Probabilistic Assessment of Liquefaction Occurrence in Calcareous Fill Materials of Kawaihae Harbor, Hawaii

Habib Shahnazari[1]; Yaser Jafarian[2]; Mohammad A. Tutunchian[3]; and Reza Rezvani[4]

Abstract: The simplified shear-wave velocity (V_s)–based procedure of liquefaction potential assessment was basically developed for terrigenous deposits, whereas its applicability for calcareous soils is not fully recognized. The present study used the seismological and geotechnical data of Kawaihae Harbor, the most strategic port of Hawaii, to evaluate conservatism of the currently used simplified procedure for this case history. During the Kiholo Bay 2006 earthquake, the port experienced extensive liquefaction and subsequent ground failure in the dredged fill and natural calcareous deposits. Using the V_s profiles of the subsoil in Kawaihae Harbor, the simplified procedure and the Monte Carlo simulation (MCS) technique were used to evaluate liquefaction potential of the site through deterministic and probabilistic frameworks. The results obtained from the deterministic and the site-specific probabilistic approaches indicate extents of liquefaction occurrence in the shallow depths between 3.5 and 6.5 m. In contrast, probabilistic analysis with the available liquefaction probability–factor of safety (P_L-FS) correlations resulted in an unconservative prediction, with the liquefied depth ranging between 5.6 and 6.1 m. Results of this study confirm that the current simplified procedure with either deterministic or site-specific probabilistic frameworks obtained reliable estimation of liquefaction occurrence in the studied site. However, further case histories of liquefaction occurrence in calcareous deposits are required to clarify applicability of the simplified procedure for such materials. Based on the results of the current study, there is still potential for liquefaction occurrence in the studied site during future earthquakes. **DOI:** 10.1061/(ASCE)GM.1943-5622.0000621. *© 2016 American Society of Civil Engineers.*

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Introduction

Construction on calcareous sediments is commonly accompanied by considerable concern regarding the unknown behavior of such soils. This is fundamentally due to the fact that a majority of geotechnical investigations have been performed on silicate soils. Inherently, calcareous soils have higher compressibility in uncemented conditions and greater crushability compared with terrigenous materials. Furthermore, cementation of calcareous sands provides some degree of uncertainty in the evaluation of their mechanical behavior. Calcareous deposits cover more than 30% of the earth's surface, but limited investigations have been carried out on their liquefaction potential. The feasibility of liquefaction occurrence in calcareous soils was not fully recognized until the occurrence of the 1993 Guam, 2006 Kiholo Bay (Hawaii), and 2010 Haiti earthquakes.

During recent years, some limited experimental studies have been performed on engineering behavior of calcareous soils. Datta et al. (1982) found that the mode of formation (i.e., chemical deposition and physical weathering) and carbonate type can completely influence the engineering behavior of calcareous deposits. Similar considerations were stated by Lee (1982), Demars and Chaney (1982), Coop (1990), and Coop and Airey (2003). Morioka (1999) considered that constitutive and material properties of calcareous soils are highly variable and cannot be classified only based on carbonate content, formation location, and depositional environments. Shahnazari et al. (2014) performed monotonic triaxial experiments on two different calcareous sands and compared their results with similar experiments on standard silicate sand of Iran. They showed that calcareous sediments have larger contractive phases than silicate sands under similar conditions. This was a result of the occurrence of particle breakage under shearing stress. Coop et al. (2004) and Shahnazari and Rezvani (2013) focused on crushability potentials of these deposits. They demonstrated that the yield point stress level of calcareous sands is mainly lower than that of siliceous sands. This is the main reason for having higher crushability potential in calcareous deposits. Sharma and Ismail (2006) and Salem et al. (2013) investigated monotonic and cyclic behavior of different calcareous sands. They concluded that obtaining complete failure state for such soils requires large strain accumulation. Ross and Nicholson (1995), Flynn (1997), Hyodd et al. (1998), Morioka (1999), Brandes (2011), and Sandoval et al. (2011) compared the cyclic behavior of various calcareous soils with siliceous sands. They found that calcareous specimens have lower liquefaction potential in comparison to siliceous samples. They also stated that calcareous soils have higher pore pressure fluctuations during cyclic loading that is a result of their porous media structure. In addition, some studies on field behavior of calcareous soils have been reported. LaVielle (2008) and DesRoches et al. (2011) investigated liquefaction occurrence in Guam and Haiti earthquakes, respectively. It should be noted that effects of uncertainty in soil parameters have not been considered in previous studies on calcareous soils.

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[1] Associate Professor, School of Civil Engineering, Iran Univ. of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran (corresponding author). E-mail: hshahnazari@iust.ac.ir

[2] Assistant Professor, Geotechnical Engineering Research Center, International Institute of Earthquake Engineering and Seismology, P.O. Box 19395-3913, Tehran, Iran. E-mail: yjafarianm@iiees.ac.ir

[3] Ph.D. Candidate, School of Civil Engineering, Iran Univ. of Science and Technology, P.O. Box 16765-163, Tehran, Iran. E-mail: amin@iust.ac.ir

[4] Ph.D. Candidate, School of Civil Engineering, Iran Univ. of Science and Technology, P.O. Box 16765-163, Tehran, Iran. E-mail: r_rezvani@iust.ac.ir

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During the past three decades, the most important applicable procedures for assessment of liquefaction potentials have been (1) the simplified procedure developed by Seed and Idriss (1971) based on standard penetration test (SPT) blow counts, (2) the simplified procedure developed by Robertson and Campanella (1985) based on cone penetration test (CPT) results, and (3) the simplified procedure developed by Andrus and Stokoe (2000) based on shear-wave velocity (V_S). Over recent years, the V_S-based procedure has frequently been used for field and laboratory studies; therefore, various boundary curves were proposed (e.g., Dobry et al. 1981; Alba et al. 1984; Tokimatsu and Uchida 1990; Juang et al. 2001; Andrus et al. 2004; Juang et al. 2005; Jafarian et al. 2011a). However, the available state boundaries are based on siliceous sands, and their applicability for calcareous deposits should be investigated. Also, the prevalent application of V_S-based liquefaction assessment methods in engineering practice shows the importance of such procedures. In addition, updating the available database of V_S-based liquefaction case histories provides an engineering advancement to the current studies.

In this study, the information gathered from the Kiholo Bay earthquake and the ground profiles reported by Stokoe and Yuan (2008) were used to investigate the applicability of the simplified V_S-based method for assessment of liquefaction potential in calcareous fill materials. Kawaihae Harbor is considered a well-documented liquefaction case history for examining whether the deterministic simplified procedure can predict liquefaction occurrence in calcareous deposits. Furthermore, Monte Carlo simulation (MCS) was implemented for the simplified V_S-based procedure to perform the mentioned examination through a probabilistic framework. Also, the results obtained from the deterministic and probabilistic frameworks were compared with the available V_S-based database of liquefaction case histories. It is worth noting that the 2006 earthquake provided the largest suite of strong motion records ever obtained in the big island of Hawaii; thus, there should be an opportunity to study liquefaction occurrence in calcareous soils.

Kawaihae Harbor: Seismicity and Liquefaction Occurrence

Kawaihae Harbor is the most important port on the west side of Hawaii. In some parts, this harbor was built on the fill materials that involve loose cohesionless soils composed of saturated calcareous sediments. Table 1 presents the index properties of Kawaihae calcareous sand (Brandes and Seidman 2008; Brandes 2011).

The rate of earthquake occurrence in Hawaii is as high as that near the most hazardous fault areas on the mainland United States (Martin and Chock, Inc. 2010). Magnitude 6 ground motions have been shown to have recurrence intervals of approximately 10 years in the region (Furumoto et al. 1990). Many studies have shown the potential hazard especially on the south side of the island of Hawaii (e.g., Wyss and Koyanagi 1992; Klein et al. 2001).

Table 1. Index Properties of Kawaihae Calcareous Sand (Data from Brandes 2011)

Soil property	Category or value
Unified Soil Classification System category	SM (silty sand)
Grain angularity	Subangular to angular
Fines content (%)	13.9
Min/max unit weight (g/cm^3)	1.34/1.68
Carbonate content (%)	100
Specific gravity	2.75
D60 (mm)	2.07
D50 (mm)	0.75
D30 (mm)	0.19
D10 (mm)	>0.075

The Kawaihae earthquake occurred on October 15, 2006, with a main shock of magnitude 6.7 and an aftershock of magnitude 6.0. The earthquake caused significant damage to infrastructures in South Kohala. The commercial port facilities at Kawaihae Harbor experienced considerable damage, especially at Pier 1 (Robertson et al. 2006; Mahoney et al. 2008). There is much evidence (e.g., sand boils, lateral spreading) to demonstrate occurrence of liquefaction in the calcareous fill materials beneath Kawaihae Harbor during the 2006 earthquake (Robertson et al. 2006; Brandes et al. 2007).

Wong et al. (2011a) believed that the 2006 event was an important earthquake that could be used for the development of empirical attenuation models for Hawaii. For such a useful model, it was necessary to obtain enough information from the subsurface ground condition beneath the USGS stations. In January 2008, a research team from the University of Texas, Austin, and URS Corporation performed spectral analysis of surface waves (SASW) surveys beneath the USGS Hawaiian strong-motion network (Wong et al. 2011b; Stokoe and Yuan 2008). The SASW measurements were used to obtain the shear-wave velocity (V_S) profiles used in the current study.

Shear Wave Velocity–Based Liquefaction Assessment

Deterministic Methods

Systematic V_s-based evaluation of liquefaction resistance of soils has been gradually developed by different researchers (e.g., Dobry et al. 1981; Seed et al. 1983; Stokoe et al. 1988; Tokimatsu and Uchida 1990; Andrus 1994; Andrus and Stokoe 2000). Andrus and Stokoe (2000) developed a simplified V_s-based procedure for liquefaction assessment; a summary of this procedure was reported by Youd et al. (2001). A more updated description of the simplified V_s-based procedure can be found in Andrus et al. (2004).

The simplified procedures mainly use a deterministic safety factor to judge whether liquefaction will occur. In this way, it is necessary to measure two parameters: (1) the cyclic stress ratio (CSR), which represents the level of cyclic loading on soil layers; and (2) the cyclic resistance ratio (CRR), which demonstrates resistance of soil layers against liquefaction. The CSR and CRR at a particular depth of a level site can be calculated by Eqs. (1) and (2) (Andrus and Stokoe 2000)

$$\mathrm{CSR} = 0.65\frac{a_{\max}}{g}\frac{\sigma_v}{\sigma'_v}r_d \tag{1}$$

$$\mathrm{CRR} = \left\{0.022\left(\frac{K_c V_{S1}}{100}\right) + 2.8\left(\frac{1}{V^*_{S1} - K_c V_{S1}} - \frac{1}{V^*_{S1}}\right)\right\}\mathrm{MSF}.K_\sigma.K_\alpha \tag{2}$$

where $a_{\max}$ = peak horizontal ground surface acceleration; g = acceleration of gravity; σ'_v = initial effective vertical (overburden) stress at the studied depth; σ_v = total overburden stress at the same depth; r_d = stress reduction coefficient to adjust for the flexibility of the soil profile; V_{S1} = stress-corrected shear-wave velocity; K_C = factor to correct for high V_{S1} values caused by cementation and aging; V^*_{S1} = limiting upper value of V_{S1} for cyclic liquefaction occurrence; MSF = magnitude scaling factor to account for the effect of earthquake magnitude; K_σ = correction factor that extends cyclic resistance ratios to high confining stresses; and K_α = correction factor that adjusts cyclic resistance ratios to sloping ground conditions. The factor of safety (FS) against liquefaction is defined as the CRR/CSR ratio at a given depth. More details about the mentioned parameters were presented by Andrus et al. (2004), Youd et al. (2001), and Andrus and Stokoe (2000).

Probabilistic Methods

The practical approaches of liquefaction assessment do not consider uncertainties of geotechnical parameters, such as shear-wave velocity measurements, SPT blow count, and cone penetration resistance. In other words, a deterministic analysis uses specific values for each input parameter. In contrast, probabilistic procedures can potentially account for the uncertainties of soil properties, model parameters, and earthquake input characteristics (e.g., Hwang et al. 2005; Juang et al. 2005; Lopez-Caballero and Modaressi-Farahmand-Razavi 2010; Jafarian et al. 2011b). A detailed inspection of uncertain parameters is necessary to specify statistical indices, such as mean and coefficient of variation.

One of the most intuitive and possibly straightforward methods for performing reliability analysis is the MCS method (Phoon 2008). Monte Carlo (MC) methods are stochastic problem-solving techniques that are generally used to approximate the probability of certain outcomes by running multiple trial runs, called simulations, using random variables. In other words, by using MCS, one can build up a picture of the response distribution from which probability estimates can be derived. More details about MC applications in civil engineering can be found in Mordechai (2011) and Phoon (2008). In a MCS analysis, the following steps are considered:

1. Creation of a parametric model: $y = f(x_1, x_2, \ldots, x_n)$.
2. Generation of a set of random inputs using a special distribution function: $x_{i1}, x_{i2}, \ldots, x_{in}$.
3. Calculation of the result using the parametric model and storing the result as y_i.
4. Repeating steps 2 and 3 for $i = 1$ to m (where m is the number of iteration in MC analysis).
5. Evaluation of the results using histograms, summary statistics, and confidence intervals.

In the V_s-based probabilistic liquefaction potential assessment of this study, two MC analyses were performed on both CSR and CRR. Per any iteration, after the calculation of CSR and CRR, the resulting FS can be obtained. Finally, a set of FS values are calculated, and probability of liquefaction occurrence is simply defined as the ratio of the cases with FS < 1 divided by the total cases (equal to m) [Eq. (3)]. A summary of the probabilistic liquefaction assessment method used in this study is presented in Fig. 1. As presented in Fig. 1, the safety margin of liquefaction occurrence is FS = 1

$$P_L = \frac{\text{No. of failures (i.e., liquefaction occurence)}}{\text{No. of trials}} \tag{3}$$

In the previously described MCS, generation of random values for each uncertain variable should follow a special type of distribution, such as uniform, normal, and lognormal distributions. Each variable has an individual probability density function (PDF), which describes the uncertainties involved. In MCS calculations, certain parameters should be considered as constant values. In this study, certain parameters of soil are the parameters associated with very little uncertainty. Considering these parameters as constant values is logical because of their insignificant uncertainty level or role in probabilistic approach.

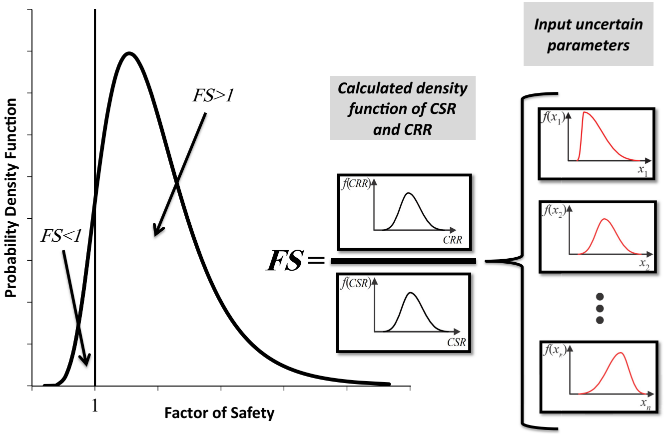

Fig. 1. Summary of probabilistic liquefaction assessment method

Liquefaction Assessment of Kawaihae Harbor

V_S Measurements

Geotechnical site investigation in the studied area involved SASW surveys within 22 USGS strong-motion sites and several additional surveys at Kawaihae Harbor that encountered geotechnical and structural damages as a result of the 2006 Kiholo Bay earthquake. The resulting V_s profiles are available from the Network for Earthquake Engineering Simulation (NEES 2008). Stokoe and Yuan (2008) and URS Group, Inc. (2008) reported the SASW surveys performed at different points of Kawaihae Harbor (Fig. 2). More details about SASW survey points at Kawaihae Harbor can be found in a report by URS Group, Inc. (2008). Fig. 3 presents depth profiles of the shear-wave velocity (V_s) measured at the site. The reported curves show similar subsoil conditions for different measurement points at Kawaihae Harbor. In this study, the average V_s values obtained from different survey points of Kawaihae Harbor were considered. Table 2 presents the average soil parameters obtained from Stokoe and Yuan (2008).

Site-Specific Deterministic and MCS Analyses

The simplified procedure recommended by Andrus and Stokoe (2000) was examined for the calcareous fill materials of the specified site through deterministic and probabilistic perspectives. The MCS was carried out to assess probabilistic liquefaction potential using the V_s profiles reported by Stokoe and Yuan (2008) and the other required data. Accordingly, the following considerations were taken into account:

1. The V_s-based simplified procedure recommended by Andrus and Stokoe (2000) and Youd et al. (2001) was implemented for deterministic and probabilistic evaluation of CSR and CRR.
2. To construct the PDF of $a_{\max}$ for the MCS analysis, the following three values were adopted from the previous seismic studies on Hawaii Island:
   a. The USGS shakemap from the 2006 M6.7 Kiholo Bay earthquake (USGS 2006),
   b. The value calculated by the ground motion equations developed by Atkinson (2010) for Hawaii, and
   c. The ground motion attenuation models developed by Wong et al. (2011a) for Hawaii.

   The peak ground acceleration (PGA) values obtained from the aforementioned references would be 0.35, 0.37, and 0.46

(a)

(b)

Fig. 2. Kawaihae Harbor: (a) aerial photo (© 2015 Google, Image © TerraMetrics); (b) SASW survey points at Kawaihae Harbor (reprinted from URS Group, Inc. 2008)

g, respectively, and the mean value of 0.393 g with a standard deviation of 0.059 is considered in the analyses.

3. Andrus and Stokoe (2000) recommended the MSF and r_d proposed by Idriss (1999) to be used in the deterministic simplified procedure. However, a significant level of uncertainties exist for the r_d and MSF relationships, proposed by several researchers. For the MCS, different values of r_d were estimated from the equations proposed by Cetin et al. (2004), I. M. Idriss and R. Golesorkhi (personal communication, 1997), Blake (1996), Golesorkhi (1989), and Liao

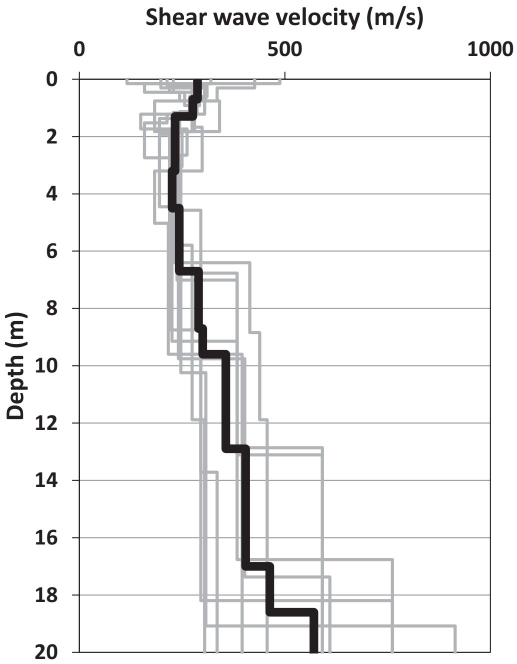

Fig. 3. Shear-wave velocity profiles of Kawaihae Harbor (data from Stokoe and Yuan 2008) (Note: the highlighted line presents the average values at each depth)

Table 2. Average Soil Parameters (Data from Stokoe and Yuan 2008)

Layer no.	Thickness (m)	V_s (m/s)	Soil unit weight (kN/m^3)
1	0.7	287.4	18.85
2	0.6	276.1	18.85
3	1.9	232.9	18.85
4	1.3	225.9	18.85
5	2.2	242.9	18.85
6	2	290.2	18.85
7	0.9	300.2	18.85
8	3.3	356.3	18.85
9	4.1	404.8	18.85
10	1.6	463.3	18.85
11	5	570.6	18.85
12	—	635.2	18.85

and Whitman (1986). Similarly, various estimations of MSF were involved in the MCS using the previous recommendations given by Cetin et al. (2004), Andrus and Stokoe (2000), Idriss (1999), Harder and Boulanger (1997), Arango (1996), Ambraseys (1988), and Seed and Idriss (1982).

4. Variability of the K_σ coefficient was completely discussed by Youd et al. (2001) and Cetin et al. (2004). The recommendation of Youd et al. (2001) in a National Center for Earthquake Engineering Research (NCEER) workshop, which was formerly proposed by Harder and Boulanger (1997), is used herein for the deterministic analysis. For the MCS, three recommendations from Youd et al. (2001), Cetin et al. (2004), and Olsen (1984) were utilized.
5. The groundwater table (GWT) was considered at 1.85 m (6 ft) below the surface (Mahoney et al. 2008; Robertson et al. 2006).

Table 3. References Used in Deterministic and Probabilistic Approaches

Input parameter	Reference(s) used in deterministic approach	Reference(s) used in probabilistic approach
V_s	Stokoe and Yuan (2008)	Stokoe and Yuan (2008) Marosi and Hiltunen (2004) Martin and Diehl (2004) Thelen et al. (2006)
$a_{\max}$	USGS (2006) Atkinson (2010) Wong et al. (2011a)	USGS (2006) Atkinson (2010) Wong et al. (2011a)
r_d	Andrus and Stokoe (2000)	Cetin et al. (2004) Andrus and Stokoe (2000) I. M. Idriss and R. Golesorkhi (1997, personal communication) Blake (1996) Golesorkhi (1989) Liao and Whitman (1986)
MSF	Andrus and Stokoe (2000)	Cetin et al. (2004) Andrus and Stokoe (2000) Idriss (1999) Harder and Boulanger (1997) Arango (1996) Ambraseys (1988) Seed and Idriss (1982)
$K\sigma$	Youd et al. (2001)	Youd et al. (2001) Cetin et al. (2004) Olsen (1984)
FC	Brandes and Seidman (2008)	Brandes and Seidman (2008)
K_c	Andrus and Stokoe (2000)	Andrus and Stokoe (2000)
Soil unit weight	Stokoe and Yuan (2008)	Stokoe and Yuan (2008)

Note: Because of a lack sufficient data about variations of FC, K_c, and soil unit weight in depth, and considering their insignificant roles in the V_s-based simplified approach, these parameters are considered as certain parameters.

6. The effect of cementation in calcareous deposits is considered by the K_c factor recommended by Andrus and Stokoe (2000) for increased values of V_S.
7. The average amount of fines content (FC) in calcareous sand of Kawaihae Harbor, as obtained from Brandes and Seidman (2008), is equal to 13.9%. Because of the insignificant effect 4 of FC in the V_s-based simplified approach, it is considered as a deterministic parameter.
8. The PDF of an uncertain parameter has a considerable effect on the results of MCS. Therefore, proper PDFs for the uncertain parameters (i.e., $a_{\max}$, r_d, K_σ, V_S, and MSF) were made based on the best-fitted density functions. However, a majority of researchers have concurred that geotechnical parameters commonly have lognormal or normal distributions (e.g., Cetin et al. 2004; Juang et al. 2008; Lopez-Caballero and Modaressi-Farahmand-Razavi 2010). In this study, the lognormal behavior was considered for $a_{\max}$, r_d, K_σ, and MSF and normal distribution for V_S.
9. Any uncertain parameter with normal or lognormal distribution can be plotted using two statistical parameters: (1) mean value (μ), and (2) standard deviation (σ or s) [refer to Eqs. (4) and (5)]. The ratio of the standard deviation to the mean value is defined as the coefficient of variation (COV = σ/μ).

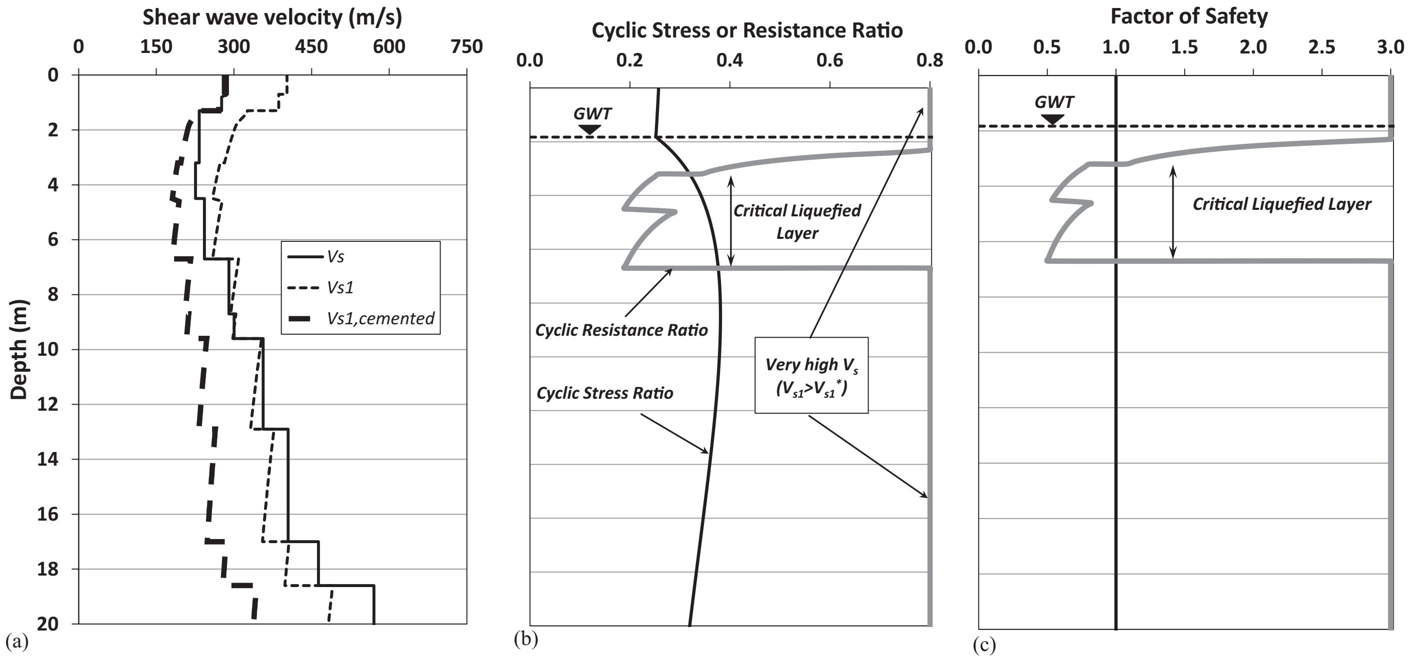

Fig. 4. Deterministic evaluation of liquefaction potential at Kawaihae Harbor, Hawaii: (a) uncorrected and corrected V_s versus depth curves; (b) CSR and CRR versus depth curves; (c) FS versus depth curve

COV is a particularly useful measure of uncertainty because of its dimensionless property

$$\mu = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{4}$$

$$s = \sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5}$$

After calculation of μ and σ for each uncertain parameter based on the values obtained from various references (as discussed earlier), the proper distribution function is fitted. In this study, the aforementioned uncertain parameters, except V_S, were characterized by lognormal distribution, and V_S was considered by normal distribution. In the literature, different values of COV for measurement of V_S by SASW technique are recommended. Marosi and Hiltunen (2004) studied the uncertainty associated with SASW measurements and reported the range of COV for this method between 10 and 15%. Martin and Diehl (2004) reported a COV of SASW-based V_S measurements of approximately 6%. Thelen et al. (2006) reported a higher range of COV (between 2 and 14%) for SASW-based V_S measurements. In this study, three different values of COV were considered for V_S (i.e., COV = 5, 10, and 15%) to investigate the effects of higher COV for V_S measurements.

10. For MCS, the V_S profiles were divided into 2-m intervals, and the simulation process considering the aforementioned notes was performed by 5,000 simulations at each depth.

Table 3 presents a list of references used in deterministic and probabilistic approaches, as described in the previous paragraphs.

Uncertainties associated with the other parameters, such as thickness of soil layers, initial position of water table, or bedrock depth, were not considered in this study.

Results and Discussion

According to the considerations discussed earlier, deterministic values of CSR and CRR were calculated for the studied site. Fig. 4 delineates the zone of potentially liquefied soil predicted by the deterministic V_S-based simplified procedure. In addition, depth profiles of uncorrected V_S, V_{S1} (i.e., V_S values corrected for effective overburden stress), and $V_{S1,\text{cemented}}$ (i.e., V_S values corrected for effective overburden stress and cementation) are presented in Fig. 4(a). The critical layer, denoting the depths with liquefaction resistance (CRR) lower than CSR, is observed in Figs. 4(b and c), wherein the calculated values of CSR, CRR, and FS are plotted with depth.

In the deterministic simplified V_s-based procedure, the limiting upper value of V_{s1} for cyclic liquefaction occurrence is defined as V_{S1}^*, which shows the maximum liquefiable V_s corrected for overburden stress. In the other words, liquefaction cannot occur when V_{s1} is higher than this threshold. The V_{S1}^* value for the studied site was estimated as equal to 211 m/s.

Fig. 4 demonstrates that the liquefied zone at Kawaihae Harbor during the Kiholo Bay earthquake was probably in the range of 3.2–6.7 m. Mahoney et al. (2008) reported that the liquefied zone, which produced surficial effects, were located within the upper fill soils at this site. They argued that intergrain cementation within the upper calcareous layer was weaker than that in natural formations. Furthermore, Brandes et al. (2007) stated that the fill layer consists of dredged calcareous sand–gravel mixture that was placed in a very loose state. Observations, such as sand boils and pavement cracks, differential settlements at Pier 1, and seaward movement of Pier 1, confirm that the liquefied zone was at shallow depths. Although the predicted liquefaction range in Fig. 4 is in agreement with the evidences following the 2006 earthquake at Kawaihae Harbor, there exist various sources of uncertainty in the deterministic approach that may cause questionable judgment of the results.

Several researchers described liquefaction potential in terms of probability (e.g., Cetin et al. 2004; Juang et al. 2001, 2002; Hwang

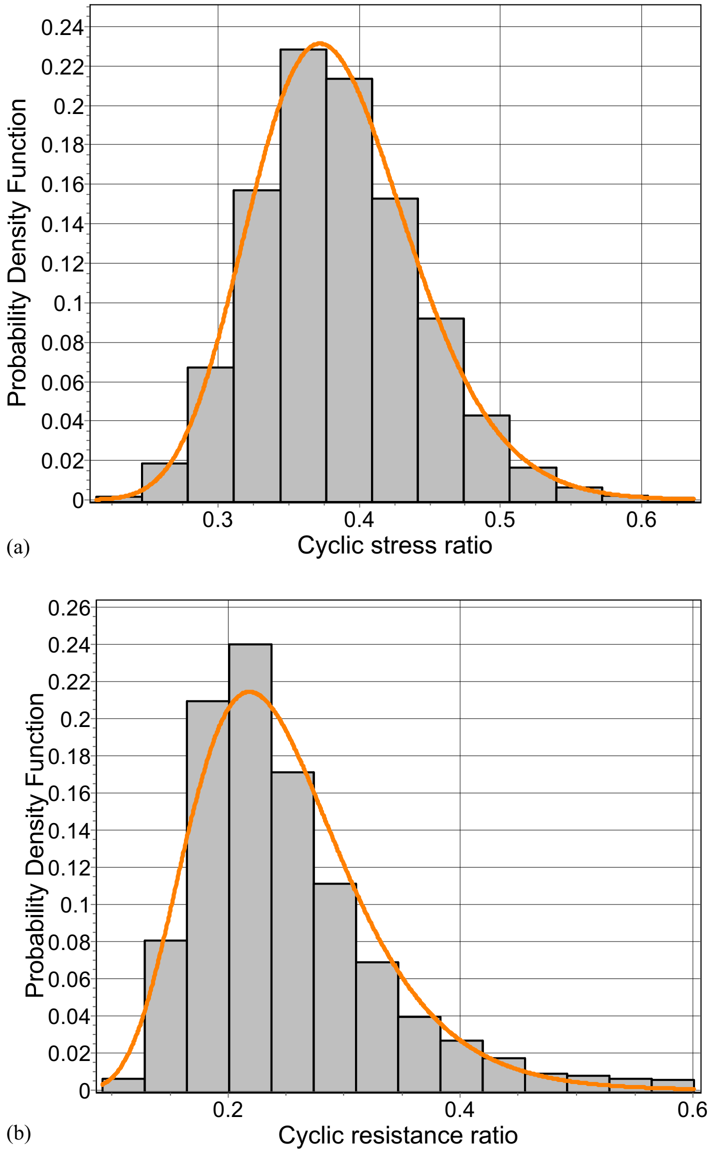

Fig. 5. Calculated probability density functions of (a) CSR and (b) CRR with lognormal distribution curves at 6-m depth

et al. 2005; Jafarian et al. 2010). Probabilistic estimation of liquefaction generates valuable information for risk-based decision making. Researchers (e.g., Jafarian et al. 2010; Juang et al. 2001) used mapping functions to link FS against liquefaction triggering, which comes from deterministic analysis, to liquefaction probability (P_L). Juang et al. (2002) used a Bayesian interpretation technique to develop a probability model for V_s-based case histories. A Bayesian mapping function might be defined for relating the deterministic FS to the P_L obtained by Bayesian interpretation (Juang and Jiang 2000).

As described previously, MC technique was performed in the current study for considering variability of the input parameters and the associated uncertainties. At each depth, two sets of CSR and CRR values using MCS were obtained, and then the corresponding FS values were calculated. Finally, the P_L value at the considered depth was obtained by dividing the number of liquefied cases ($\mathrm{FS} < 1$) by the total number of simulated cases. Fig. 5 demonstrates the PDF curves obtained for CSR and CRR at a depth of 6 m. The standard deviation and mean values of the fitted lognormal curves are 0.1508 and –0.9648 for CSR and 0.3038 and –1.7042 for CRR, respectively (the presented values are in natural logarithmic base).

The liquefaction probabilities based on MCS are dependent on the uncertainty level of V_s. Fig. 6 shows the P_L-depth curves obtained from MCS of the current study using different COV values for V_s.

As presented in Fig. 6, in a layer with high liquefaction potential (i.e., layers with low V_s and FS values), considering higher COV values for V_s causes lower P_L. This fact in a layer with low liquefaction potential is inverse. For instance, at a 6-m depth, the result obtained by MCS analysis by considering 5% COV for V_s shows higher P_L values than similar analysis based on 10 or 15%. Moss (2009), after performing comprehensive research on COV values for V_s obtained from SASW surveys, concluded that a reasonable estimate of COV for V_s variability is approximately 5%. Therefore, for the following conclusions, the results of MCS analysis based on 5% COV are considered.

For better comparison of deterministic and MCS probabilistic results, Fig. 7 presents the liquefied zone at Kawaihae Harbor using a cross section containing the Points 2, 3, and 7. It illustrates that the results of deterministic and MCS probabilistic approaches are in good agreement with each other. Also, the results of this study show that the liquefied zone at Pier 2 is larger than the liquefied zone at Pier 1. Nevertheless, Pier 2 showed better performance during the 2006 event (Robertson et al. 2006; Mahoney et al. 2008).

Robertson et al. (2006) reported that Pier 1 moved as much as 15–30 cm (6–12 in). laterally toward the harbor. This displacement indicates that the piles were moved under the effects of the lateral spreading of the liquefied soil beneath. This area will likely liquefy again in another strong earthquake if the soil is not densified or if no other mitigation measures are undertaken.

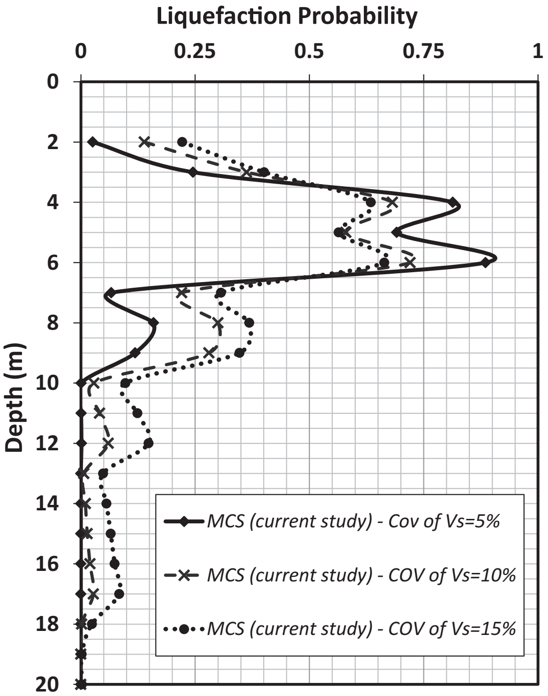

Fig. 6. Comparison of the liquefaction probabilities obtained from MC analyses using different COV of V_s

The liquefaction probability obtained from MCS can be compared with previous studies that used the deterministic FS to calculate the P_L. Fig. 8 presents the P_L-depth curves obtained from the current study and the models developed by Juang et al. (2001, 2002). In addition, a classification rule of the likelihood of liquefaction defined by Chen and Juang (2000) is illustrated in this figure (see descriptions presented on the horizontal axis of Fig. 8).

As presented in Fig. 8, the results obtained by the regression-based mapping approach and Bayesian mapping technique have considerable differences by MCS analysis. However, there are some similarities between the trend of the curves of MCS analysis and the other two mapping techniques in Fig. 8. In layers with higher V_s values, differences between MCS, regression-based mapping approach, and Bayesian mapping technique are completely obvious.

At a 6-m depth, the P_L calculated by MCS (using 5% COV) is approximately 40% higher than predicted values by the mapping techniques. Adopting the classification ranges defined by Chen and Juang (2000), and considering the P_L values higher than 0.65 as the states with high liquefaction probability, the critical depths calculated by MCS and mapping techniques range between 3.6 and 6.5 m and between 5.6 and 6.1 m, respectively. Therefore, the mapping function obtained through regression and Bayesian techniques led to a considerably lower liquefiable range than MCS and deterministic approaches. This comparison does not aim to criticize the mapping techniques of Juang et al. (2001, 2002) because the MCS performed herein is a site-specific assessment in calcareous materials, whereas the other two relationships were developed based on field performance of noncalcareous deposits. Hence, site-specific probabilistic evaluation is suggested to be performed for calcareous soil formations rather than implementation of a predetermined FS–P_L relationship.

Comparison with Available Database

The worldwide V_s-based database of liquefied/nonliquefied case histories has been gathered mainly from case histories occurring in terrigenous soils. To evaluate the position of Kawaihae Harbor in

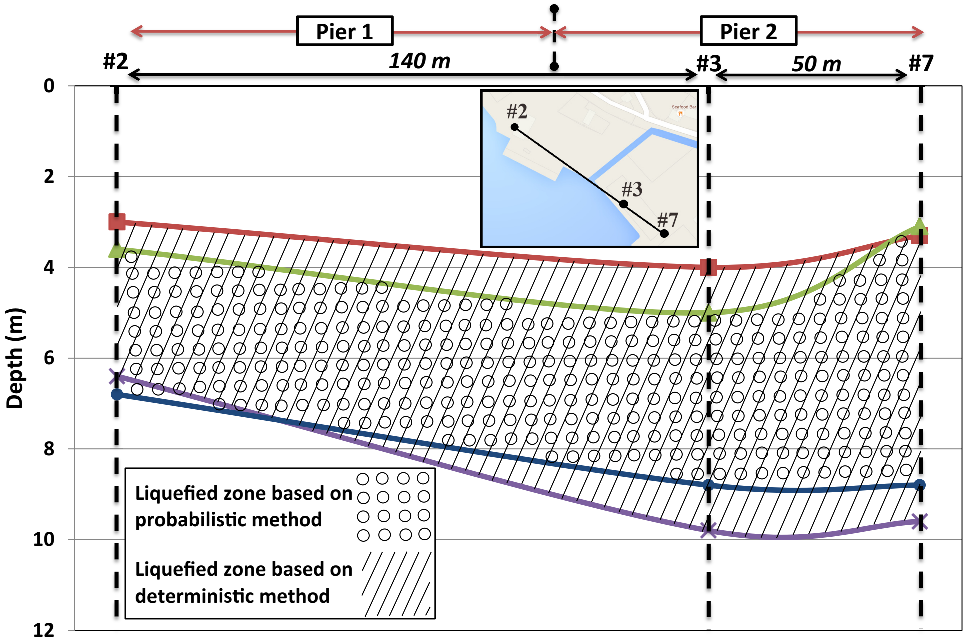

Fig. 7. Estimated liquefied zone at Kawaihae Harbor obtained from deterministic and probabilistic approaches

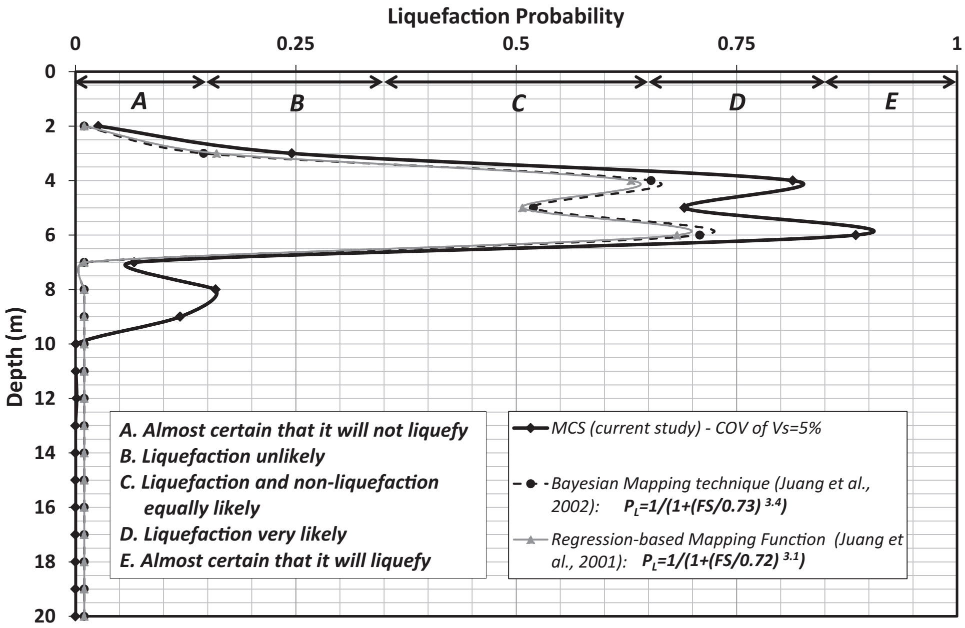

Fig. 8. Comparison of the liquefaction probabilities obtained from MC analyses of the current study and the models developed based on regression and Bayesian mapping techniques

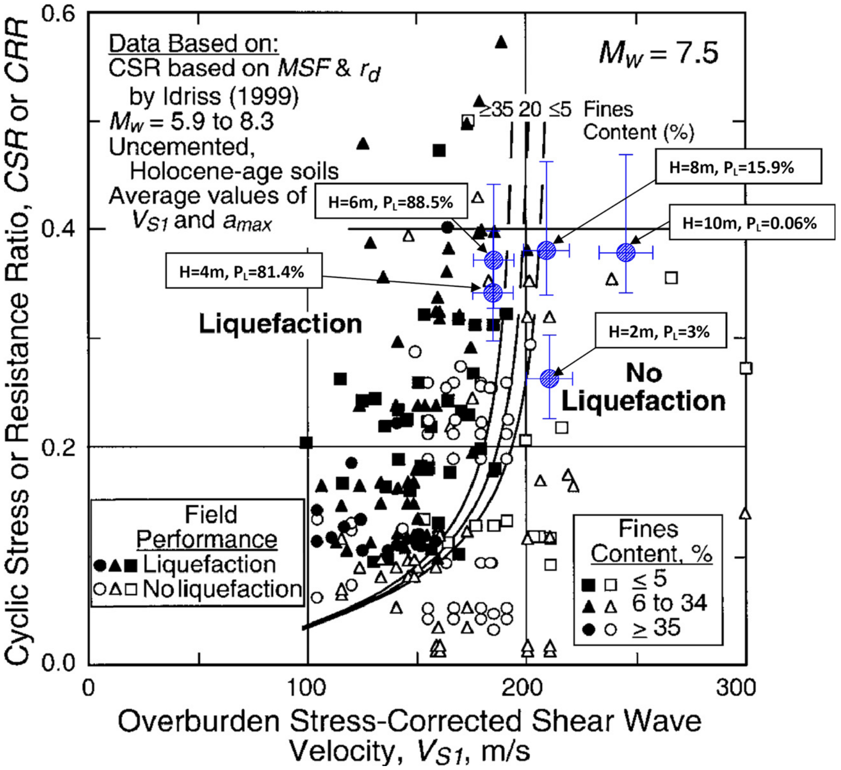

Fig. 9. Results of probabilistic and deterministic analyses on calcareous deposits of Kawaihae Harbor superimposed on the V_s-based database of liquefaction case histories (adapted from Andrus and Stokoe 2000, © ASCE) (Note: the circle points indicate the deterministic values, and the lines with end limits indicate the mean ± standard deviation values)

the worldwide V_s-based database, the deterministic and probabilistic results are superimposed on the database of Andrus and Stokoe (2000). Fig. 9 demonstrates the positions of liquefied depths on the V_{s1}-CSR curve reported by Andrus and Stokoe (2000). The circle points represent the deterministic results, and the crossed lines represent the probabilistic results involving variation in the range of CSR and V_{s1} for different depths. Also, the P_L values calculated for different depths are shown in Fig. 9.

As mentioned earlier, both deterministic and probabilistic studies demonstrate similar ranges for liquefaction between approximately 3.5 and 6.5 m. In Fig. 9, the positions of results obtained for 4- and 6-m depths are in the liquefied zone, and the results of 2-, 8-, and 10-m depths are in the nonliquefied zone. It should be noted that the position of the 8-m depth is close to the liquefaction boundary, and considering the variability of V_{s1}, the position of this point may change from the nonliquefied to the liquefied zone. In addition, considering the curves of Fig. 8, at an 8-m depth, there are considerable differences between P_L values obtained from MCS analyses and the values obtained from the models proposed by Juang et al. (2001, 2002). Therefore, it seems that the boundaries of liquefaction in the V_{s1}-CSR curve, which are mainly developed based on silicate soils, are proper for calcareous deposits of the studied case history.

It is worth noting that the V_s profiles used in this study were measured in 2008, 2 years after the liquefaction occurrence. The earthquake action and the consequent occurrence of liquefaction have probably densified the soil. Therefore, the increased values of shear-wave velocity have probably decreased the liquefaction potential compared with the pre-earthquake conditions. It can be concluded that the liquefied zone caused by the Kiholo Bay earthquake was probably greater than what was predicted in this study. However, the predicted zone represents the critical soil layer in the future probable earthquakes having the same characteristics as the 2006 event.

Conclusions

Shear wave velocity is a promising measure for evaluating liquefaction potential in soils. In this study, geotechnical evidences gathered in Kawaihae Harbor during the 2006 Kiholo Bay earthquake were considered as a well-documented case history to investigate applicability of the simplified V_s-based procedure of liquefaction assessment for calcareous fill materials. Site-specific analysis was carried out through both deterministic and probabilistic frameworks; the latter was performed using MC technique. The certain and uncertain parameters were estimated from the available reports, and the following major conclusions have been drawn:

1. The results showed that, for an earthquake with the same intensity as the 2006 Kiholo Bay event, the liquefied zone calculated by the deterministic approach is between approximately 3.2 and 6.7 m. However, probabilistic analyses using site-specific MCS and a correlation derived from the mapping techniques determined critical depths between 3.6 and 6.5 m and between 5.6 and 6.1 m, respectively. This finding was obtained based on an average V_s profile of Kawaihae Harbor.
2. The liquefied zone during the 2006 earthquake was reportedly larger than the possible liquefied zone evaluated in the current study. This fact might be a result of the densification of soils and consequent increase in shear-wave velocity resulting from the Kiholo Bay earthquake (in 2006). Note that the current study used the V_s data acquired from the site characterization conducted 2 years after the earthquake.
3. Although the V_s-based simplified procedure of liquefaction assessment is mainly suitable for terrigenous soils, its application for the studied calcareous deposit was shown to be reliable. However, further investigation is required when more case histories of calcareous soils are available. Some calibration parameters might be defined for the current procedure to make the procedure more trustworthy for calcareous soils. Also, it seems that the concept of a limiting upper-bound V_{s1} needs to be revised for calcareous deposits because of their cementation effects.
4. The effects of different COVs for V_s values were investigated in the probabilistic part of this study. Higher COVs in layers with low V_s (or low FS values) cause lower P_L values, but this fact is inverse in layers with high V_s or FS values.
5. The results of deterministic and MCS probabilistic, simplified, V_s-based approaches are in good agreement with each other. Also, this study showed that the liquefied zone at Pier 2 is larger than the liquefied zone at Pier 1. Nevertheless, Pier 2 showed better performance during the 2006 event, which was a result of its better structure.
6. It is suggested that site-specific probabilistic assessment be performed for calcareous soil formations instead of using predetermined FS–P_L relationships.
7. New data on liquefaction occurrence in calcareous deposits were added to the worldwide database of liquefaction case histories reported by Andrus and Stokoe (2000).

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