

Universities /Institutes	Industrial Participants
Port and Airport Research Institute	Japan Reclamation and Dredging Association
Civil Engineering Research Institute	Japan Association for Steel Piles
Waseda University	Japan Association for Marine Structures
University of Tokyo	Japan Gas Association
University of California, Berkeley	Tokyo Electric Power Company
University of California, San Diego	Kanden Kogyo
PEER	Sato Kogyo
	Caltrans
	Pacific Gas & Electric
	California Energy Commission

Figure 40 shows construction photographs and the general arrangement of each of these installations.

Figure 41 displays measurements that reveal typical behavior of the Tokachi site during a blast-induced liquefaction event. Four data traces are shown as a function of time for transducer located near the pipeline/conduit installation. The red and blue traces show pore-pressure ratio calculated from two independent peizometers, and the green and purple traces show longitudinal ground-surface displacement as measured with two antennae of a high-resolution real-time GPS system. The peach-colored background shows the duration of the primary sequence of blasting used to induce liquefaction. The large spikes in the data occur as the blasting sequence is adjacent to the pipelines. These data show that pore pressure buildup begins almost instantaneously with initiation of blasting, even for this location that is relatively distant from the initial blasts. Ground displacements begin slowly when the pore-pressure ratio approaches 50%. Total ground-surface displacement at this location of the site was on the order of 35 cm during this first event. A second event caused a similar level of displacement. The ground-surface displacements induced during these experiments were sufficient to induce yielding in the single pile and transverse pipelines/conduits. Pile cap motions were significantly smaller with the 9-pile group moving about half of the free-field displacements. Figure 42 shows the 9-pile group after the first liquefaction event. Notice the settlement of the ground surface both surrounding the pile cap and beneath it. This observation may have implications regarding modeling of the coupling of laterally spreading ground beneath a foundation. Ahmed Elgamal is now heading a program of detailed analyses of the Tokachi test results through a PEER-Core project.



6. Installation of Pipeline A

8. Pipeline A and B in Place

13. Compaction of 3rd Layer

4. Placement of 10 cm Lean Concrete

6. Construction of Reinforcement

8. Pile Cap after Concrete Work

Figure 40. Construction of pipelines (left) and pile-group foundation (right) at the Tokachi, Japan blast-induced liquefaction test site. (Ashford & Juirnarongrit, 2002 [63])

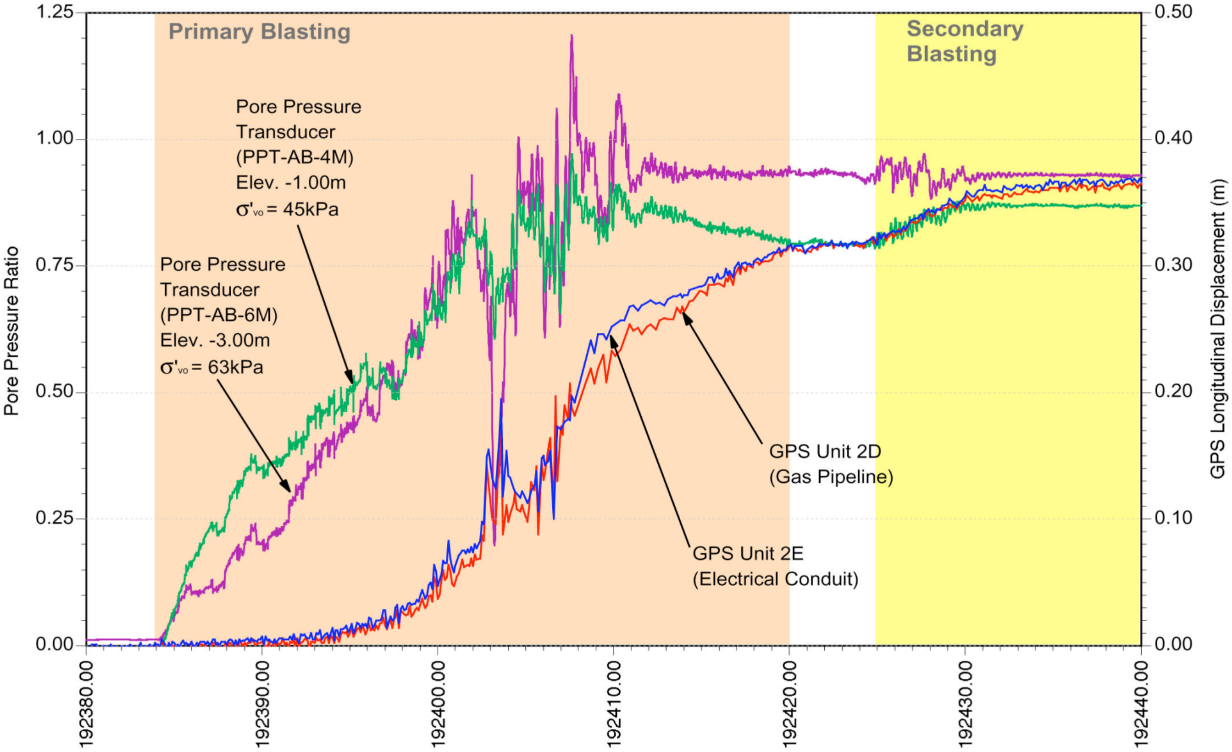


Figure 41. **Time-dependent traces of excess pore-pressure ratio and GPS-measured longitudinal displacement of the Tokachi site near the transverse pipes. (Turner, 2002 [64])**

More recently, PEER-LL has joined a major international collaborative project that will conduct a series of comparative experiments related to lateral spreading and its effects on pile foundations. Institutional participants include the National Research Institute for Earth Science and Disaster Prevention (NIED), Tokyo Institute of Technology (TIT), UC-San Diego (UCSD), and Rensselaer Polytechnic Institute (RPI). These experiments will be performed in both small-scale conditions using geotechnical centrifuges and in near-full-scale conditions using the large NIED shaking table in Japan. One of the primary objectives of the project is to validate the applicability of centrifuge test results since this type of testing is much less expensive to perform and will allow for a greater variety of model configurations to be tested.

Overall, results from the TILT project, the UC-Davis centrifuge experiments, the Tokachi test site, and the current program of testing under the US-Japan collaboration are providing the data needed to

Figure 42. **Settlement and expelled pore water near the 9-pile group (left) and underside of pile cap (right) after the 1st liquefaction event (from Ashford & Juirnarongrit, 2002 [63])**

constrain SFSI models for liquefied ground. These results are being used as the basis for development and evaluation of alternative design oriented models that can be expected to emerge in the next few years.

6.0 SUMMARY OF POTENTIAL RESEARCH IMPACT

This report provides an overview of wide ranging earthquake-hazard research activities ultimately aimed at the development of improved engineering design tools and practices. A remarkably diverse group of investigators, institutional resources, research strategies, and partnerships are involved in the execution of these programs. These and related subsequent investigations are expected to yield the following deployable products applicable to utility design practice:

- A suite of next-generation attenuation models that more fully account for near-field rupture directivity effects and basin depth effects for application to the specification of design response spectra;
- A comprehensive suite of test problems and expert-consensus solutions for use in the qualification of probabilistic seismic hazard codes;
- A design ground-motion library to aid designers in the selection of an appropriate suite of ground motion time histories for application in non-linear structural analyses;
- Guidelines for the application of alternative scaling methods and for identification of the needed number of time histories to achieve representative inelastic structural response within a specified level of confidence;
- Recommended consensus-based standards and a functional pilot virtual data center for electronic archive and exchange of geotechnical site-characterization data for application to site reconnaissance phases of a geotechnical investigation;
- Depth-dependent soil material models for use in equivalent-linear site-response analysis for design application to site-specific calculation of geotechnical site amplification;
- A fault surface-rupture model that quantitatively accounts for uncertainties in mapping, the distribution of slip along fault strike, the complexity of faulting, and the incidence of distributed secondary faulting for either probabilistic or deterministic specification of design surface rupture displacement as a function of facility footprint size and distance from mapped fault;
- A complete and consistent methodology for probabilistic assessment of liquefaction triggering potential using either SPT, CPT or Vs site characterization techniques for application to site-specific screening of potentially liquefiable sites;
- A complete methodology, including demonstration maps, for regional-scale mapping of liquefaction deformation hazard for application to route planning, design screening, and assessments of network reliability;
- A recommended procedure and guidelines for practical modeling of soil-structure interaction of pipelines and pile foundations located within liquefied and laterally displacing ground.

Another valuable legacy of this research program is a suite of both data and modeling resources that can be used for future research and to provide guidance for designers. Modeling resources include well-validated seismological simulation codes for both 1-D and 3-D analyses. Data resources include:

- A data set of uniformly-processed strong motion recordings including spectra, time histories, and both earthquake source and recording site metadata;
- A database of 3-D simulation results for 60 earthquake scenarios and 1600 sites in the Los Angeles region;
- A data set of 1-D hard-rock simulation results for over 10,000 generic source-site combinations emphasizing the near-source region;
- A data set of foamquake near-source motions capturing directivity for cases of uniform slip and with asperities;
- A suite of generic site-amplification factors as a function of input motion amplitude, site classification and site depth;
- A web-accessible archive of site characterization information for SMR sites;
- A web-accessible database of laboratory non-linear material properties test results;
- A comprehensive GIS database of mapped fault surface ruptures from recent earthquakes;

- A compilation of worldwide liquefaction triggering case histories along with subsurface characterization information using SPT, CPT, and Vs techniques;
- A GIS database of worldwide lateral spread case histories;
- Extensive experimental data sets from both laboratory and field studies quantifying soil-foundation interaction for the special case of liquefied and laterally spreading ground.

Overall, this combination of deployable products and legacy resources have led to significant advancements in earthquake engineering and hazard characterization. At the time of this writing, new attenuation models are being proposed through the NGA project that promise more accurate hazard estimates, resulting in more efficient engineering design and improved reliability. A fault rupture model and design tool is nearing release that will quickly become an indispensable tool for projects sited in close vicinity to earthquake faults. New probabilistic liquefaction triggering procedures are already being adopted by industry. Significant advancements on many important fronts, all effecting engineering design practice, have been achieved through the PEER-LL program. The authors of this report hope that the momentum gained over the last 5 years can be utilized to maintain a high level of achievement in the years ahead.

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