SOIL LIQUEFACTION POTENTIAL IN ILAN CITY AND LOTUNG TOWN, TAIWAN

Sao-Jeng Chao [1], Hui-Mi Hsu [2], and Howard Hwang [3]

ABSTRACT

This paper summarizes an evaluation of the soil liquefaction potential in the Ilan County of Taiwan from the geotechnical earthquake engineering point of view. The Lanyang Plain, located in the central part of the Ilan County, is considered an area with liquefaction potential where the subsurface conditions are characterized by loose uniform grained soils and high groundwater table. The evaluation of liquefaction potential provides important information for preventing liquefaction-related damages predicted by earthquakes. The subsurface soil conditions throughout the Lanyang Plain were investigated in detail using boring logs collected from a total of 685 sites. The SPT approach was utilized in this study for the characterization of liquefaction resistance. This paper describes the procedure for constructing the soil liquefaction potential maps of the densely populated Ilan City and Lotung Town within the Lanyang Plain using two scenario earthquakes. These maps can provide information for formulating disaster reduction strategy in order to mitigate damages and losses predicted by the liquefaction hazards.

Key words: Boring log, earthquake, Ilan, liquefaction.

1. INTRODUCTION

Ilan County is located in the northeastern part of Taiwan as shown in Fig. 1. Ilan County can be mainly divided into three parts: The Snow Mountain range, the Central Mountain range, and the densely populated Lanyang Plain. Lanyang Plain is surrounded by the mountain ranges and is formed at the mouths of several rivers by sedimentary deposit. As a result, the subsurface conditions in the Lanyang Plain are generally characterized by layers of loose uniform grained soils. Furthermore, the groundwater table in the whole Lanyang Plain is typically fairly close to the ground surface, which is also illustrated in Fig. 1. The high probability of earthquake occurrence in this region has resulted in the unavoidable study of the soil liquefaction phenomenon.

The maps of soil liquefaction potential generated by reasonable scenario earthquakes can be used for earthquake emergency response planning. This paper presents the simulation of soil liquefaction potential predicted by two scenario earthquakes for two densely populated areas, Ilan City and Lotung Town, within the Lanyang Plain. The maps of soil liquefaction potential can be used for formulating disaster reduction strategy so that damages and losses from earthquake hazards could be mitigated.

2. SITE CONDITIONS IN THE ILAN AREA

Ilan area, on the geological point of view, can be divided into the Snow Mountain Range, the Central Mountain Range, and the Lanyang Plain area. The Snow Mountain Range, which is located in the northwest region of Ilan County, consists of the West-stratigraphic major, the Schnabelia sandstone, the Dagangou layer, and the Groove-hill. The Central Mountain Range in the southern region of Ilan County consists of the West-stratigraphic major, the Lushan layer, the Tananao Schist, and the South Suao Layer. Lanyang Plain area based on the Lanyang River alluvial deposit mainly structure with clay, silt, sand and gravel.

The boring logs collected from a total of 685 sites in Ilan County during a period of 10 years were used to study the subsurface soil conditions. These boring logs are received from the National Center for Research on Earthquake Engineering (NCREE), Ilan County's strong motion stations, and the National Ilan University (NIU) under the permission of the Ilan County Government. The sources and quantities of collected boring logs are summarized in Table 1. The locations of the boreholes are shown in Fig. 2. It is notable that the majority of the boreholes are located in the urban regions within the Lanyang Plain, including the municipalities of Toucheng, Chiaohsi, Ilan, Lotung, Suao, since more construction projects are happening in these regions.

Based on the boring logs collected from the 685 sites in Ilan County, the common characteristics of the subsurface soil conditions within the Lanyang Plain's different regions were observed (Chao 1999). Figure 3 summarizes four typical sets of boring logs using Unified Soil Classification System taken in the Ilan City region, located in the northern part of the Lanyang Plain. The subsurface conditions in the Ilan City region are characterized by several layers of soft clay and loose sand. From the top of the boring records downward, a layer of soft clay can generally be found first. Following the clay layer, a quite thick layer of loose sand is underlain with an average thickness of 12 m. The subsurface conditions in the Lotung Town region are characterized by similar layers of soft clay and loose sand as shown in Fig. 4.

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[1] Associate Professor and Chairman (corresponding author), Department of Civil Engineering, National Ilan University, Ilan, Taiwan 26045, R.O.C. (e-mail: chao@niu.edu.tw).
[2] Associate Professor, Graduate Institute of Architecture and Sustainable Planning, National Ilan University, Ilan, Taiwan 26045, R.O.C. (e-mail: hmhsu@niu.edu.tw).
[3] Dean, College of Engineering, National Ilan University, Ilan, Taiwan 26045, R.O.C. (e-mail: hmhwang@niu.edu.tw).

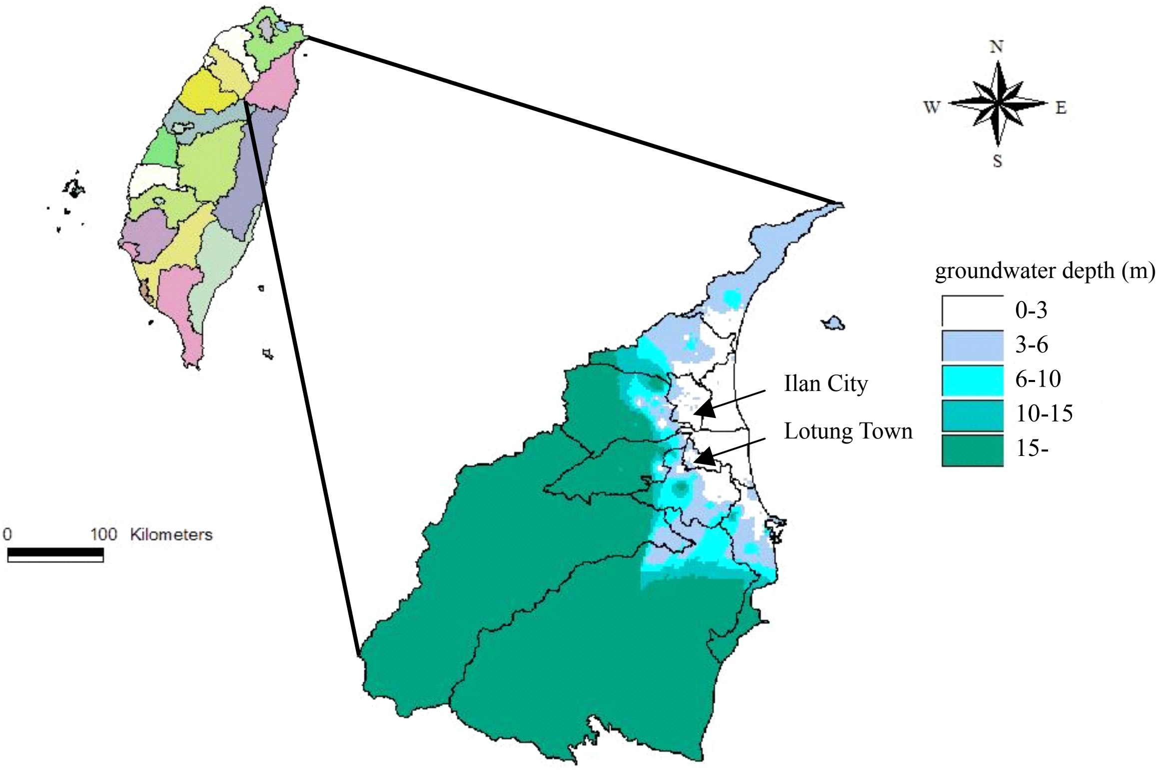


Fig. 1 Location and the depth of the groundwater table of Ilan County

Table 1 Sources and numbers of the collected boring logs in the Ilan area

Sources	No. of boring logs
NCREE	479
Strong motion station sites	31
NIU	175
Total	685

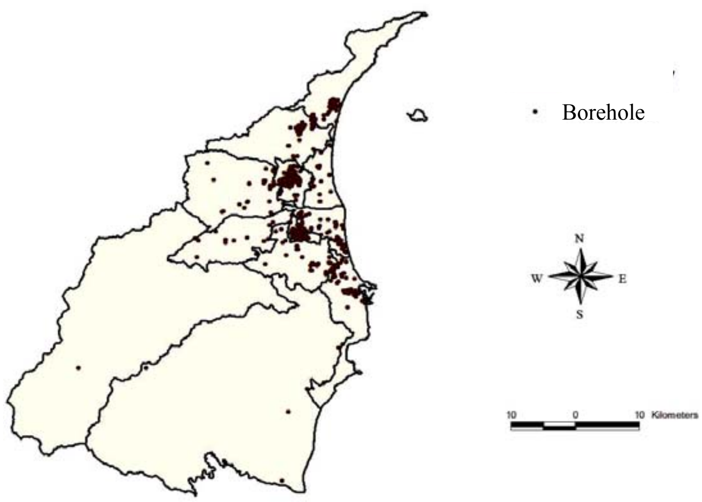


Fig. 2 The locations of the collected boring logs in Ilan County

The subsurface deposits of the Lanyang Plain mainly are structured with the silty sand layer and the silt/clay layer of alluvial deposition cross-holdings. The particle size distribution of sand layer is somewhat uniform, at the same time as the SPT-N value is not high at all. Therefore, the density of the sand strata should be in loose to medium condition, the water table very close to the ground surface as well. As a result, it is necessary to consider prevention of earthquake and soil liquefaction disaster.

3. METHOD USED FOR EVALUATING SOIL LIQUEFACTION POTENTIAL

Even though a great number of approaches for evaluating the soil liquefaction potential have been proposed over the years, this study employed the most commonly used standard penetration test (SPT) approach to evaluate the liquefaction potential because the SPT approach has been conducted for most geotechnical engineering services not only in Ilan County but also in most other parts of Taiwan.

Seed and Idriss (1971) proposed that the uniform cyclic shear stress amplitude for level site can be estimated as follows:

$$CSR = (\tau_{av} / \sigma'_{v0}) = 0.65(a_{\max} / g)(\sigma_{v0} / \sigma'_{v0})\, r_d \tag{1}$$

where $a_{\max}$ is the peak ground surface acceleration, g is the acceleration of gravity, σ_{v0} is the total vertical stress, and r_d is the value of a stress reduction factor at the depth of interest, which can be approximated by the following equation (Youd *et al*. 2001):

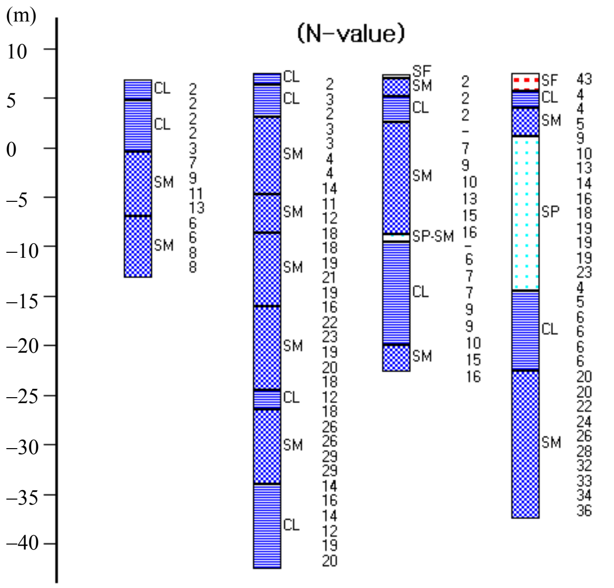


Fig. 3 Cross-section of 4 typical boring logs in the Ilan City region

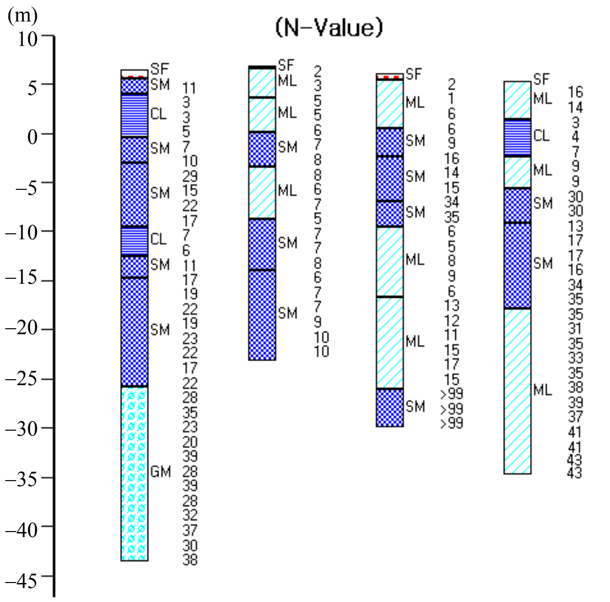


Fig. 4 Cross-section of 4 typical boring logs in the Lotung Town region

$$r_d = \frac{(1-0.4113z^{0.5}+0.04052z+0.001753z^{1.5})}{(1-0.4177z^{0.5}+0.05729z-0.006205z^{1.5}+0.001210z^{2})} \quad (2)$$

where z = depth beneath ground surface in meters.

Seed *et al*. (1983) compared the corrected SPT resistance and cyclic stress ratio for clean sand and silty sand sites to determine the cyclic stress ratio by a given SPT resistance. The presence of fines can affect SPT resistance and therefore must be accounted for in the evaluation of liquefaction resistance (Seed *et al*. 1985). The corrected normalized SPT value, $(N_1)_{60}$, is defined as

$$(N_1)_{60} = N_m \times C_N \times (ER_m / 60) \quad (3)$$

where N_m is the measured SPT value, C_N is an overburden factor, and ER_m is the actual hammer energy ratio. Recently, Youd *et al*. (2001) further proposed several corrections for better prediction of $(N_1)_{60}$ as follows:

$$(N_1)_{60} = N_m \times C_N \times C_E \times C_B \times C_R \times C_S \quad (4)$$

where C_E is the correction for hammer energy ratio ($ER_m/60$), which is described quantitatively in the subsequent example; C_B is the correction factor for borehole diameter; C_R is the correction factor for rod length; and C_S is the correction for samplers with or without liners.

As soon as the value of $(N_1)_{60}$ being determined, the following equation can be used for correction of $(N_1)_{60}$ to an equivalent clean sand value, $(N_1)_{60cs}$:

$$(N_1)_{60_{CS}} = \alpha + \beta(N_1)_{60} \quad (5)$$

where α and β = coefficients determined from the following relationships:

$$\begin{cases} \alpha = 0 & \text{FC} \le 5\ \% \\ \alpha = \exp[1.76 - 190/\text{FC}^2] & 5\ \% < \text{FC} < 35\% \\ \alpha = 5 & \text{FC} \ge 35\% \end{cases} \quad (6)$$

$$\begin{cases} \beta = 1.0 & \text{FC} \le 5\ \% \\ \beta = 0.99 + (\text{FC}^{1.5}/1000) & 5\ \% < \text{FC} < 35\% \\ \beta = 1.2 & \text{FC} \ge 35\% \end{cases} \quad (7)$$

The CRR curve for the clean sand under earthquakes with magnitudes of approximately 7.5 has been proposed for routine engineering calculations as follows:

$$\text{CRR}_{7.5} = \frac{1}{34-(N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{[10\times(N_1)_{60cs}+45]^2} - \frac{1}{200} \quad (8)$$

Once the cyclic loading imposed by an earthquake and the liquefaction resistances of the soils have been characterized, using the definitions of cyclic stress ratio (CSR) and cyclic resistance ratio (CRR), the factor of safety (FS) against liquefaction can be evaluated as follows:

$$\text{FS} = (\text{CRR}_{7.5} / \text{CSR})\ \text{MSF} \quad (9)$$

When the earthquake magnitude is not equal to 7.5, the CSR value needs to be adjusted by a magnitude scaling factor (MSF), which is defined by the following equation:

$$\text{MSF} = 10^{2.24} / M_w^{2.56} \quad (10)$$

When the factor of safety against liquefaction is less than 1, it means that soil liquefaction may occur during the earthquake at the site.

The severity of liquefaction can be furthermore evaluated based on a weighting procedure proposed by Iwasaki *et al.*

(1982). They proposed a procedure to evaluate liquefaction potential index, P_L, based on the in situ test data over the entire borehole (or more accurately, the top 20 m). The liquefaction potential index is defined as:

$$P_L = \int_0^{20} F(z)\, w(z)\, dz \quad (11)$$

where $F(z) = 1 - FS$ for $FS \le 1.0$; $F(z) = 0$ for $FS > 1.0$; $w(z) = 10 - 0.5z$; and z is the depth in meters. The depth of soil layers is limited to 20 m.

4. SIMULATION USING SCENARIO EARTHQUAKES

The comprehensive description of the identification of the possible seismic source zones in Ilan County can be found in a paper by Hwang *et al*. (2007). In this study, the seismic activities around the Ilan area are presumed as the two scenario earthquakes based on the seismic data in the past. From the distribution of epicenters, seismic source zones can be identified. The earthquakes that occurred in the Okinawa trough seismic zone section A and in the Suao-Hualien offshore seismic zone, described in detail in Table 2, are considered to have significant impacts on the environment in Ilan County. It is notable that for the purpose of the earthquake emergency response planning, the Richter magnitude is set as 7.0 in this study under the suggestion from the National Science and Technology Center for Disaster Reduction.

The earthquakes that occurred in the above-mentioned two seismic zones were considered the scenario earthquakes for the estimation of the intensity of ground shaking in the study area. As described in the paper by Hsu *et al*. (2008), an appropriate attenuation relation and a site modification factor were used to predict the peak ground horizontal accelerations in the densely populated Ilan City and Lotung Town within the Lanyang Plain.

Figure 5 shows the distribution of the peak ground horizontal accelerations (PGA) predicted by the Okinawa trough seismic zone section A in Ilan City and Lotung Town. Using the shading presentation technique, it was found that the PGA in the eastern part of the Ilan City is in the range of 0.46g ~ 0.48g, and in the western part 0.37g ~ 0.39g. The same scenario earthquake produces PGA of 0.42g ~ 0.46g in the Lotung Town.

In the calculations mentioned above, the PGA is used to indicate the excitation intensity, while the earthquake magnitude is used to indicate the duration of excitation. With the material properties obtained from the boring logs and the PGA value predicted at each location by the scenario earthquake, the liquefaction potential index, P_L, can then be calculated by using the approach described by Eqs. (1) to (11).

In order to describe the procedure for evaluating P_L in detail, calculation steps for the illustrating site of the National Ilan University is used here as an example. The depth of the water table is 1.2 m from the ground surface. It is notable that a correction ER_m value of 73.5%, commonly accepted in Taiwan's geotechnical field, is used in the calculations. As a result, the correction for hammer energy ratio (C_E) is 1.225. The magnitude of the earthquake is $M_L = 7.0$, which makes the MSF = 1.193, and the maximum ground acceleration at the site is $a_{max} = 0.397$g. Table 3 summaries the results in the computation procedure for evaluation of the liquefaction potential index and provides the result as $P_L = 17.0$ in conclusion.

Table 2 Source parameters of the two scenario earthquakes in the Ilan area

Seismic sources	Fault types	Fault length (km)	Fault azimuth (°)	Epicenter		M_L	Focus depth (km)
				Longitude (°)	Latitude (°)		
Okinawa trough seismic zone section A	Normal fault	35	60	121.869	24.742	7.0	10
Suao-Hualien offshore seismic zone	Thrust fault	55	125	122.03	24.367	7.0	10

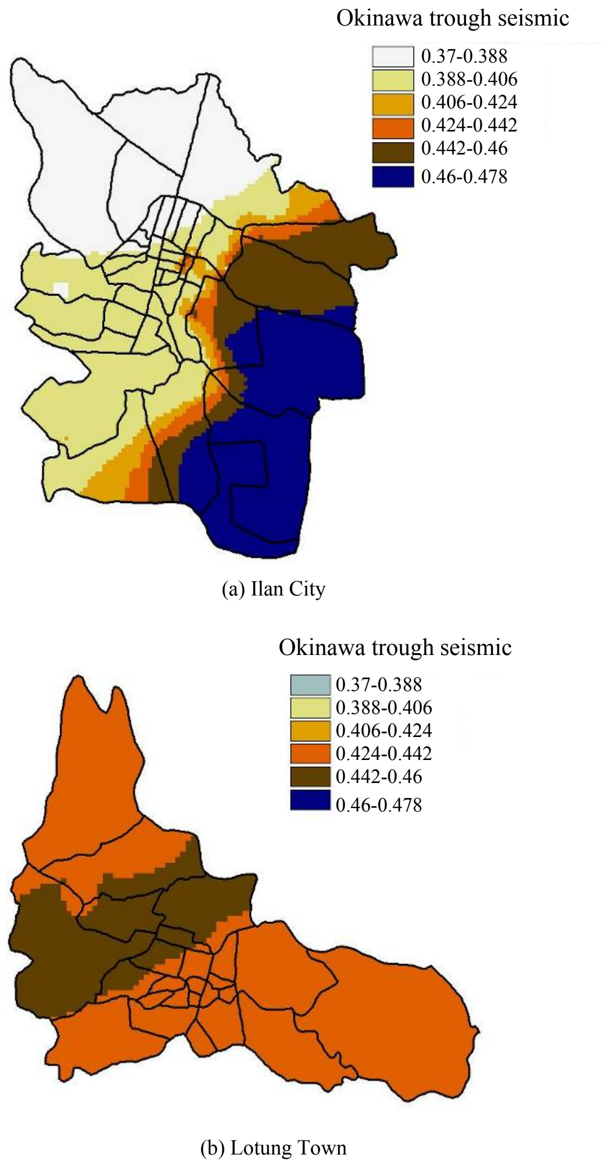


Fig. 5 Distribution of PGA (g) predicted by an earthquake occurred in the Okinawa trough seismic zone section A

Table 3 The results in the computation procedure for evaluating P_L for National Ilan University

Depth (m)	Thickness (m)	SPT-N value	Soil class	Fine content (%)	γ_t (kN/m^3)	CSR	CRR	FS (z)	F (z)	W (z)	P_L (z)
1.5	1.5	3	ML	92	17.56	0.288	0.129	0.533	0.467	9.25	6.48
3.0	1.5	5	ML	91	17.85	0.379	0.163	0.514	0.486	8.50	6.20
4.5	1.5	7	CL	90	18.15	–	–	–	–	7.75	0.00
6.0	1.5	9	CL	88	17.85	–	–	–	–	7.00	0.00
7.5	1.5	11	CL	86	18.84	–	–	–	–	6.25	0.00
9.0	1.5	13	CL	86	18.74	–	–	–	–	5.50	0.00
10.5	1.5	14	ML	77	19.13	0.439	0.295	0.799	0.201	4.75	1.43
12.0	1.5	15	ML	77	20.01	0.422	0.295	0.832	0.168	4.00	1.01
13.5	1.5	16	ML	76	19.33	0.403	0.297	0.879	0.121	3.25	0.59
15.0	1.5	17	SM	25	20.01	0.379	0.257	0.810	0.190	2.50	0.71
16.5	1.5	18	SM	24	20.50	0.354	0.253	0.853	0.147	1.75	0.39
18.0	1.5	19	SM	23	19.82	0.333	0.251	0.901	0.099	1.00	0.15
19.5	0.5	19	SM	23	19.82	0.314	0.171	0.648	0.353	0.13	0.02
										P_L	**17.0**

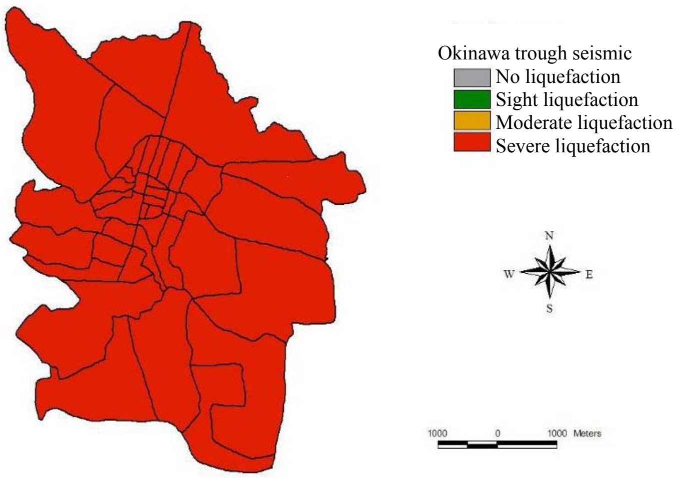
Iwasaki *et al*. (1982) proposed the correlation between the degree of liquefaction and the values of the liquefaction potential index as shown in Table 4. Indications of liquefaction risk based on the liquefaction potential index are as follows: $0 \le P_L \le 5$, liquefaction risk is low；$5 < P_L \le 15$, liquefaction risk is moderate；and $P_L > 15$, liquefaction risk is very high.

In this study, the definition proposed by Iwasaki was followed to describe the degree of liquefaction predicted by the scenario earthquake. The module of Spatial Analyst in the ArcView software was utilized to construct the liquefaction potential maps of the Ilan City and the Lotung Town as shown in Fig. 6. It is noted that this study presents the predicted soil liquefaction potential based on the level of Li, which is the basic unit of city/town administration. The results of soil liquefaction potential from this study are thus consistent with that used in the TELES software (Yeh 2003) compiled by the National Center for Earthquake Engineering Research (NCREE). It was found, as shown in Fig. 6, that Ilan City would experience severe soil liquefaction while the Lotung Town moderate to severe liquefaction.

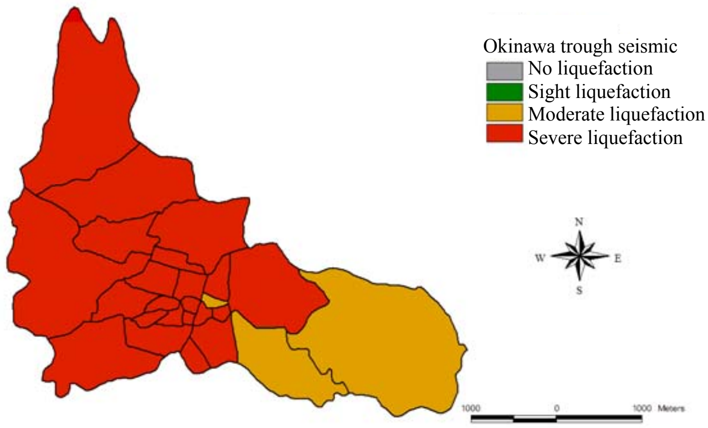
In addition, the predicted maximum ground horizontal accelerations for the Ilan City and the Lotung Town assuming the scenario earthquake occurs in the Suao-Hualien offshore seismic zone is shown in Fig. 7. Using the shading presentation technique, the PGA of the eastern part of the Ilan City would be in the range of 0.29g ~ 0.31g, the middle part 0.22g ~ 0.29g, and the western part 0.20g ~ 0.22g. The same scenario earthquake predicted PGA of 0.24g ~ 0.29g in the Lotung Town.

Table 4 Liquefaction potential classification

Liquefaction potential index	Degree of liquefaction
$P_L = 0$	No liquefaction
$0 < P_L <= 5$	Slight liquefaction
$5 < P_L <= 15$	Moderate liquefaction
$P_L > 15$	Severe liquefaction



(a) Ilan City



(b) Lotung Town

Fig. 6 Degree of liquefaction predicted by an earthquake occurred in the Okinawa trough seismic zone section A

The liquefaction potential index, P_L can be calculated based on the engineering properties obtained from the boring records together with the PGA predicted by the scenario earthquake. The liquefaction potential maps for Ilan City and Lotung Town are shown in Fig. 8. It was found that nearly the entire Ilan City domain reached severe liquefaction state. A few areas in Lotung Town also reached severe liquefaction state.

5. CONCLUSIONS

The subsurface conditions of the Lanyang Plain generally contain several layers of loose uniform grained soils. Furthermore, the groundwater table of the Lanyang Plain is fairly close to the ground surface. Together with the high probability of earthquake occurrence in this area, soil liquefaction phenomena need to be carefully investigated.

In order to provide the information for Local Disaster Prevention and Reduction Project, this study performs simulation of soil liquefaction potential caused by possible scenario earthquakes for Ilan City and Lotung Town. This paper describes the approach and the evaluated results of the soil liquefaction potential in Ilan area utilizing the procedure of the deterministic seismic hazard analysis (DSHA) for the soil liquefaction potential, which is never proposed for Ilan area previously.

In this study, the earthquakes occurred in the Okinawa trough seismic zone section A and in the Suao-Hualien offshore seismic zone were used as scenario earthquakes to determine the simulated virtual PGA as the presumable conditions to predict liquefaction potential in the Lanyang Plain. The maps of the liquefaction potentials of two densely populated areas in Lanyang Plain, Ilan City and Lotung Town, were constructed for the purpose of implementing the strategy for seismic disaster reduction. It was found that nearly the entire Ilan City domain reached severe liquefaction state. A few areas in Lotung Town also reached severe liquefaction state. The results of this research can be used to provide information for formulating disaster reduction strategy so that damages and losses from earthquake hazards could be mitigated.

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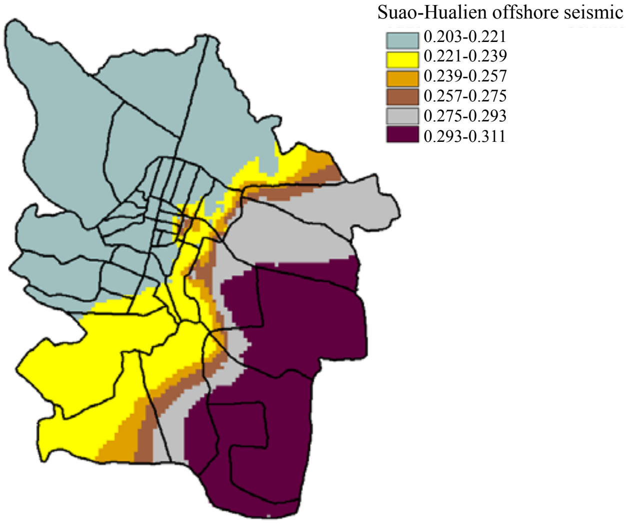
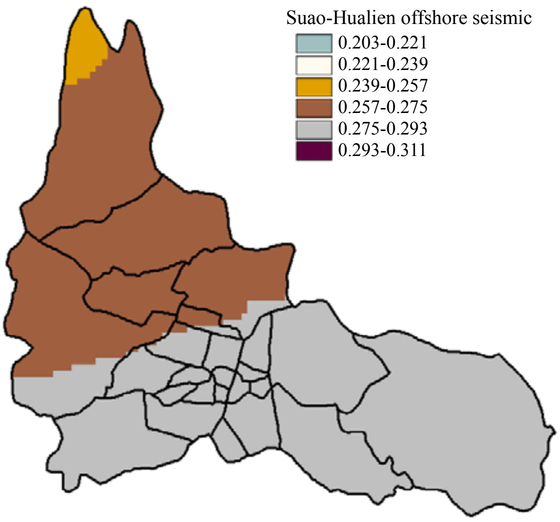
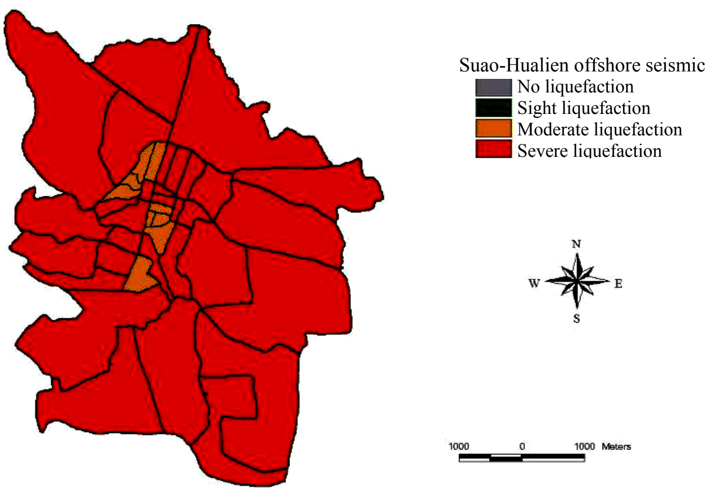


(a) Ilan City

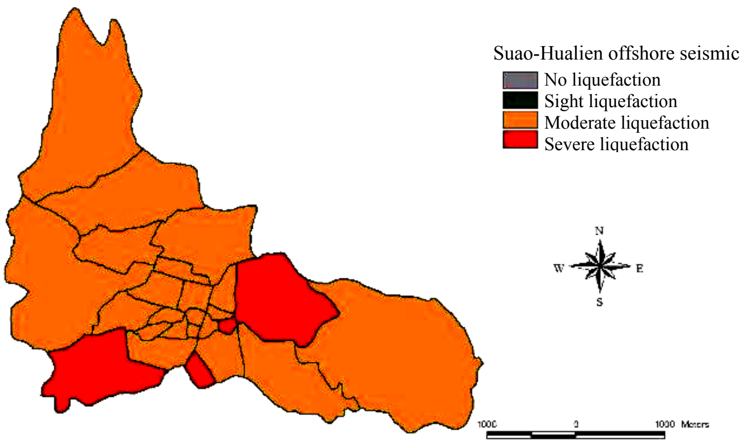


(b) Lotung Town

Fig. 7 Distribution of PGA (g) predicted by an earthquake occurred in the Suao-Hualien offshore seismic zone



(a) Ilan City



(b) Lotung Town

Fig. 8 Degree of liquefaction predicted by an earthquake occurred in the Suao-Hualien offshore seismic zone

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