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Journal

GEO-CONGRESS 2022: GEOPHYSICAL AND EARTHQUAKE ENGINEERING AND SOIL DYNAMICS, 334(GSP 334)

ISSN

0895-0563

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Publication Date

2022-03-17

DOI

10.1061/9780784484043.030

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Updated SPT-Based Seismic Soil Liquefaction Triggering Global Database

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ABSTRACT

The standard penetration test (SPT) has been used to assess the triggering of seismic soil liquefaction since the early 1970s. The currently available liquefaction case history database is updated and extended with the case histories from recent earthquake events. An updated database, which consists of 405 case histories from several recent major earthquake events (e.g., 1999 Chi-Chi, 2008 Achaia-Ilia, 2010 El-Mayor, 2011 Van, 2011 Tohoku, 2011 Christchurch, 2012 Emilia-Romagna, 2016 Kaikōura, 2018 Jia Sian, etc.) was compiled. This new SPT-based field case history database consists of (1) 405 case histories from (2) 33 new earthquake events, (3) with different faulting mechanisms including strike-slip, normal, reverse, and subduction earthquake events, and introduced (4) new event parameters (e.g., R_{rup} , R_{jb} , Z_{tor} , etc.), (5) gravelly and silty critical layers with the introduction of new correction terms (e.g., gravel correction), (6) fully digitized borehole information, GPS coordinates, and comparative assessment of new screening criteria with the nearby CPT and V_s data, (7) site response and deconvolution analyses at strong ground motion liquefaction sites to estimate CSR, (8) new parameters related to ground motion and site information (e.g., event type, rupture distance, V_{s30m} , etc.), (9) a description of geological settings, and (10) new stress (C_N), energy (C_E), and rod length (C_R) correction terms. Within the confines of this manuscript, this database compilation and processing details will be presented. The resulting database is to be used to develop new probability-based liquefaction triggering relationships.

INTRODUCTION

Standard Penetration Test (SPT) is commonly used worldwide in a large number of geoenvironmental assessments. Among several other alternative field test-based liquefaction triggering databases (e.g., cone penetration test (CPT), shear wave velocity test (V_s)), SPT-based liquefaction triggering field case history database will be the focus of this paper. Seed et al. (1985) presented the pioneering SPT-based liquefaction triggering database and methodology. A database, consist of 125 case histories was plotted on the capacity (equipment and procedure corrected SPT blow counts, $N_{1,60}$) versus demand (cyclic stress ratio, CSR) space by Seed et al. (1985). This first deterministic triggering relationship set was developed for three different fines content (FC) levels (5, 15, and 35%) that separates liquefied and non-liquefied field performances. This study inspired further research projects and since then, several research teams have developed liquefaction triggering relationships (Cetin et al. (2004, 2018), Moss et al. (2006), and Idriss and Boulanger (2010), Boulanger and Idriss (2012, 2014), etc.). The scope of

this study involves revisiting Cetin et al. (2004, 2018) databases with the current state of knowledge, and update them with the addition of new case histories from recent earthquake events.

The new SPT-based liquefaction triggering field case history database introduces a larger number of case histories, from events that occurred between 1996-2020 (e.g. 2001 Nisqually, 2003 Tokachi-oki, 2003 Lefkada, 2010 El-Mayor, 2011 Van, 2012 Emilia-Romagna, 2011 Christchurch, 2011 Tohoku Earthquakes, etc.) with different faulting mechanisms including strike-slip, normal, reverse, and subduction earthquake events. Additionally, a wider range of moment magnitude ($M_w=4.6-9.1$) events was included in the database along with the relevant event parameter terms (dip angle, event type, rupture distance (R_{rup}), Joyner-Boore distance (R_{jb}), etc.). Some new descriptive variables (e.g., geological conditions, etc.) were also added. Another important contribution to note is the presence of gravelly and silty critical layers, which enable the introduction of new correction terms (e.g., gravel corrections). All the available data is digitized, GPS coordinates of the case histories were provided and presented in a transparent format in the new database. When possible, 1-D equivalent linear site response and deconvolution analyses were performed mostly for case histories at strong ground motion station (SMS) sites to estimate more accurately the CSR values. Additionally, the legacy case history sites were also re-studied with the current state of knowledge based on revised screening criteria. For example, the intensity parameter (peak ground acceleration, PGA) is estimated from updated local ground motion models calibrated with available strong ground motion recordings. Intensity-based estimation of PGA was judged to be not acceptable according to revised screening criteria. Hence those cases existing in the previous databases were excluded. These updated criteria cover a set of new insights (e.g. presence of organics which decrease the degree of saturation, presence of very soft fine-grained layers which make the accurate estimation of r_d and a_{max} through simplified procedures very difficult, etc.) which are not presented herein due to page limitations of this paper. A new probability-based liquefaction triggering model is to be proposed by using the updated SPT catalog utilizing the Bayesian updating scheme. More details regarding the database compilation efforts and the updated models can be found in Ilgac (2022).

NEW FIELD DATA

A significant number of earthquakes occurred in the last 25 years, which caused excessive damage to structures due to seismic soil liquefaction. SPT case history catalog of Cetin et al. (2018) consists of events until the 1995 Hyogoken-Nambu (Kobe) Earthquake. The purpose of this study is to update and enrich the database with new field case history data. Among numerous earthquake events that triggered liquefaction in the world, 45 of them were judged to be significant events to be added to the new database. Field data and liquefaction performance along with ground motion parameters were studied in detail for these events. The final screening scheme reduced the number of the new events to 33 from which 195 new case histories were extracted. Some of the reasons for the exclusion of these events were listed as lack of strong ground motion recordings which enable the accurate estimation of intensity parameters (e.g. a_{max} , etc.), or the lack of information regarding SPT procedure which prevents the proper correction of SPT-N values to calculate $N_{1,60}$. The new database consists of case histories from previously studied 5 earthquakes (e.g., 1976 Tangshan, 1989 Loma Prieta, etc.) with the help of recently available information in the literature. The new database provides not only a broader catalog in terms of quantity but also helps us to better understand and evaluate some of the parameters that

affect seismic soil liquefaction. For example, the moment magnitude (M_w) range for the new case histories varies from 4.6 to 9.1 as contrary to M_w range of legacy case histories which are compiled from events with M_w ranging from 5.9 to 8.3. The new database fills the gap of low and high magnitude range of legacy case histories, which is expected to better assess magnitude (duration) corrections. Ilgac (2022) presents the details of the new case history database compilation efforts comprehensively. The locations of new events that are recently added to the database are shown in Figure 1. The numbers in the first brackets are M_w values of the events, and the number of case histories populated from those events is shown in the second bracket. The total number of events is 38, which enabled the population of 195 new case history.

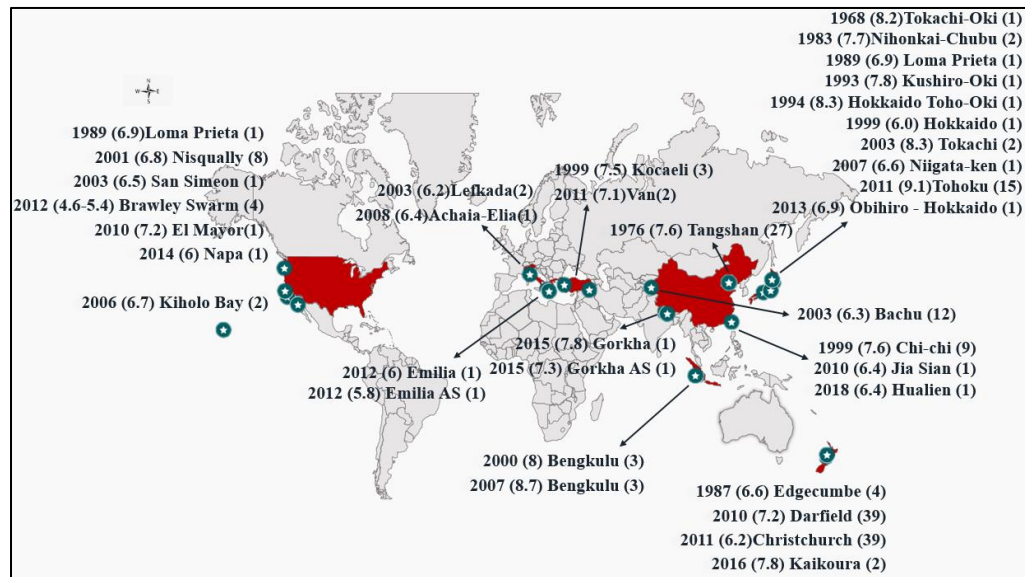


Figure 1. The location of the new earthquake events.

Three example Case Histories from the USA, Turkey, and New Zealand

The processing details of three new case histories will be illustratively presented next. These events are compiled from i) 2001 Nisqually, Seattle, USA, ii) 2011 Van, Turkey, and iii) 2011 Christchurch, New Zealand earthquakes. Those case histories are unique examples of SPT-based seismic soil liquefaction triggering database expansion efforts and they were not included by the previous databases.

Case history #1: 2001 Nisqually Earthquake, USA – Capitol Lake

The 2001 M_w 6.8 Nisqually earthquake was an intraslab earthquake that caused damage to Seattle, USA. As an illustrative example, Capitol Lake case history will be discussed in this paper. Capitol Lake is located in Seattle (47.0381, -122.9069). Lateral spreading was observed with slumping of newly constructed shoreline along the east side of the lake. Sand boils were observed in the restricted access area, which is shown in Figure 2a by Pacific Earthquake Engineering Research Center (PEER) teams after the 2001 Nisqually earthquake. Maximum acceleration (a_{max}) is determined from a nearby recording station as 0.238 g, which is the geometric mean of the two horizontal components of 0.222 g and 0.255 g (Unites States

Geological Survey, USGS station #2101). The a_{max} that is recorded at the SMS (USGS2101) is decided to be representative of the site since it is located only 1.1 km away from the site which has similar site conditions (i.e., V_{s30} values) and is found on a similar geological setting. Additionally, the USGS global geospatial PGA model was also checked, which suggests $a_{max} > 0.2$ g as shown in Figure 2b, lending credibility to the selection of $a_{max} = 0.238$ g.

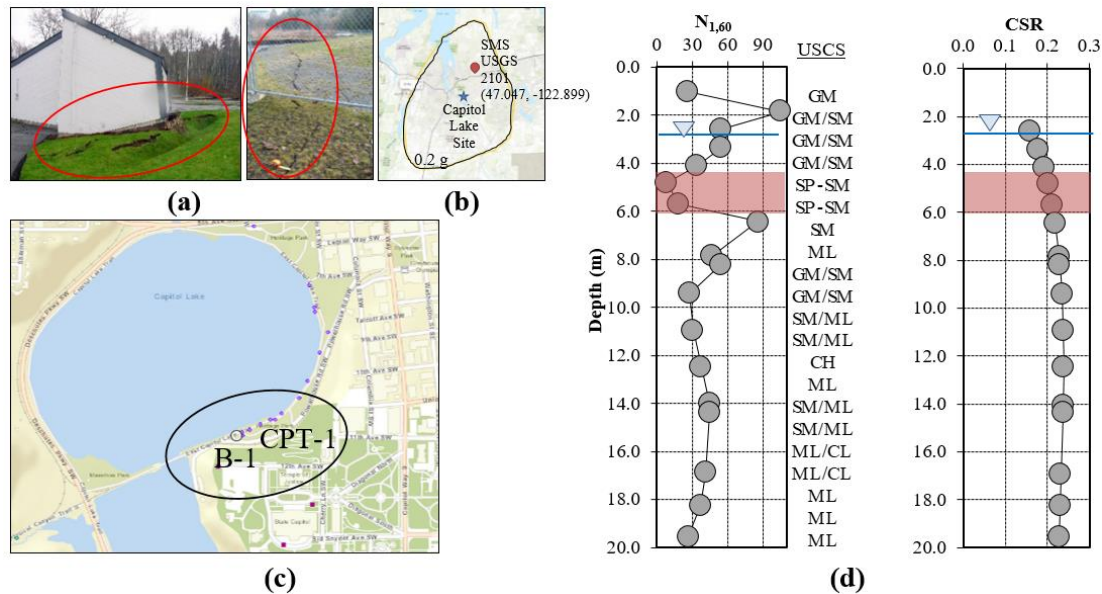


Figure 2. a) Ground distress around the Capitol Lake and cracking through recently placed fill (PEER), b) USGS shake map, c) CPT and SPT locations and profiles (WGIP), d) corrected $N_{1,60}$ and CSR vs. depth plots along with USCS of the soil layers.

The borehole and CPT information is retrieved from Washington Geological Information Portal (WGIP, <https://geologyportal.dnr.wa.gov/>) as shown in Figure 2c. The SPT data is digitized and raw SPT-N blow count values were corrected for equipment and procedure corrections (e.g., short rod correction (C_R), hammer energy correction (C_E), etc). The soil borehole information for Capitol Lake is summarized along with soil stratigraphy in Figure 2d, which presents the $N_{1,60}$ and CSR plots with respect to depth and the corresponding United Soil Classification System (USCS) of the soil samples. The critical layer is selected as 4.5-6.0 m (shaded), which consists of silty sand and poorly graded sand layers. The groundwater table (GWT) is located at 2.4 m depth. The mean $N_{1,60}$ and CSR values for the mid-depth of the potentially liquefiable layer are estimated as 13 blows/30 cm and 0.207, respectively.

Case history #2: 2011 Van Earthquake – Karasu River LBH1, Turkey

The 2011 $M_w 7.1$ Van earthquake caused severe damage in the cities located in the eastern and south-eastern parts of Turkey. For example, liquefaction in the form of sand boils was observed in Karasu area (38.5989, 43.2439), which is located on loose alluvial deposits (Late Pleistocene lacustrine). Figure 3a shows sand boils that were documented by the reconnaissance teams after the event. The SMS in that area were not close to the site. Hence a locally calibrated ground motion model is developed by the authors as shown in Figure 3b to assess the intensity of

shaking at the site. The closest distance to the rupture is calculated approximately as 3.9 km, which corresponds to $a_{\max}$ levels of 0.235 ± 0.07 g, also comparable with the site response analysis of Akin et al. (2013).

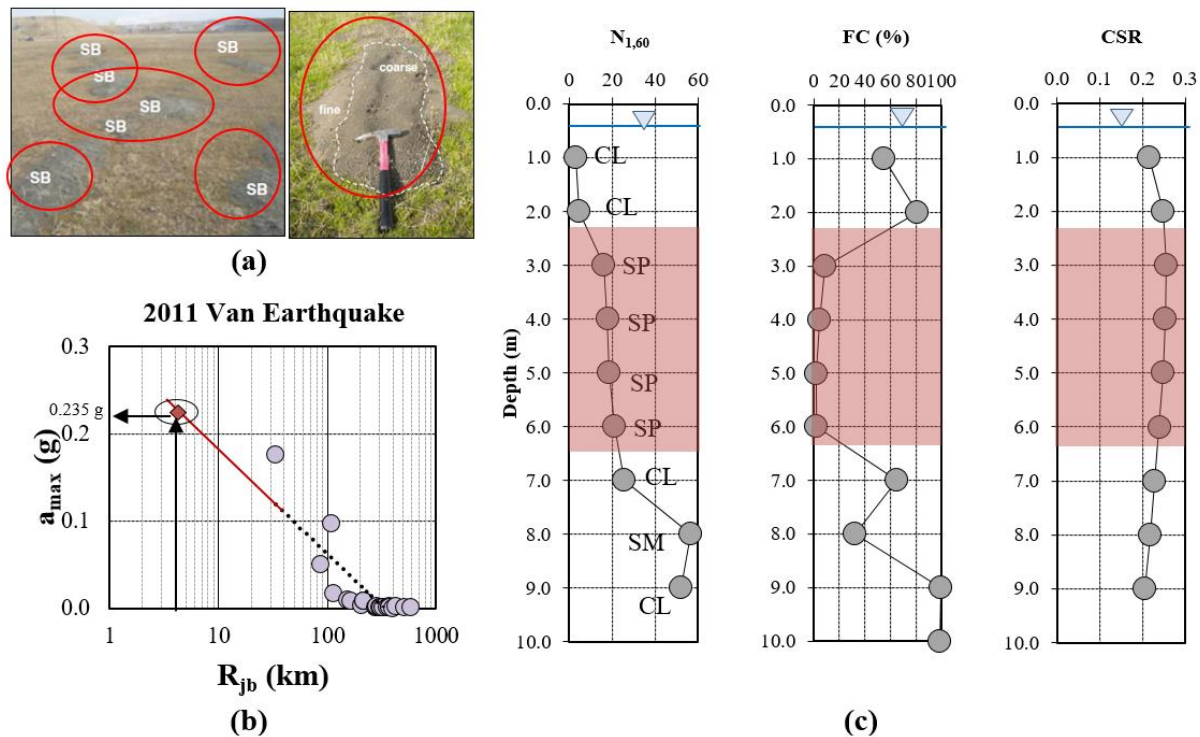


Figure 3. a) Sand boils around Karasu River, Turkey (after Akin et al. 2013), b) locally calibrated ground motion model, c) corrected $N_{1,60}$, FC, and CSR vs depth plots.

Borehole data is again digitized, and SPT blow counts were corrected for equipment and procedural differences. Figure 3c presents $N_{1,60}$, FC, and CSR plots with respect to depth. The USCS soil classification is also presented in the same figure next to each SPT-N values. The critical layer is selected as the medium dense clean sand (SP) layer with 4% fines content, located at 2.4–6.4 m depth range. The GWT is at 0.4 m depth. The average $N_{1,60}$ and CSR for the mean depth are calculated as 19 blows/30 cm and 0.252.

Case history #3: 2011 Christchurch Earthquake, NZ – 20 Corhampton Street ($V_s V_P$ 57194)

The 2011 M_w 6.2 Christchurch earthquake occurred on a reverse fault and caused extensive damage in the city of Christchurch, New Zealand due to seismic soil liquefaction. Ilgac (2022) presents 39 case histories from this event. An example case history of this dataset: 20 Corhampton Street ($-43.5116, 172.7114$), which is also included in CPT catalog of McLaughlin (2017) will be discussed herein. The site is shown in Figure 4a along with the in-situ test locations of CPT, V_s , and SPT (McLaughlin, 2017). The borehole information is retrieved from New Zealand Geotechnical Database (NZGD). The borehole data is digitized, and SPT values are corrected for equipment and procedural differences. $N_{1,60}$ values are calculated for the sand layers as shown in Figure 4b. $a_{\max}$ is reported as 0.48 g by McLaughlin (2017) based on the

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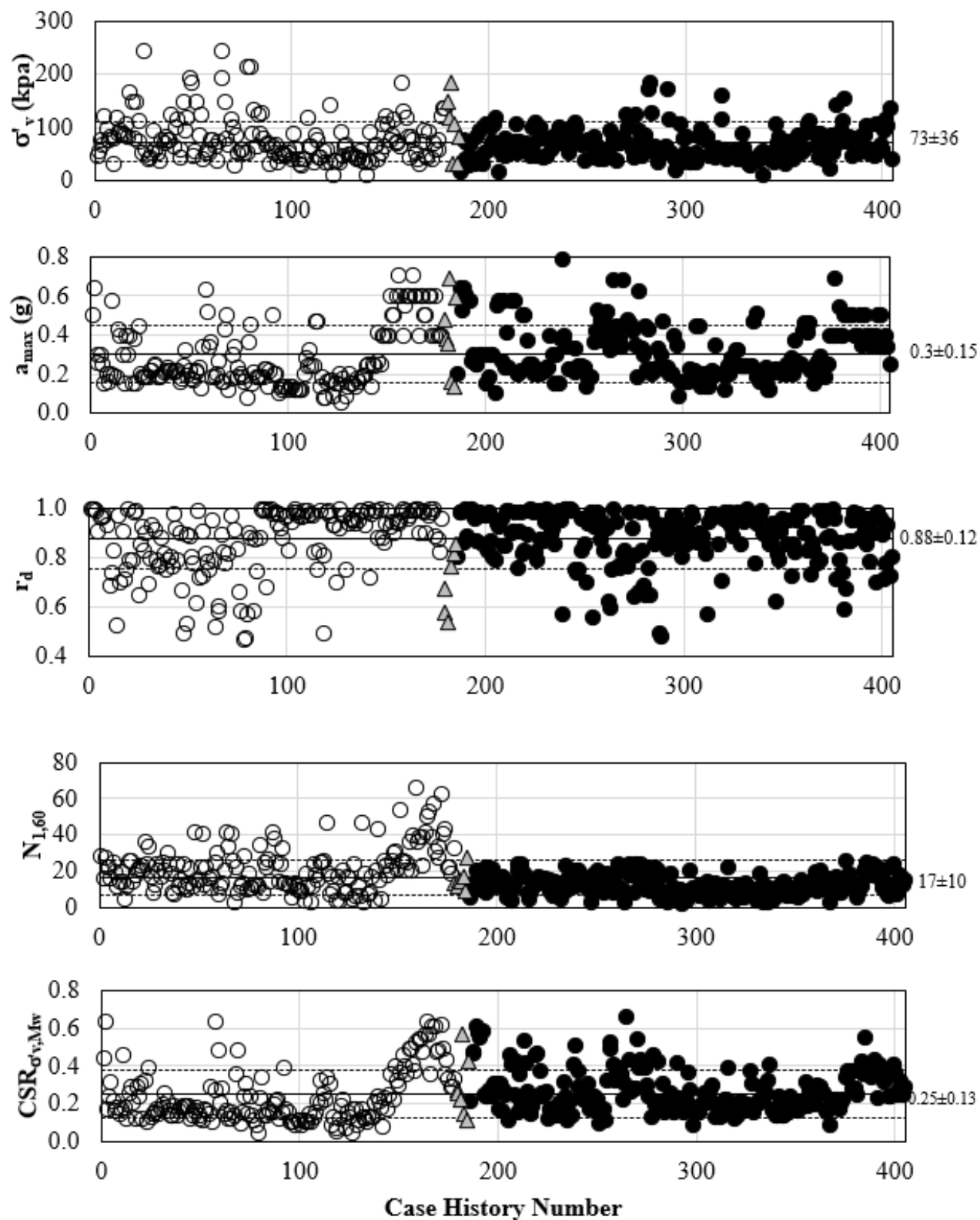


Figure 5. Input parameters a) d_{crtc} , b) σ'_v , c) a_{max} , d) r_d , e) $N_{1,60}$, f) $CSR_{\sigma'_v, Mw}$ for the new SPT database (405 case histories)

Table 1. The summary of all case histories SPT-based Liquefaction Triggering Database.

Database	mean	st.dev.	min	max
$d_{crtc.}$ (m)	5.92	3.23	1.05	22.55
GWT (m)	2.04	1.21	0.00	7.65
σ_v (kPa)	110.92	63.16	17.75	388.98
σ_v' (kPa)	72.89	36.56	10.40	242.69
r_d	0.88	0.12	0.47	1.00
a_{max} (g)	0.30	0.15	0.05	0.78
M_w	7.08	0.73	4.61	9.10
$CSR_{\sigma'_v, M_w}$	0.25	0.13	0.05	0.66
$N_{1,60}$	16.52	10.03	2.19	65.47

Figure 6a presents the mean values of the corrected $N_{1,60}$ versus raw $CSR_{\sigma'_v, M_w}$ (not normalized for K_σ , K_{M_w} , K_α effects) data points for the legacy case histories (210 case histories), and Figure 6b shows new catalog (195 case histories), and Figure 6c presents the entire SPT catalog with 405 case history data on the same space. Visual inspection reveals the new case histories add data for the mid to large $N_{1,60}$ and high CSR region.

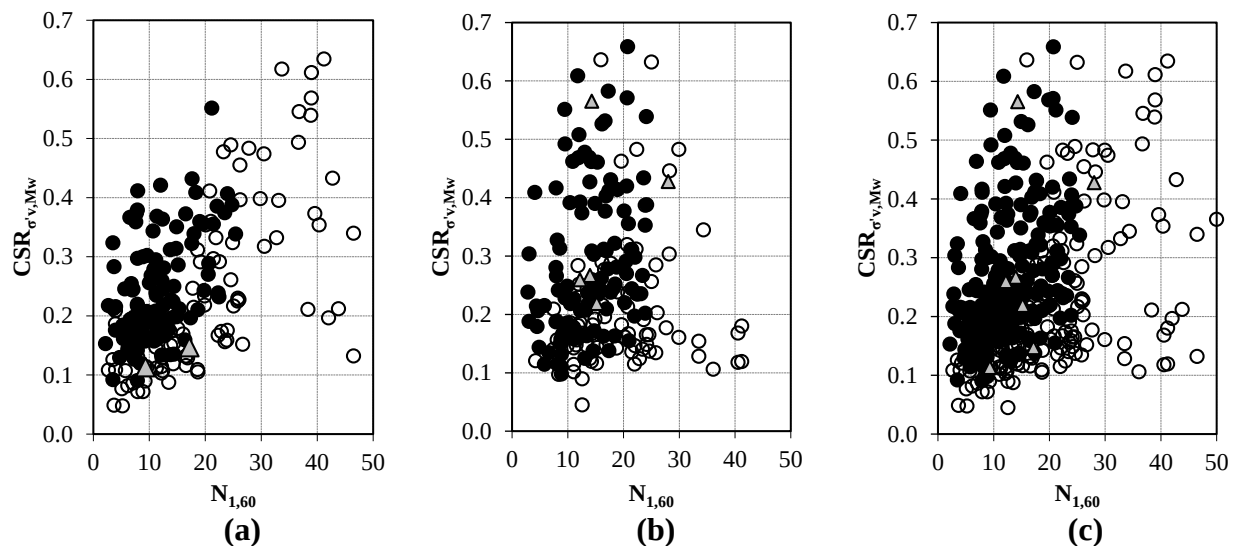


Figure 6. a) Legacy (210), b) New (195), c) total SPT catalog (405) case histories on corrected $N_{1,60}$ versus $CSR_{\sigma'_v, M_w}$ (dots, circles, and triangles represent liquefied, non-liquefied and marginal sites, respectively).

CONCLUSIONS

The updated SPT-based liquefaction triggering field case history database is briefly introduced in this paper. The revised database consists of 405 case history sites, including 195 newly added and 210 re-studied legacy case histories. The new case histories are mainly populated from earthquake events that occurred between 1996-2020 (e.g., 2001 Nisqually, 2010-2011 New Zealand, 2011 Tohoku earthquakes). These events occurred on strike-slip, normal,

reverse, and subduction zone fault systems with a moment magnitude range of $M_w=4.6-9.1$. The updated SPT catalog presents new event terms (R_{rup} , R_{jb} , etc.), and new descriptive parameters related to site information (e.g., gravel content, geological setting, V_{s30m} , etc.). The critical layers consist of the sandy, gravelly and silty sublayers, which enable the assessment of new correction terms (e.g., gravel content corrections.). A series of site response analyses along with deconvolution analyses were performed mostly at the strong ground motion station liquefaction sites to estimate the site and event-specific CSR values.

In the current database, all available information is digitized and documented (e.g. full borehole information, available digital ground motion recordings, GPS coordinates, etc.). The screening protocol is followed in the processing of both legacy and new case histories. This new protocol is proposed to increase data quality in an unbiased manner. For example, when available nearby CPT and V_s data is also examined collectively to determine the critical layers or strong ground motion recordings were warranted to estimate the intensity parameters (e.g. a_{max} , etc.). These protocols are presented in detail in Ilgac (2022). The SPT-N values are estimated with new stress (C_N), energy (C_E), and rod length (C_R) correction terms, considering the recent advances in SPT correction terms. An updated probability-based liquefaction triggering model is to be proposed on the basis of this updated SPT database, which is not discussed herein due to page limitations.

ACKNOWLEDGEMENTS

This research was developed from the first author's Ph.D. research at the Middle East Technical University. Partial support for this research was provided by the TUBITAK 2214-A International Research Fellowship Program for Ph.D. students. We would also like to thank Prof. Dr. Robb Moss from California Polytechnic University for providing insights during the conduct of this research and related projects.

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