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An updated SPT-based seismic soil liquefaction triggering database

Une base de données de déclenchement de la liquéfaction sismique des sols basée sur SPT mise à jour

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ABSTRACT: The use of in-situ “index” testing continues to be the dominant approach in engineering practice for the assessment of seismic soil liquefaction triggering. The currently available liquefaction case history database is extended with the addition of new SPT-based case history data. The previous databases cover the events until the 1995 Hyogeken - Nambu Earthquake. Since 1995, a number of major earthquakes occurred, producing a large number of new case histories. Some of these events are listed as 1999 Chi-Chi, 2001 Nisqually, 2008 Achaia-Ilia, 2010 El-Mayor (Baja), 2011 Tohoku, 2010-2011 New Zealand-Canterbury earthquakes. Within the confines of this manuscript, an updated liquefaction performance case history database is presented along with a discussion of the implemented probabilistic case history processing methodology. The resulting database is intended to be used for the development of updated probability-based liquefaction triggering relationships, the discussion of which is not within the scope of this manuscript.

RÉSUMÉ : L'utilisation de test “d'indice” in-situ continue d'être l'approche dominante dans la pratique de l'ingénierie pour l'évaluation du déclenchement de la liquéfaction sismique du sol. La base de données d'histoires de cas de liquéfaction sera étendue avec les nouvelles données d'historique de cas basées sur le test in-situ le plus largement utilisé, le test de pénétration standard (SPT). Les bases de données précédentes couvrent les événements jusqu'au tremblement de terre de Hyogeken - Nambu en 1995. Depuis 1995, un certain nombre de tremblements de terre majeurs se sont produits, produisant un grand nombre de nouvelles histoires de cas. Certains de ces événements sont répertoriés comme suit: Les tremblements de terre de 1999 à Chi-Chi, 2001 à Nisqually, 2008 à Achaia-Ilia, 2010 à El-Mayor, 2011 à Tohoku, 2010-2011 à Nouvelle-Zélande-Canterbury. Dans les limites de ce manuscrit, la base de données mise à jour d'historique de cas de performance de liquéfaction est présentée avec une discussion de la méthodologie de traitement de l'histoire de cas probabiliste qui a été implémentée. La base de données résultante est destinée à être utilisée pour développer des relations de déclenchement de liquéfaction basées sur les probabilités mises à jour, dont la discussion n'entre pas dans le cadre de ce manuscrit.

KEYWORDS: soil liquefaction, liquefaction triggering, SPT, earthquakes.

1 INTRODUCTION.

The use of in-situ field test results is proven to be a reliable approach to assess the resistance against seismic soil liquefaction triggering. Several in-situ field tests are commonly used to assess the triggering of seismic soil liquefaction. The most commonly used in-situ field tests are listed as i) standard penetration test (SPT), ii) cone penetration test (CPT), ii) Becker hammer test (BHT), and iv) shear-wave velocity test (V_s). Among these tests, in-situ penetration tests SPT, and CPT are more widely applied in engineering applications. Each of these field tests has its unique advantages and disadvantages. SPT and CPT are large strain tests that are judged to be more suitable for the assessment of a large strain problem such as soil liquefaction. SPT and CPT resistances are strongly correlated with relative density, which governs the cyclic behavior of sands (Kayen et al 2013., Idriss & Boulanger 2008). SPT has the advantage of soil sampling, however, the discrete nature of SPT disables the continuous characterization of the soil layers. On the other hand, CPT provides a more complete characterization of thin soil layers, since it supplies continuous data throughout the sounding. However, CPT lacks penetration capability in gravelly sites, which are proven to be vulnerable to soil liquefaction (e.g. 2010-2011 New Zealand Sequence), whereas BHT is a more viable alternative. Contrary to these, the shear-wave velocity test is a small strain test that lacks soil classification capabilities. However, it is the only test that measures a fundamental property of the soil: stiffness (Kayen et al. 2013). Hence, V_s test results are proven to be successful in the determination of liquefaction triggering boundaries. (e.g. Andrus and Stokoe 2000, Kayen et al. 2013, etc.). Among these alternative field tests, despite the growing CPT and V_s databases, SPT is still used more commonly worldwide, hence SPT-based liquefaction triggering relationships are used in a large number of engineering projects, which will be the scope of this study.

Seed et al. 1985 first introduced the pioneering SPT-based liquefaction triggering database and methodology, which inspired many other research teams (e.g.: Cetin et al. 2004, 2018, Idriss & Boulanger 2010, Boulanger & Idriss 2014, etc.), which have proposed deterministic liquefaction triggering relationships. The scope of this study is defined as presenting an extended SPT-based database with the case histories from relatively more recent earthquake events. For this purpose, the legacy case histories were revisited and an updated probabilistic framework is employed along with the introduction of the new set of parameters (e.g.: Closest distance to the rupture (R_{rup}), gravel content (GC), etc.). The new SPT-based liquefaction triggering field case history database i) is a collection of a larger suite of case histories consisting of 405 sites, ii) includes new earthquake events that occurred in between 1996-2020 (e.g. 2001 Nisqually, 2010-2011 New Zealand, 2011 Tohoku Earthquakes) iii) covers normal, reverse, and subduction earthquake events, which have a wider range of moment magnitudes (M_w=4.6-9.1) along with the event parameter terms (R_{rup}, R_{jb}, z_{tor}, etc.), iv) has gravelly and silty critical layers with the introduction of new correction schemes (e.g.: gravel corrections), v) fully documents digitized borehole information, GPS coordinates, and comparatively assesses and applies new screening criteria with nearby CPT and V_s data, vi) introduces a series of site response analyses in conjunction with deconvolution analyses for the strong ground motion sites, vii) introduces new parameters related to ground motion and site information (e.g. N_{cycle}, V_{s30m}, etc.) and viii) documents differing geological conditions. The database is processed with improved knowledge and understanding of standard penetration test data, which provides new stress (C_N), energy (C_E), and rod length (C_R) correction terms. The updated database is used to develop probability-based liquefaction triggering boundary curves utilizing the Bayesian updating scheme, which is discussed in Ilgac 2022.

1.1 *Review of SPT-based Liquefaction Triggering Relationships*

The seismic soil liquefaction triggering relationships were assessed on a two-dimensional capacity versus load domain by Seed et al. 1985. The first deterministic triggering relationship by Seed et al. 1985 was developed as a boundary that distinguished liquefied and non-liquefied case history data for three different fines content levels (5, 15, and 35%), by using equipment and procedure corrected SPT blow counts, $N_{1,60}$ as the capacity term, and cyclic stress ratio, CSR as the demand term, as shown in Figure 1. Benefitting from these pioneering studies, several research groups have developed deterministic and probability-based liquefaction triggering relationships. Since then, several researchers proposed liquefaction triggering relationships (Liao et al. 1988, Youd & Noble 1997, Toprak et al. 1999, Cetin et al. 2004, 2018, Juang et al. 2002, Moss et al. 2006 and Idriss & Boulanger 2008, 2010, Boulanger and Idriss 2012, etc.). Figure 1 provides a comparative plot of the mostly used triggering boundaries of Seed et al. 1985, Cetin et al. 2018, Boulanger & Idriss 2012. As discussed in Cetin et al. 2018, direct comparisons between these relationships are not possible due to different case history processing and correction schemes followed.

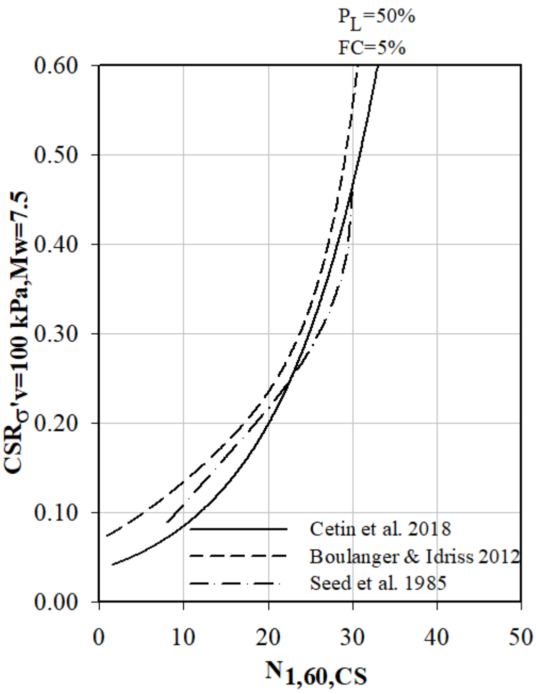

Figure 1. Clean sand boundary curves ($N_{1,60,CS}$) for the deterministic curve of Seed et al. 1985 (as modified slightly by Youd et al. 2001) and the P_L = 50% contours of Boulanger & Idriss 2012 and Cetin et al. 2018

Ongoing discussions related to the position of the boundary curve have initiated the need to update the case history database since previous databases lack i) relatively small and large magnitude events and PGA levels, ii) gravelly and silty sites, iii) specific descriptive parameters regarding the event mechanism, additional intensity parameters, presence of a crust layer, etc. The development of a more precise estimation of the soil liquefaction triggering boundary urges the need for a high-quality case history database that is assessed with the current state of knowledge and data. The scope of this paper does not include the development of a boundary curve but to present the expanded case history database along with the discussion of the new developments and understanding of liquefaction engineering in the last decades.

1.2 *History of SPT-based Liquefaction Triggering Database*

The reporting of field case histories initiated with the 1964 Niigata and 1964 Alaska Earthquake events that caused widespread liquefaction. The first triggering field dataset was compiled by Seed et al. 1985 which has 51 non-liquefied, 7 marginal, and 67 liquefied case histories (numbers are retrieved from Seed et al. 1984, Table 6). Cetin 2000 and Cetin et al. 2004 adopted a probabilistic data processing scheme and have processed additional case history data and studied the 125 case histories from Seed et al 1985. 90 case histories from Seed et al. 1985 passed the screening criteria of Cetin 2000 and the case histories were re-assessed probabilistically along with updated SPT correction schemes and site-specific estimated CSR. Cetin 2000 and Cetin et al. 2004 added 111 new case histories and published 201 case histories among which 158 are liquefied, 41 non-liquefied, and 2 marginal sites. Idriss & Boulanger 2010 database consists of 230 case histories, 115 of which are liquefied, 112 non-liquefied, and 3 marginal case history sites. Boulanger and Idriss 2014 database excluded 2 case histories (1979 Imperial Valley earthquake, Wildlife B site and 1987 Superstition Hills earthquake, McKim Ranch A), and additional 24 cases from the 1999 Kocaeli and 1999 Chi-Chi earthquakes were added. The updated database (264 case histories) was not used to develop an updated model but to test the performance of Idriss & Boulanger 2010 triggering relationship which was developed based on 230 case histories. Ilgac 2015 updated Cetin et al. 2004 database by excluding 2 case histories (1975 Haicheng M_s=7.3 Shung Tai Zi R and 1994 Northridge M_w=6.7 Malden Street Unit D) and included 13 new cases from 1983 Nihonkai-Chubu M=7.7 and Loma Prieta 1989 M_w=6.93 Earthquakes. The total number of cases reached a value of 211. Cetin et al. 2018 published an updated relationship with this dataset excluding 1 data point so the resultant number was 210 case histories: 113 liquefied, 95 non-liquefied, and 2 marginal data.

As part of these studies, the updated database has now reached 405 case history data, including 220 liquefied, 178 non-liquefied, and 7 marginal data points. The database sizes of existing databases are presented in Table 1.

Table 1. The summary of the SPT-based Seismic Soil Liquefaction Triggering Case History Database.

Database	*Liquefied*	*Non-Liquefied*	*Marginal*
Seed et al. 1985	67	51	7
Cetin et al. 2004	158	74	2
Cetin et al. 2018	113	95	2
Idriss & Boulanger 2010	115	112	3
Boulanger & Idriss 2014	134	117	3
This Study (Ilgac 2022, Ilgac and Cetin 2022)	220	178	7

2 NEW FIELD DATA

As mentioned above Ilgac 2022 database documents 405 case histories. The discussion regarding the update of Cetin et al. 2018 database will be briefly presented in this paper due to page limitations; however, further details can be found in Ilgac 2022. The additional 195 case histories are discussed in a more detailed manner.

The new case histories (195 case histories) are divided into regional groups to give an idea about the regional distributions of the events and geographic locations. Figure 2 presents the location of these new case histories. Table 2 summarizes the list of these new case history earthquake events and the corresponding number of field data that was collected. Among approximately 500 case history data, 195 of them have passed the data quality and completeness screening criteria, and Ilgac 2022 presents the details of the reasons for the exclusion of the data and further details regarding those sites.

Figure 2. The location of the new earthquake events according to regions.

When documenting these new case histories, unique processing details were used. The implemented digital information enables authors to determine the exact GPS coordinates of site locations for 405 case histories. Additionally, field performances were confirmed with the satellite images, if and when available. The nearby acceleration recordings were accessed and examined to determine the intensity and duration parameters, and these data are also provided electronically in Ilgac 2022.

The new case histories are grouped under 5 geographical regions, which are highly seismically active. These are i) Japan, ii) the United States, iii) Far East (China-Nepal-Indonesia-Taiwan), iv) Mediterranean and v) New Zealand.

2.1 *Case Histories from Japan*

Japan is located in the conjunction of the two plate boundaries. Due to the country's location, high annual seismicity levels are monitored. 49 new case histories were compiled from the 2011 Tohoku Earthquake event, 15 of which were successfully included in the database.

The total number of new field case history sites from Japan is 21. The breakdown of these events is given as follows: i) 1994 Hokkaido Toho-Oki, ii) 1999 Hokkaido, iii) 2003 Tokachi-oki, iv) 2007 Niigata Chuetsu-oki, v) 2011 Tohoku, and vi) 2013 Obihiro - Hokkaido Earthquakes. The case histories from Japan are mostly compiled from ground motion station sites, which are qualified as the highest quality case histories (e.g. less uncertainty from ground motion and site characterization points of view). The nearby shear wave velocity profiles and the collocated recording stations enabled the calculation of r_d values more accurately.

2.2 *Case Histories from the USA*

The Pacific coastal region of the United States is a highly active tectonic region. During the last decade, many destructive events caused widespread liquefaction-induced damages (e.g. 1989 Loma Prieta earthquake). The previous database includes events until the 1994 Northridge Earthquake. Since then several additional earthquake events have occurred, and liquefaction was observed to affect the areas on the west coast and Hawaii. Although numerous sites have been studied, case histories are successfully extracted from the following 9 events to meet the screening criteria of the current database (e.g. standard penetration test equipment detail, local recordings availability, field reconnaissance documentation within a couple of days after the event, etc). These 9 events can be listed as follows: i) 2001 Nisqually Earthquake, Seattle, ii) 2003 San Simeon Earthquake, Oceana, iii) 2006 Kiholo Bay Earthquake, Hawaii, iv) 2010 El Mayor-Cucapah (Baja) Earthquake, Mexico (the earthquake has affected Salton basin area in California), v) 2012 Brawley Earthquake Sequence (M=4.60, M=5.41, M=4.4, M=5.0), Salton basin, vi) 2014 Napa Earthquake, Napa Valley. A total of 17 case histories were included in the new 2022 database.

The 2001 Nisqually Earthquake in Seattle and the 2006 Kiholo Bay earthquake are intra-slab and normal fault events respectively. The remaining events are reverse and strike-slip events during which liquefaction was triggered. These events are valuable since it provides data from scarce normal and reverse events. The moment magnitude values range from 4.61 to 7.20, which fills the gap in terms of durational factors since the earlier events mostly cover M_w range of 5.9-6.93. Maximum ground acceleration values change from 0.13-0.45 g. The 2012 Brawley sequence is a unique example of low magnitude (M_w=4.61) and high-intensity level (0.30 g) event, which will help to understand the durational effects in liquefaction triggering response.

The critical depth range differs from 2.7-9 m, which is typical for liquefaction databases. The groundwater table (GWT) varies in the range of 1.2 to 4.85 m. The average representative $N_{1,60}$ value for the critical layer is 5-36 blow/30 cm. Half of the sites are located on artificial fills, and the remaining sites are located on Holocene flood plain or quaternary alluvium. Site response analyses were performed for the Wildlife array to estimate the cyclic stress ratio, CSR after the 2010 El-Mayor and 2012 Brawley sequence. The majority of the sites have nearby V_s and CPT, which are utilized collectively to understand the characteristics of liquefiable layers. All 17 case history sites' liquefiable layers consist of sandy materials (SP and SM) with fines content ranging from 3 to 27%, and gravel content of 0 to 50%. Among 17 sites, 11 of them are liquefied sites, where surface manifestation was observed. There was no surface manifestation observed for 5 of the sites. Additionally, 2 of the case histories had no reported manifestation but the co-located piezometers indicated liquefaction (excess pore pressure ratio, r_u=1). Hence they are also studied separately to understand the liquefaction triggering response, although they are classified as no-liquefaction based on surface manifestation criterion.

2.3 *Case Histories from Far East (China, Nepal, Indonesia, Taiwan)*

Previous databases had case histories from China but not from Nepal, Indonesia, and Taiwan. 12 case histories from China which are also available in the NGL database (Next Generation Liquefaction Project, NGL, Zimmaro et al. 2019) are added to the resulting database. The performance of other potential sites shaken by the 2003 Bachu Earthquake was also studied by Li 2012. 12 of them have passed the screening criteria and were included in the database.

Two subduction earthquake events, shaking 2 sites in Indonesia, are included in the database. These events are i) 2000 Bengkulu Earthquake (M_w=8.0) and ii) 2007 Bengkulu Earthquake (M_w=8.7). These cases are valuable since they were shaken by two different large magnitude events, which enable the researchers to assess the effects of seismological factors on liquefaction triggering.

2015 Gorkha (Nepal) Earthquake and the consecutive aftershocks in Nepal are studied by Sharma et al. 2017. The same sites have been repetitively shaken by these two events. The mainshock triggered liquefaction-induced damages in Duwakot, Nepal, but the aftershocks did not. The 2015 Gorkha (Nepal) Earthquake mainshock and aftershock are produced by thrust faulting systems with moment magnitude values of 7.8 and 7.3. Duwakot is a sandpit site with lacustral and fluvial origin (Sharma et al. 2017) sands, and the critical layer is a silty sand (SM) layer with FC=18%.

The island of Taiwan is located in the Pacific Ocean, where liquefaction-induced damages were reported extensively in the last decade. The 1999 Chi-chi Earthquake case histories were studied in detail to be added to the new database. The sites are very well documented by PEER teams (PEER 2000), Chu 2006, Chu et al. 2004. The majority of the sites are located within the proximity of the structures; hence they do not qualify to be a free field site. However, 9 sites fulfilled the free field conditions, and are added to the new database. Atterberg limit test results, grain size distribution curves, very detailed SPT equipment information, and energy measurements are available. However, ground motion recording stations are scarce in the area; hence authors have to develope locally calibrated ground-motion models to estimate the PGA levels for these sites.

The other two events that contributed to the population of the database are the 2010 Jia Shan and the 2018 Hualien Earthquakes. One site from each event is included in the database. The sites are very well documented and V_s measurements, nearby CPT soundings, Atterberg limits, and grain size distribution curves are available. 2018 Hualien Earthquake is the most recent event in the entire SPT database.

The sites from Taiwan are composed of silty sand layers with FC of 8-40 %, and one of them is a good example of a gravelly liquefaction case with gravel content greater than 50%. The earthquake mechanism is reported as trust and oblique faulting systems. The average critical layer thicknesses are 2.1-11.1 m with an average $N_{1,60}$ of 4-25 blows/30 cm. The PGA levels vary from 0.18 to 0.57 g, with the moment magnitude varies in the range of 6.4 to 7.6.

2.4 *Case Histories from the Mediterranean*

The cases from Turkey, Greece, and Italy are discussed in the Mediterranean region. The events can be listed as follows: i) 2003 Lefkada Earthquake, Greece, ii) 2008 Achaia-Elia Earthquake, Greece, iii) 2012 Emilia Earthquake mainshock and iv) aftershock, Italy, v) 1999 Kocaeli Earthquake, Turkey, vi) 2011 Van Earthquake, Turkey. The earthquake mechanisms are listed as strike-slip and thrust faulting. The average depth of critical layers vary in the range of 4.4-20 m with an average $N_{1,60}$ of 13-21 blows/30 cm. The critical layers are classified as silty sands, sand, and gravel with FC of 4-30% and GC of 0-21 %. The PGA and moment magnitude levels vary from 0.08 to 0.50 g and 5.8 to 7.5, respectively.

2.5 *Case Histories from New Zealand*

The greatest number of case histories in the entire database is compiled from the 2010-2011 New Zealand sequence. The current New Zealand dataset developed by Ilgac 2022 is the first study to examine the SPT-based triggering relationships specific to New Zealand events. CPT databases of i) McLaughlin 2017, ii) Wotherspoon et al. 2015, iii) Wood et al. 2017, and iv) Beyzaei 2017 were also studied. However, SPT data were compiled from New Zealand Geotechnical Database, NZGD. A total number of 72 sites are studied which are consecutively shaken by two events i) the 2010 Darfield Earthquake and ii) the 2011 Christchurch Earthquake. Among 144 case histories that are fully documented, many of the sites were excluded due to i) presence of organics, ii) partial saturation problems, iii) presence of cyclic mobility vulnerable very soft fine-grained layers. The co-located CPT and V_s data have also been studied to jointly assess the site characterization. These efforts populated a total number of 78 case histories for the 2010-2011 New Zealand Sequence.

Site response analyses were performed for all the case history sites in New Zealand. Additionally, deconvolution analyses were performed for the strong ground motion sites, which are presented in Ilgac 2022 in detail.

2016 Kaikoura Earthquake also contributed to the overall database with 2 case histories which were studied by Bray et al. 2018 and Cubrinovski et al. 2017.

The earthquake mechanisms of cases from New Zealand are strike-slip, reverse, and subduction. The average critical layer depth is 2.5-18.3 m with an average $N_{1,60}$ of 3-41 blows/30 cm. The critical layers are composed of gravel, sand, silt, sand-gravel matrix, and sand-silt matrix with FC of 3-70% and GC of 0 to >50%. The PGA level vary from 0.13 to 0.68 g and the moment magnitude from 6.2 to 7.8.

2.6 *New Field Data before 1995*

Although the previous case history databases cover most of the earthquake events before 1995, the updated database added 37 new case histories from these older events. These additional new case histories are from i) 1968 Tokachi-Oki, ii) 1976 Tangshan, iii) 1983 Nihonkai-Chubu, iv) 1987 Edgecumbe, v) 1989 Loma Prieta, vi) 1993 Kushiro-Oki, and vii) 1994 Hokkaido Toho-Oki Earthquakes. The details related to those case histories can be found in Ilgac 2022.

2.7 *Updating legacy case histories*

The new database presents additional descriptive variables for the legacy case histories. Additionally, some of the earlier parameters were modified based on new information which becomes recently available. These include but are not limited to i) the event parameter terms (R_{rup}, R_{jb}, z_{tor}, etc.), ii) soil type within the critical layer (e.g. silty sand, clean sand, silt, etc.), iii) gravel content, iv) modifications of FC, SPT-N, a_{max} critical layer, GWT parameters, and v) GPS locations. New stress (C_N), energy (C_E), and rod length (C_R) corrections were utilized. The details related to those case histories can be found in Ilgac 2022.

3 PROBABILISTIC CASE HISTORY PROCESSING METHODOLOGY

The assessment of the updated database is performed with a well-defined case history processing protocol. The probability-based liquefaction triggering mathematical expression is developed to consider the probabilistic nature of input parameters. This section summarizes the main parameter selection (mean and standard deviation of input parameters) protocols with a discussion on how the uncertainty of each parameter is estimated. The parameters discussed here can be listed as follows i) critical depth ($d_{crt.}$), ii) groundwater table (GWT), iii) unit weight, iv) mass participation ratio (r_d), v) maximum acceleration (a_{max}), vi) fines content, vii) standard penetration test resistance (SPT-N) value ($N_{1,60}$), viii) moment magnitude (M_w), ix) cyclic stress ratio (CSR).

Critical depth is selected by considering potentially liquefiable soil layer (e.g. fully saturated low plastic most vulnerable layer). If there are multiple suspect layers, then the site is excluded. Some of the sites have very soft (SPT-N=1) clay layers, which suggests that the manifestation may be attributed to the cyclic mobility of these very soft fine-grained layers. Hence these sites are also excluded. The standard deviation of the critical depth is calculated by dividing the thickness of the liquefied layer by 6 so that the layer boundaries are capped within the $\mp 3\sigma$ around the mean.

The groundwater level is determined i) directly from the related borehole data if available, ii) seasonal information enabling to determine the GWT at the time of the earthquake event, iii) collocated CPT data pore pressure measurement, and lastly iv) V_s/V_p ratio shifts from V_s profiles. The standard deviation of groundwater level (GWT) is calculated by different water level source data. If there is only one measurement standard deviation is assigned as a function of the soil type where the water table is located.

Unit weights for each case history site are assigned as a function of $N_{1,60}$ values and the soil type unless case-specific information is stated otherwise. Standard deviations of the unit weights are assigned 0.5 kN/m^3 unless there is site-specific information.

Mass participation ratios, r_d are calculated from the correlation proposed by Cetin et al. 2004 as a function of M_w, a_{max}, depth, V_{s12m}, if site response analysis were not performed. The standard deviation is also calculated by Cetin et al. 2004.

Maximum ground acceleration (a_{max}) is obtained from i) recording stations if available, and a_{max} for a site is selected as the geometric mean of the two components of the available acceleration, ii) site response analysis, iii) event-specific ground motion prediction equations. The uncertainty is estimated as proposed by Ilgac 2015.

Fines content (FC) values are adopted for the critical soil layer from the related borehole data or grain size distribution curves when they are available. If more than one fines content data exists, mean value and standard deviation are calculated.

The average SPT-N values are calculated from the related borehole data which is digitized and the SPT correction factors are implemented as discussed in Ilgac 2022. If more than one SPT-N data exist, the mean value and standard deviation are calculated, however, if a single value exists, the standard deviation of $N_{1,60}$ is taken as 2 blows/30 cm.

CSR is calculated as proposed by the simplified procedure (Seed & Idriss 1971). CSR includes the uncertainty of the various terms (a_{max}, σ'_{vo}, r_d etc.). The uncertainty of the CSR is calculated by using the first-order second-moment reliability method. If site-specific site response analyses were performed (e.g. 88 of the new data, and previously Cetin 2000 performed 47 site response analyses for the legacy sites), CSR is directly estimated based on 1-D site response analysis results.

The protocols on all the input parameters are not limited to the discussions presented herein, and more details can be found in Ilgac 2022.

4 STATISTICS FOR THE NEW CASE HISTORY DATA

After having processed case histories, a data classification scheme is utilized by considering the uncertainty levels in CSR and $N_{1,60}$. The case histories with large uncertainties in these descriptive parameters are again excluded from the database, details of which can be found in Ilgac 2022. Table 2 summarizes the mean, standard deviation, minimum, and maximum input parameters of the resulting 405 case histories.

Table 2. The summary of the current SPT-based Liquefaction Triggering Database.

Database	*mean*	*st.dev.*	*min*	*max*
$d_{crtc.}$ (m)	9.34	0.94	8.68	10.00
GWT (m)	2.18	1.66	1.00	3.35
σ_v (kPa)	189.58	30.33	168.13	211.02
σ_v' (kPa)	119.19	4.79	115.80	122.58
r_d	0.71	0.18	0.58	0.84
a_{max} (g)	0.22	0.02	0.21	0.24
$CSR_{\sigma'v,Mw}$	0.16	0.03	0.14	0.19
$(N_1)_{60}$	17.30	10.42	9.93	24.67

Figure 3a presents mean values of the corrected $N_{1,60}$ versus raw $CSR_{\sigma'v,Mw}$ (not normalized for K_σ, K_{Mw}, K_α effects) data points, and Figure 3b shows the same data points along with the associated uncertainty in $N_{1,60}$ and $CSR_{\sigma'v,Mw}$. The resulting database is to be used for the development of new probability-based liquefaction triggering relationships, the discussion of which is beyond the scope of this manuscript.

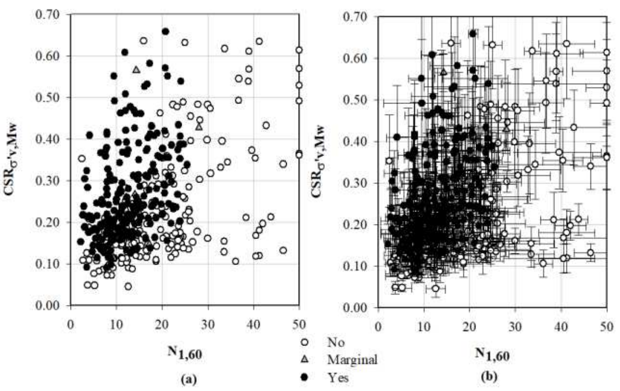

Figure 3. a) $N_{1,60}$ versus $CSR_{\sigma'v,Mw}$, b) data points along with the associated uncertainty in $N_{1,60}$ and $CSR_{\sigma'v,Mw}$ domain.

5 CONCLUSIONS

The updated SPT-based liquefaction triggering field case history database is introduced in this paper. The case history database i) is a collection of a larger suite of case histories consisting of 405 sites, ii) includes new earthquake events that occurred between 1996-2018 (e.g. 2001 Nisqually, 2010-2011 New Zealand, 2011 Tohoku Earthquakes), iii) includes additional data from the pre-1996 period, which do not exist in earlier catalogs, iv) covers normal, reverse, and subduction zone earthquake events, which have a wider range of moment magnitudes (M_w=4.6-9.1), v) benefits from a series of site response analyses in conjunction with deconvolution analysis for the assessment of strong ground motion characteristics of case history sites, v) documents additional new descriptive parameters including but not limited to V_{s30m}, geological setting, gravel content, etc. Last but not least, the SPT N values were processed with improved knowledge and understanding of standard penetration test data, as part of which new stress (C_N), energy (C_E), and rod length (C_R) corrections were used. The updated database is used for the development of probability-based liquefaction triggering boundary curves given in Ilgac 2022.

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