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An Updated Shear Wave Velocity-Based Seismic Soil Liquefaction Triggering Database

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ABSTRACT

The small-strain shear wave velocity (V_s) is a means to assess the triggering of seismic soil liquefaction since the early 1990s, and the size and quality of these data sets have grown enormously in the past decades. Based on these data, researchers from 1991 to the present have developed V_s -based seismic soil liquefaction triggering relationships. The authors revisited the V_s -based database to update the case histories with the current state of knowledge and include new case histories (e.g., 2011 Tohoku earthquake, 2010–2011 New Zealand-Canterbury earthquakes, etc.). This paper presents the updated V_s -based database, along with the details and statistics of the case history database. The updated database consists of (1) 537 case histories, (2) new earthquake events, (3) multiple inversion method, (4) assessment of nearby standard penetration test (SPT) and cone penetration test (CPT) data, (5) dispersion curves, (6) multiple shear wave velocity profiles, (7) digitized V_s profiles of the literature case histories, (8) implementation of the improved selection of unit weight, (9) new parameters related to site information (e.g., V_{s30m} , etc.), (10) standard protocol to process data in an unbiased manner, (11) uncertainties of each input parameter, and (12) and geological site classification. Every input parameter was revisited, reanalyzed, and updated. The new database is organized to develop new probabilistic shear wave velocity-based seismic soil liquefaction triggering relationships using Bayesian analysis and system reliability methods.

INTRODUCTION

Shear wave velocity (V_s) testing is one of the most widely used in-situ field tests in engineering applications. Since 1991, V_s tests results were studied to understand the relationship between soil resistance to liquefaction and V_s (e.g., Robertson et al. 1992, Kayen et al. 1992, Lodge 1994, Andrus and Stokoe 2000, Zhou and Chen 2007, Kayen et al. 2013, Dobry et al. 2015, Guoxing et al. 2019, 2020). The Standard Penetration Test (SPT) and Cone Penetration Test (CPT) are large strain in-situ field tests that provide a direct correlation to the relative density of soils which affects the cyclic behavior of soil (Idriss and Boulanger 2008), but these tests fail in gravels. The BHT and V_s are applicable for gravelly site conditions that are prone to soil liquefaction. The V_s test does not provide soil layer characteristics (e.g., fines content or plasticity), but is the only field test that measures a fundamental soil property, the initial shear modulus. This soil “stiffness” term has been shown to have a strong influence on seismic soil liquefaction behavior (Dobry, et al. 1982).

V_s -based seismic soil liquefaction triggering relationships based on field case histories are commonly used in engineering applications (e.g. Robertson et al. 1992; Lodge 1994, Kayen et al. 1992, Andrus and Stokoe 2000, Kayen et al. 2013, Dobry et al. 2015, Guoxing et al. 2019). There are also laboratory-based assessments to evaluate shear wave velocity-based liquefaction triggering relationships (Zhou and Chen 2007, Ahmadi and Paydar 2014, Dobry et al. 2015, Oka et al. 2018, Guoxing et al. 2020).

Direct measurement methods for V_s need drilling of one or two boreholes to measure the V_s of the soil layers or a CPT truck, hence they have a higher cost as compared to noninvasive V_s testing methods (Kayen et al. 2013 will be referred as KEA2013 hereafter). Non-invasive surface wave methods provide an easier mobilization in the field without the need for drilling. Non-invasive methods indirectly estimate the V_s profiles, and uncertainties must be assessed in the estimation of the V_s profile.

The main scope of this study is to revisit and update the KEA2013 database with the current state of knowledge and extend the database with recent field testing and literature data. The database presented herein represents a 20-year field measurement campaign augmented with literature case histories. The V_s -field testing included more than 600 test locations across the world. The new V_s -based liquefaction-triggering field case history database consists of a subset, 537 sites including case histories from new earthquake events including the 2010-2011 Canterbury Earthquake Sequence, 2011 Tohoku, and the 2014 Napa Earthquakes.

V_s -based Liquefaction Triggering Database and Relationships

The Cyclic Stress Ratio (CSR)-shear wave velocity-based method for seismic soil liquefaction assessment was originally presented by Seed et al. (1983) based on SPT- V_s correlations. The seismic cone penetration method allowed Robertson et al. (1992) to advance the CSR- V_s model with a database of 4 earthquake events. Kayen et al. (1992) and Lodge (1994) added V_s -data for the 1989 Loma Prieta Earthquake for the soil sites along the East Bay shoreline. Andrus and Stokoe (2000), presented a suite of literature-derived case histories from the 1975 Haicheng, 1999 Lotung, and 1964 Niigata earthquakes, as well as case histories measured by the authors from the 1983 Borah Peak, 1979 Imperial Valley, 1981 Westmoreland and assessed within a probabilistic framework by Juang et al. (2001) and Juang et al. (2002). Zhou and Chen (2007) present a laboratory-based framework of liquefaction assessment. KEA2013 presented the results of an 11-year international project to collect new V_s site data and developed a probabilistic liquefaction boundary from a database of 422 case histories. These data represent 301 new liquefaction field case histories in China, Japan, Taiwan, Greece, and the United States at locations of SPT and CPT data; and 121 case histories from the literature. Recent studies explore laboratory-derived measure of liquefaction triggering on soil mixtures and soils of different provenance (e.g., Dobry et al. 2015, Ahmadi and Paydar 2014, Oka et al. 2018, Guoxing et al. 2019, 2020)

The authors of this paper revisit KEA2013 to update the case histories with recent event data, principally 2011 Tohoku, and the 2010-2011 Canterbury Earthquake Sequence, and apply advancements in parameter estimation and uncertainty measurement.

NEW V_s -BASED CASE HISTORY DATABASE

The new earthquake events that are added to the database which were not covered by KEA2013 are i) 1987 Edgecumbe, iii) 2010 Darfield, iii) 2011 Christchurch, iv) 2010 Jiasian,

and v) 2014 Napa Valley. A set of new data is compiled for the site performance from the previously studied earthquakes. (e.g. 2011 Tohoku, 1999 Kocaeli Earthquakes.) The total of 44 earthquake events passed the screening criteria of this study with 537 case histories from these events. There exist many case histories that were processed but later excluded from the database due to i) partial saturation, ii) presence of organics, iii) poor V_s profile, and iv) lack of ground motion parameters, etc. The locations of the V_s -based seismic soil liquefaction case histories are shown in Figure 1 along with the number of case histories for each region.



Figure 1. The locations from the shear-wave velocity case history database (537 case histories from 44 earthquake events)

The name of the earthquake event and the number of case histories processed are listed in Table 1. The current dataset has 158 new case histories. The legacy case histories were also restudied. Some of the legacy sites are excluded based on an unacceptable level of uncertainty or merged considering the proximity of nearby sites. The resulting number of legacy case histories after this screening process is 379.

Updating legacy case histories

The legacy case history data from the KEA2013 database were reprocessed using two new inversion alternatives i) the SIM method of Pelekis and Athanosopoulos (2011) here called ‘MAT’ and ii) Haskell-Thomson, here called ‘HT’ are studied to develop V_s profiles at approximately 1 m depth increments which are presented in the new catalog. The mean and standard deviation of V_s and V_{s1} are calculated as the average (e.g. $(V_{s,MAT} + V_{s,FFT})/2$) and standard deviation (e.g. $\text{SQRT}(\sigma_{V_s,MAT}^2 + \sigma_{V_s,FFT}^2)$) based on these inversion alternatives. The calculated combined variance enabled authors to capture the uncertainty of different inversion methods. The V_s profiles that are obtained from the literature were also digitized and provided electronically in the new database, and if more than one measurement is available for the literature sites, the mean and standard deviation of the capacity term is calculated similarly.

Table 1. Distribution of earthquake events within the V_s database

Earthquake	# of sites	Earthquake	# of sites
1906 San Francisco	2	1989 Loma Prieta	49
1948 Fukui	11	1993 Hokkaido-Nansei-Oki	27
1964 Niigata	9	1993/1994 Kushiro-Oki/Kushiro	8
1968 Tokachi-Oki	4	1995 Hyogo-Nambu	83
1973 Miyagi-Ken Oki	11	1999 Chi-Chi, Taiwan	14
1975 Haicheng	5	1999 Izmit Earthquake	1
1976 Tangshan	24	2000 Tottori Seibu	3
1978 Miyagi-Ken Oki	8	2001 Geiyo-Hiroshima	5
1979 Imperial Valley	7	2002 Denali Fault	9
1980 Mid-Chiba	2	2005 Sanriku Minami	11
1981 Westmorland	7	2003 Tokachi-Oki	10
1983 Borah Peak	19	2003 Tokachi-Oki Aftershock	1
1983 Nihonhai-Chubu	8	2007 Niigata Chuetsu Oki	2
1983 Nihonhai-Chubu Aftershock	2	2008 Achaia-Elia	2
1986 Chiba-Ibaragi-Kenkyo	2	2010 Darfield	61
1986 Lotung Sequence	5	2010 Jiasian	1
1987 Chiba-Toho-Oki	1	2011 Christchurch	61
1987 Edgecumbe	2	2011 Tohoku	35
1987 Elmore Ranch	7	2011 Tohoku Aftershock	10
1987 Superstition Hills	7	2014 Napa Valley	1
Sum of V_s-based case history data: 537			

A more robust selection of unit weight by Mayne et al. (2009) is implemented. Mayne et al. (2009) provide a unit weight estimation as a function of V_s and depth for a wide range of soil types (e.g. clay, silt, sand, gravel, intact rocks, peat). The mass participation ratio (r_d) provided by Cetin and Seed (2004) utilizes V_{s12m} that is calculated from the mean of V_{s12m} of each case history inversion profile.

The new catalog follows a protocol to process the data in an unbiased manner that includes the uncertainty estimations for each input parameter. The authors also determined the geological units of each site. Among the 537 case histories, the geological units of 468 sites have been determined and 17% of the sites are located on placed fills and 83% of the sites are located in native deposits.

Large case history catalog from New Zealand

The new database includes site data from the following earthquakes 1987 Edgecumbe, 2010 Darfield, 2011 Christchurch, 2011 Jiasian, 2011 Tohoku, and 2014 Napa Valley Earthquakes. Two of these datasets represent significant additions in terms of the number of case histories: New Zealand and Japan.

The 2010-2011 Canterbury Earthquake sequence caused significant damage to Christchurch, New Zealand due to liquefaction. Two events: the 2010 Darfield and the 2011 Christchurch Earthquakes were studied for the population of new V_s -based case histories. For that purpose,

three main studies by i) Wood et al. (2017), Green et al. (2014), ii) McLaughlin (2017), and iii) Wotherspoon et al. (2015) which examine the CPT and V_s data around the Christchurch area were studied. Along with the CPT dataset, the SPT catalog of Ilgac (2022) is also used jointly to assess the soil characterization of the case histories. A total number of 78 sites (x 2 events) are studied and among 156 case histories that are fully documented, some of the sites were excluded due to i) presence of organics, ii) partial saturation problems, and iii) presence of cyclic mobility vulnerable very soft fine-grained soil layers. These efforts populated a total number of 61 V_s sites for the 2010-2011 Canterbury Earthquake which corresponds to 122 new case histories.

An illustrative case history site (KAN03) is presented as an example site for V_s -based case histories in New Zealand, the location of the V_s measurement and the aerial image after the 2011 Christchurch Earthquake is shown in Figure 2a. Very small sand boils (>1 m in diameter) formed in isolated spots around the park are noted by Wood et al. (2017) after the 2010 Darfield Earthquake and no surficial evidence of liquefaction is reported after the 2011 Christchurch Earthquake. The surface waves are measured by using the spectral and multi-channel analysis of surface waves (SASW and MASW) methods and the dispersion curve is shown in Figure 2b. Figure 3a-d presents V_s , r_d , CSR, and V_{sl} versus depth plots that are drawn for KAN03 after the 2010 Darfield Earthquake. The shear wave velocity profile for the two alternative inversion plots is co-plotted on the same figures, and the critical depth range is shaded by red color which is a sand layer with an average tip resistance of $q_c=8.3$ MPa. The potentially liquefiable layer is selected by considering the nearby CPT data. The soil profile consist of sensitive fine grained materials in the upper 3.7 m followed by a 3 m thick sand layer. The sand layer located at 3.75-6.7 m which is fully saturated and non-plastic is claimed to be the potentially liquefiable layer. The liquefiable layer is followed by sandy mixtures with plastic material (RF=3%) and underlain by relatively stiff sand layer with an average tip resistance of $q_c=13$ MPa.

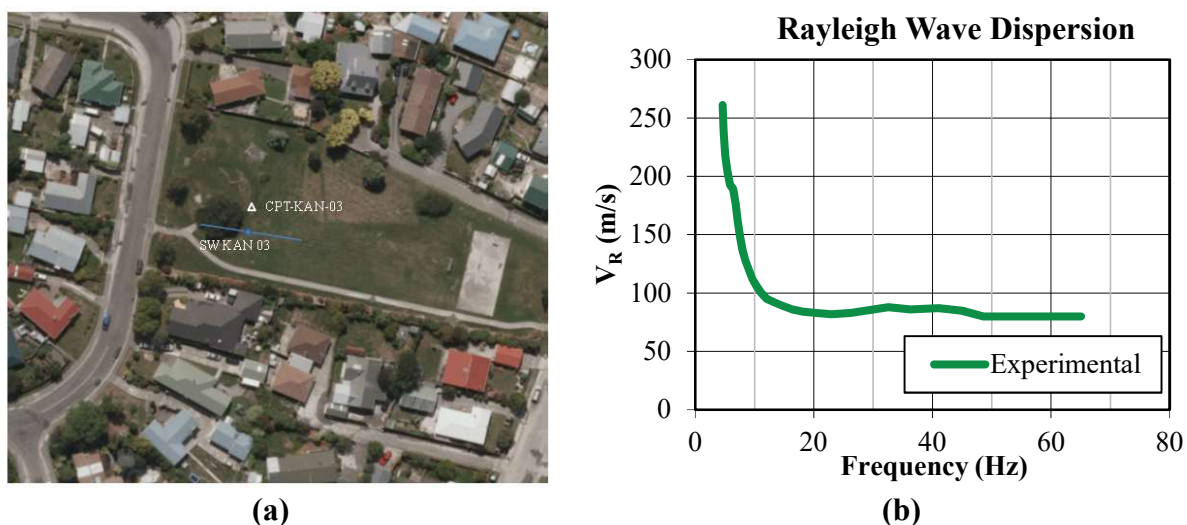


Figure 2. a) Aerial image of KAN03 (after Wood et al. 2017) after 2011 Christchurch Earthquake, b) experimental dispersion curves at KAN03.

Among 122 case histories from 2010 Darfield and 2011 Christchurch events, 50 of the sites were tested with SCPT, and 72 of them were measured by SASW and MASW. The dataset of New Zealand consists of 4 marginal, 57 positive liquefaction, and 61 no liquefaction case

histories. The critical depth for the New Zealand case histories has an average of 5.3 m with a standard deviation of 2.6 m. The PGA varies from 0.13 to 0.68 g. The range of CSR and V_{s1} is calculated as 0.09 to 0.69 and 118 to 240 m/s, respectively. This sub catalog presents case histories of good quality which will significantly contribute to the development of V_s -based liquefaction triggering boundaries.

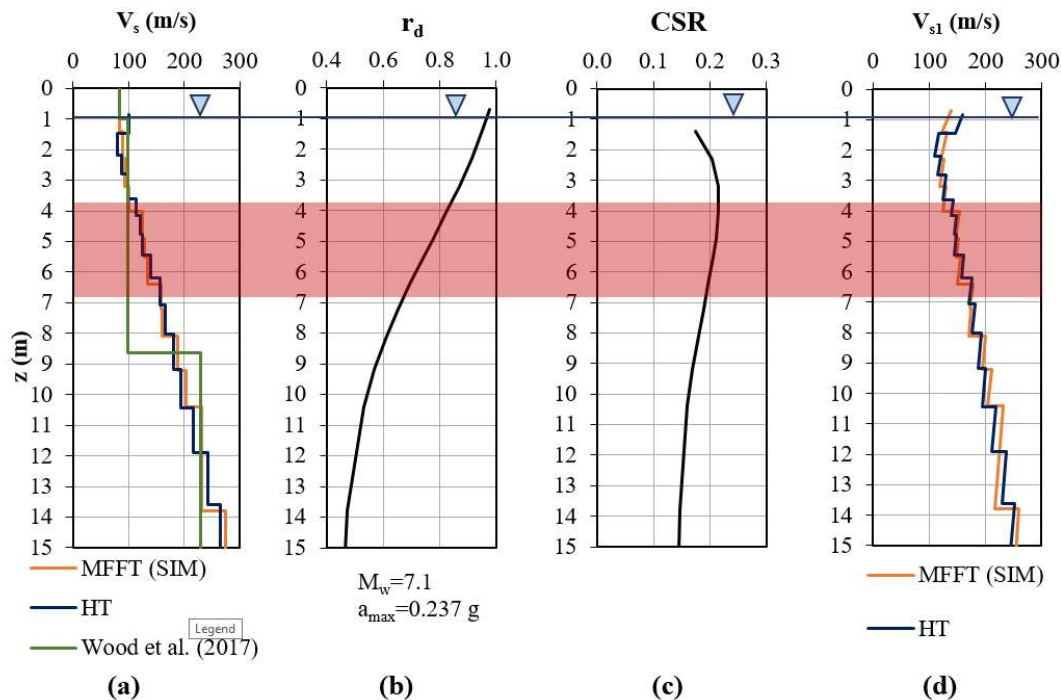


Figure 3. a) V_s , b) r_d , c) CSR, and d) V_{s1} versus depth plots drawn for KAN03 after the 2010 Darfield Earthquake.

Large case history catalog from Japan

The GEER association used Japanese reports and subsurface investigations, to perform new studies at sites that liquefied during the 2011 Tohoku Earthquake. A total of 39 new shear-wave velocity sites were collected for sites in the Urayasu district of Tokyo (Cox et al. 2013). The authors made additional measurements in Chiba, Ibaraki, and Miyagi Prefectures using MASW, SASW, and microtremor array measurements. For brevity, we have left out figures associated with Japan data, please refer to the GEER report and Cox et al. (2013) for more detail.

STATISTICS FOR THE NEW CASE HISTORY DATA

The new database consists of 537 case histories which have a mean critical layer depth that varies from 1.25 to 18.15 m. The moment magnitude of the events varies from 5.9 to 9.0 and the PGA levels from 0.02 to 0.76 g. The resultant $CSR_{\sigma'v}$, M_w , and V_{s1} values that represent the mean value of the critical layer are calculated as 0.01 to 0.80 and 104 to 391 m/s.

Figure 4a-f presents the distribution of critical layer depth selection, groundwater table (GWT), peak ground acceleration (a_{max}), r_d , V_{s1} , and CSR with respect to case numbers for liquefied, non-liquefied, and marginal sites for the 537 case histories.

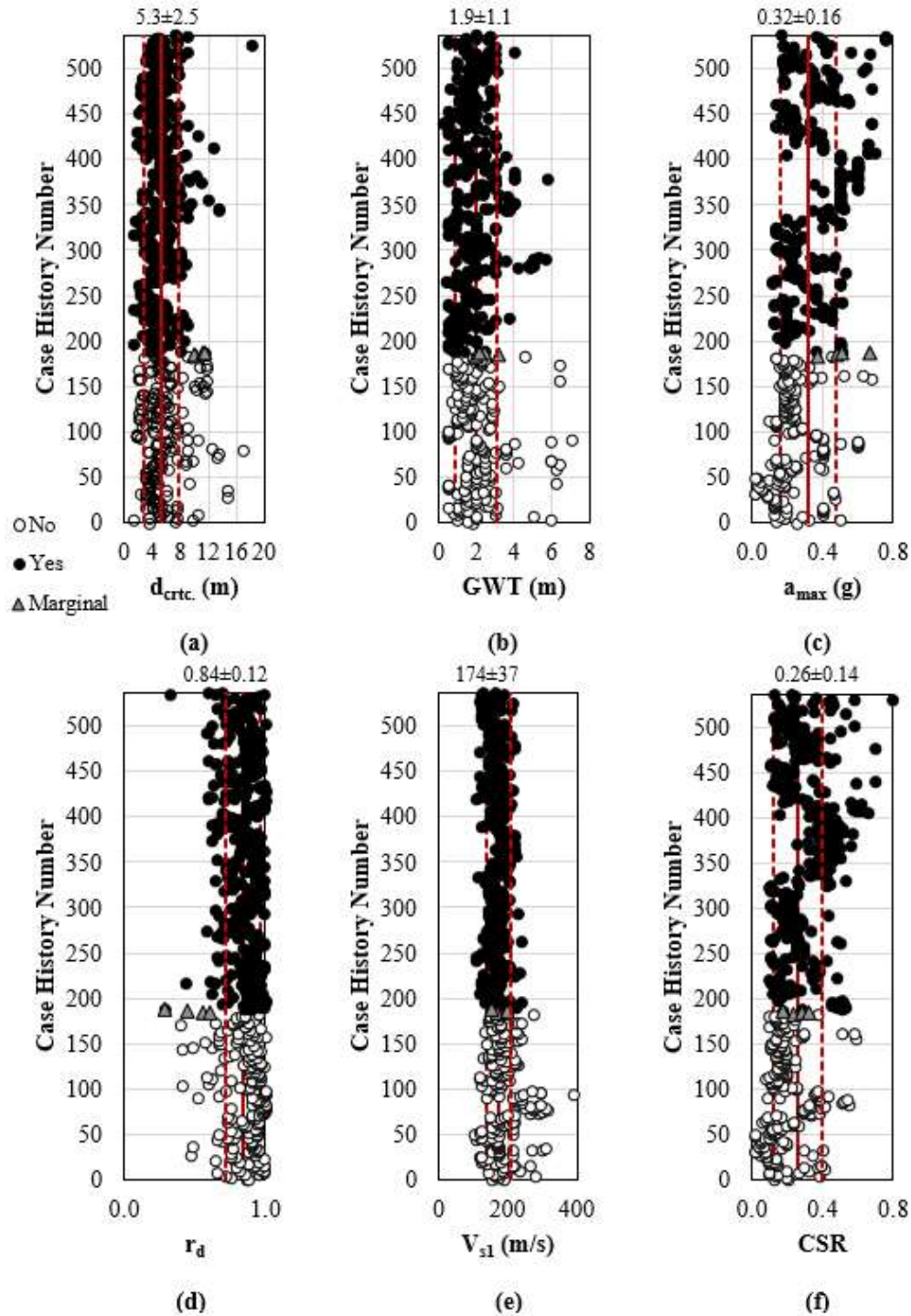


Figure 4. The distribution of a) d_{crtc} , b) GWT, c) a_{max} , d) r_d , e) V_{s1} and f) CSR with respect to case numbers for the entire catalog (537 data). (dots, circles, and triangles represent liquefied, non-liquefied and marginal sites, respectively.)

The mean values of V_{s1} and CSR for all case histories are shown in Figures 5a and 5b where overburden stress (K_σ), magnitude (duration factor) (K_{Mw}), correction for sloping sites (K_α)

effects on the CSR calculation are not considered for points in Figure 5a, and in Figure 5b the same data is corrected for K_σ , K_{Mw} , K_α effects (i.e., $CSR_{\sigma'_v=100\text{kPa}, Mw=7.5}$). The resulting database is being used to develop new probabilistic shear wave velocity-based seismic soil liquefaction triggering relationships by Bayesian analysis.

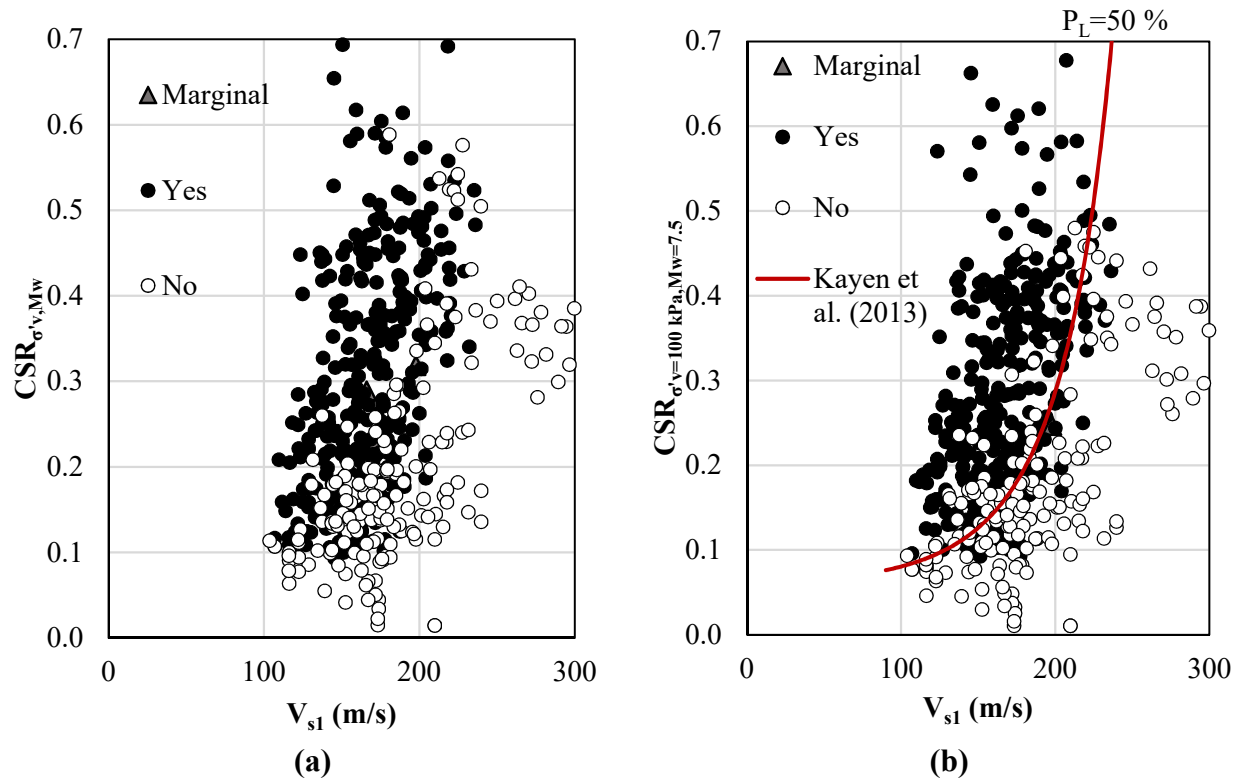


Figure 5. Updated V_s -based case history database (V_{s1} versus $CSR_{\sigma'_v, Mw}$ domain), b) on V_{s1} versus $CSR_{\sigma'_v=100\text{ kPa}, Mw=7.5}$ along with Kayen et al. (2013) $P_L=50\%$ curve. (dots, circles, and triangles represent liquefied, non-liquefied and marginal sites, respectively.)

BAYESIAN ANALYSIS AND LIMIT STATE FUNCTION

This dataset is used to assess the likelihood that a site tips towards liquefaction or away from it based on prior data and observations. This method of estimating probabilities based on priors is called Bayesian analysis. We establish a limit state function with initial conditions of mean values of the entire dataset and estimate the probability of liquefaction occurrence by contrasting the individual site parameters with the prior dataset. As we incrementally evaluate sites they get added to the priors. An example of a limit state function for shear wave velocity assessment is presented in KEA2013 and also in Equation 1. The parameters (e.g. a_{max} , V_s , M_w , σ'_v , r_d , etc.) are measured properties of load or capacity, and θ 's (θ_1 , θ_2 etc.) are the coefficients modeled through Bayesian analysis. Updated version of θ 's for the KAE2013 can be found in Kayen et al. (2015). The data presented in this paper is still under review. We are currently reevaluating the structural form of the limit state function. Hence the digital updated version of the database and the limit state model will be available in another paper.

$$g_{V_{s1}} = \theta_1 V_{s1}^{\theta_2} + \theta_3 \ln(CSR) + \theta_4 \ln(M_w) + \theta_5 \ln(\sigma'_v) + \theta_6 FC + \varepsilon \quad (1)$$

CONCLUSION

This paper presents authors' efforts to advance the V_s -based liquefaction triggering methodology. The updated database consists of 537 case histories and includes new earthquake events; and multiple inversion methods. As with KEA2013, most of the sites are nearby SPT and CPT logs. Importantly, each input parameter is evaluated in terms of mean-variance. The updated database is being used to develop new probabilistic shear wave velocity-based seismic soil liquefaction triggering relationships by implementing Bayesian analysis which is not discussed here due to page limitations is the scope of another paper.

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