

Final Project Summary— PEER Lifelines Program

Project Title—ID Number	<i>Probabilistic Liquefaction Assessment by Shear Wave velocity—3D03</i>		
Start/End Dates	4/1/01 – 6/30/04	Budget/ Funding Source	\$47,450 / PG&E/CEC
Project Leader (boldface) and Other Team Members	Kayen (USGS/UCB)		

INTRODUCTION

Shear wave velocity (V_s) offers engineers a tool to assess liquefaction triggering of soil that is lower cost and provides more physically meaningful measurements than penetration methods. Development of the shear wave velocity liquefaction method has been hampered by a paucity of published velocity profiles; particularly in deeper soil deposits (>10m) and deposits subjected to high cyclic stress ratios ($CSR > 0.3$). To remedy the scarcity of data, we set out to assemble a global V_s dataset by acquiring new data at over 300 sites in Japan, Taiwan, China, and the United States (US). These data are merged with the exiting catalog of published velocity data. To acquire new field data, we use the continuous swept-sine wave spectral analysis of surface waves test (SASW). This test has proven to be extremely reliable at rapidly gathering high signal-to-noise dispersion data sufficient to invert 20-40 meter V_s profiles at liquefaction sites. This new dataset represents the majority of the worlds documented sites of liquefaction occurrence since instrumental recording.

To correlate the global shear wave velocity data set with likelihood of initiation of seismic-soil liquefaction, we utilize high-order probabilistic tools (Bayesian updating) and structural reliability techniques. A limit-state function for liquefaction triggering is modeled and evaluated based on the means, distributions and uncertainties of each model-variable. Each case history is sub-divided into ‘quality’-ranking categories based on the conjugate-uncertainties of CSR and V_{s1} . A cut-off threshold of the coefficient of variation is used filter-out poorly constrained sites. A Bayesian updating procedure is used to estimate coefficients for the limit-state function that minimize model error. The probability of liquefaction is then calculated using first- and second-order reliability methods (FORM and SORM). The intended outcome of this effort is a new evaluation of the V_s -liquefaction-triggering boundary in light of a global data set and modern limit-state probabilistic tools.

NEW DATA COLLECTION

Our project sought to elevate the V_s liquefaction-catalog to a level par with the penetration-based methods by conducting new investigations at sites previously documented using conventional tests. The catalogs developed for SPT and CPT correlations served as initial ‘road maps’ for new site investigation, and subsequent on-site access to local knowledge, observations, data-sets, and domestic publications allows us to fine-tune and expand our data collection efforts, particularly in the identification of non-liquefaction sites. At first step, we identified Asia and the United States liquefaction-investigation sites documenting conventional exploration and missing shear wave velocity logs. Recent well-documented historic events, spanning in time from the disastrous 1948 Fukui City earthquake up to the most recent 2003 Miyagi earthquake, were the principal targets of our field investigation. To efficiently re-evaluate these documented sites without drilling apparatus we are using the Spectral Analysis of Surface Waves (SASW) method to rapidly and non-invasively evaluate the shear wave velocity characteristics of soil. Surface wave methods are particularly useful for rapid, lightweight, high-resolution surveys of liquefaction sites where characterization of the near surface (typically <15m) are needed, and work well in difficult materials such as gravely deposits and stiff soils. Between 2001 and 2004, we visited and profiled at 315 liquefaction and no-liquefaction evaluation sites Asia and the US using surface wave techniques (Figure 1). Nearly all of well-documented liquefaction sites in East Asia, originally evaluated only by conventional penetration apparatus, have been re-tested in our study using surface wave methods.

BAYESIAN UPDATING for PROBABILISTIC ASSESSMENT of LIQUEFACTION

Bayesian updating is a rigorous probabilistic framework within which we experiment to identify a model that best describes the bounding frontier between regions of high- and low-likelihood of liquefaction occurrence. The curves in this bounding region express our degree-of-belief that initial triggering of liquefaction has, or will, occur. The model for seismic soil liquefaction is formulated in a traditional manner that limit-state models are formulated for single-component structural reliability problems: That is, capacity minus load. An example of one of the limit-state models we are testing is presented as:

$$g_{V_{s1}} = V_{s1}(1 + \alpha_1 FC) + \alpha_2 FC - \alpha_3 \ln(CSR) - \alpha_4 \ln(M_w) - \alpha_5 \ln(\sigma'v) + \alpha_6 + \alpha_7;$$

where V_{s1} is effective stress normalized shear wave velocity; FC is fines content (est. from other tests); CSR is earthquake-induced cyclic stress ratio; M_w is moment magnitude; σ'_v is effective stress; σ'_6 is the standard normal variate for an unbiased model, and ϵ is the model error term. We formulate a limit state model with positive-capacity and negative-load terms and solve, through iterative Bayesian updating, for the best-fit model parameters, σ'_6 's, that minimize the model error term, ϵ . The generalized model is a limit-state expression of strengths minus stresses. When the model tips into negative terrain, we have some degree-of belief that failure has, or will, occur. The Bayesian updating process used to solve for the model parameter, σ'_6 's, and model error term, ϵ involves selecting the critical liquefaction evaluation layer from the shear wave velocity logs and then computing the appropriate statistics for each model parameter. For our data set, critical layers are selected from adjacent SPT or CPT logs using the NCEER-workshop guidelines. Each variable in the limit-state function (CSR , V_{s1} , etc.) is assessed for their distribution statistics.

Bayesian updating involves forming an experimental likelihood function, selecting a non-informative prior distribution, calculating a normalizing constant, and then calculating a best estimate of the posterior statistics. Starting with a non-informative prior distribution allows for the computation of an unbiased posterior distribution. The experimental process of Bayesian updating is a search for the optimal likelihood function that minimizes model error. The equal probability contours for V_{s1} are presented in Figure 2 for approximately 60% of the dataset processed to date. These preliminary contours are generated by a mean value-first order-second moment (MVFOSM) estimation of the failure surface, and will be assessed for quality using higher order first- and second-order reliability methods (FORM and SORM) and Monte Carlo simulations.

SUMMARY

This project presents our efforts to expand the worldwide data set of shear wave velocity at liquefaction evaluation sites, and process these data within a Bayesian framework for probabilistic assessment of seismic-triggering of liquefaction. Since 2001, we have investigated approximately 300 Asia and US liquefaction evaluation sites using SASW. The elements of our investigation are (1) cataloging locations of all documented liquefaction and non-liquefaction sites, (2) identifying critical layers and their textural characteristics; (3) re-evaluating sites by active-source and passive-signal surface wave methods; and, (4), applying Bayesian updating and structural reliability methods to assess the likelihood of liquefaction occurrence. The objective of this project is a formal re-evaluation of the liquefaction resistance assessment methodology by shear wave velocity in light of a new global data set and higher order probabilistic data processing.

ACKNOWLEDGEMENTS

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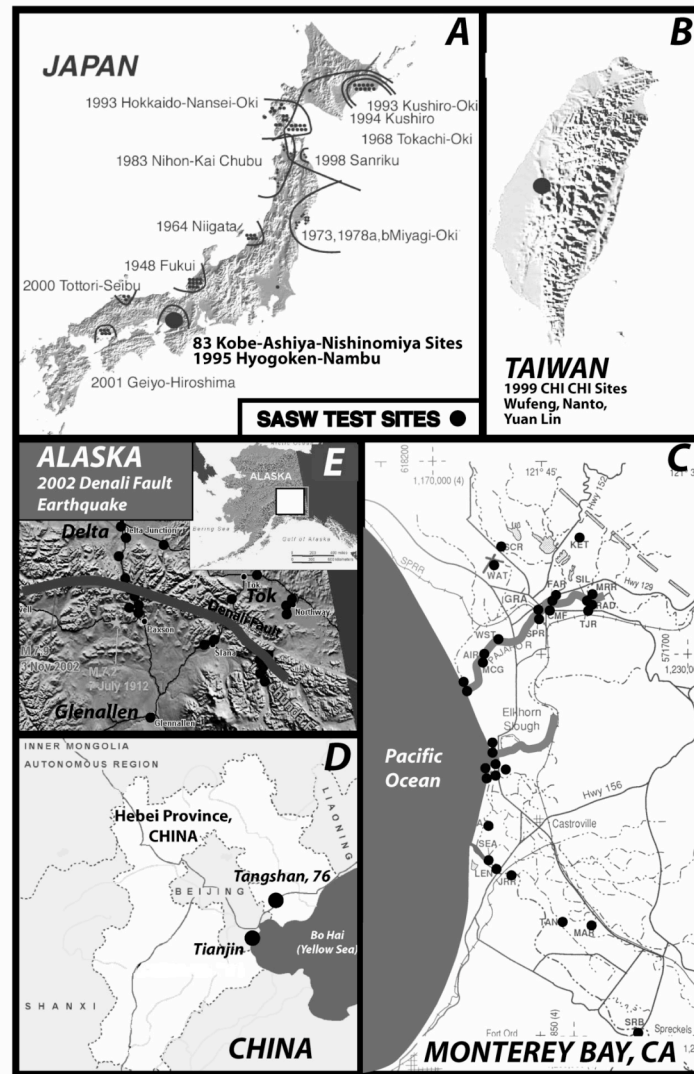


Figure 1. New shear wave velocity profiles at liquefaction evaluation sites (clockwise from top-left): (A) 168 - Japanese test sites (83 in Kobe area) collected in 2001-2; (B) 14 - Chi Chi, Taiwan, earthquake sites collected in 2001, and new sites collected in Nov. 2003; (C) 36 - Moss Landing, Pajaro, Salinas River sites and inner Bay Area sites (not shown) collected 2001-2003; (D) 26 Tangshan and Tianjin, China sites collected in October 2003; (E) 26 - Denali Fault earthquake sites, central Alaska and 22 - 1964 Alaska earthquake (not shown).

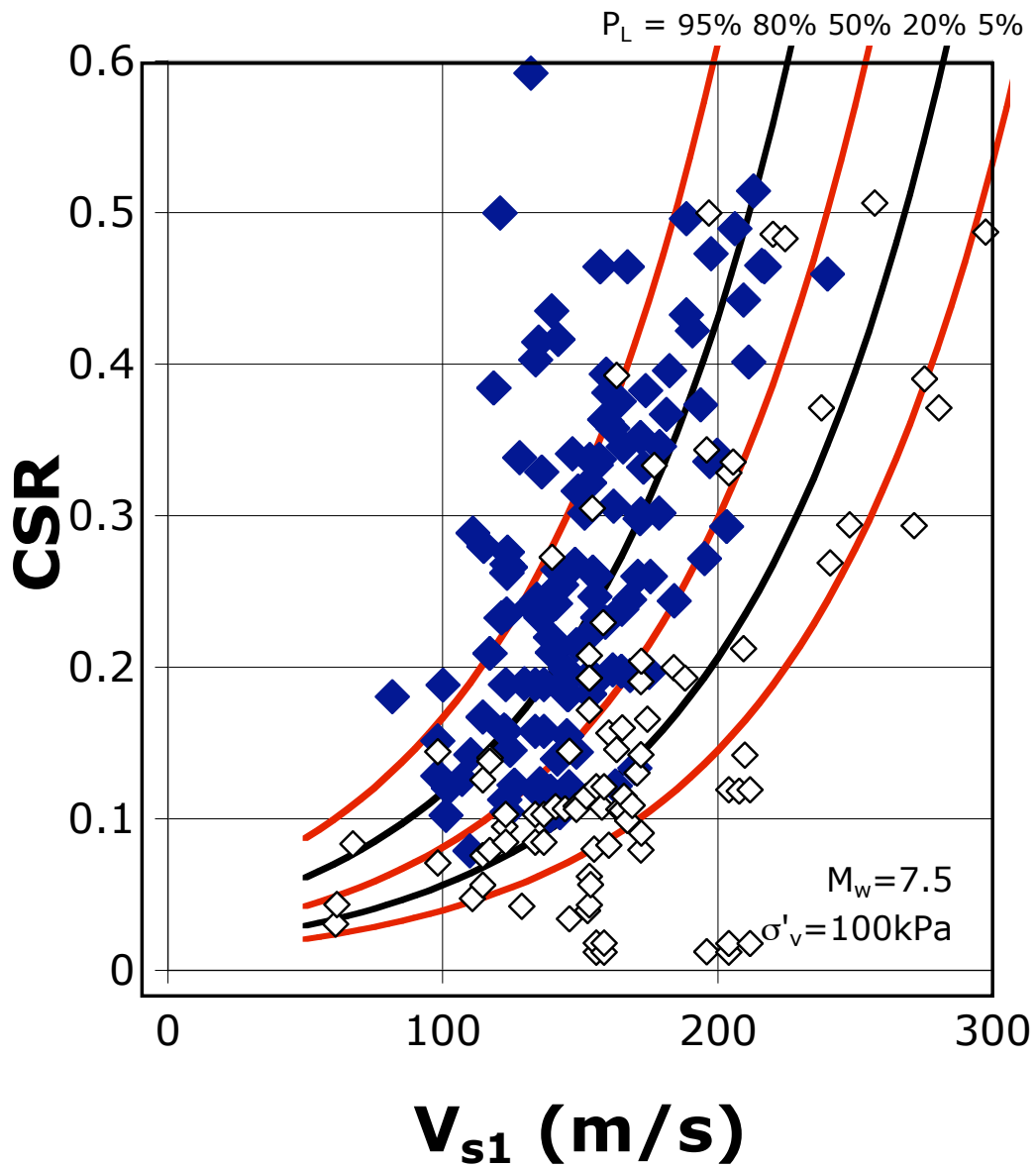


Figure 2. Preliminary probabilistic liquefaction triggering contours for ~60% of the global V_{s1} data set processed to date. P_L is the probability (degree-of-belief) that liquefaction has occurred.