Evaluation of Liquefaction Potential and Post-Liquefaction Settlement of Tzuoswei River Alluvial Plain in Western Taiwan

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ABSTRACT

Taiwan is located in the conjunction area between Eurasia Plate and Philippine Sea Plate. As a result, the geology condition of the island is complex and the earthquake activity is frequent. On September 21, 1999, a severe earthquake (M_L = 7.3) hit Chi-chi Town and resulted in significant damages and casualties in the mid-west plain of Taiwan. The alluvial deposits of Tzuoswei River, the largest river system of the island, had also experienced serious liquefaction damages during the shaking. The aim of the study was to assess the potential of liquefaction and the associated post-liquefaction settlement of the area. A total of about 1200 effective boreholes were collected. Three types of liquefaction analysis procedures were adopted, including Seed, Tokimatsu & Yoshimi, and the new version of Japanese Roadway Authority methods. A weighing technique suggested by Iwasaki was then used to evaluate the overall liquefaction potential. In addition, post-liquefaction settlements were estimated based on the procedures proposed by Ishihara. Contours of liquefaction potential and post-liquefaction settlement were also generated for the entire study area. Finally, results of the analyses were compared with the regional topography, geology, environmental factors, as well as the locations of critical projects in this area.

INTRODUCTION

Tzuoswei River originates from the southern sideslope of Mt. Hehuan, in the Central Mountain Range of Taiwan. The river is the longest (186 Km) in length and has the second largest drainage area (3157 Km^2) in the island. The head of its alluvial fan starts from Bitzetou (Ersui Railroad Bridge) and spreads out towards the east coastline, with a radial distance of about 40Km. The alluvial fan (plain) is bounded by the Old Tzuoswei River to the north and the Peikang River to the south, which contains the most parts of Changhua County and the northwest portion of Yunlin County.

The Tzuoswei River plays an essential role for the agriculture development in Taiwan. Due to economic development, many critical projects are currently under construction in these years. The eastern side of the plain consists of hilly terrain of Changhua and Yunlin Counties, with some faults being identified, e.g., Changhua Fault, Dajanshan Fault, and Meishan Fault, etc. (CGS 2000). As being close to the fault zone, soil liquefaction in the loose, saturated alluvial deposits (sands) of the area is vulnerable due to earthquakes. It has been found that extended soil liquefaction incidents occurred in Changhua and Yunlin Counties during the 1999 Chi-chi Earthquake, with the affected townships including: Shenkang, Lukang, Yuanlin, Shertou, Datsuen, Mailiao, Tounan, Touliu, and Gukeng (NCREE 2000). Accordingly, the prevention and mitigation of liquefaction disaster has become an important issue for the Tzuoswei River Alluvial Plain. This paper herein discusses results of the liquefaction assessment, with three most widely adopted methods in Taiwan.

ANALYSIS CONDITIONS

Analysis Methods

A total of 1571 borehole logs in Changhua and Yunlin Counties were collected in recent 20 years for this research, in which 1149 boreholes were checked with completeness and adopted for analysis. The distribution of the effective borehole locations is shown in Fig.1. A geological database has been established and used in the liquefaction analysis with three SPT-N-based empirical approaches: Seed's method (Seed et al. 1985, Youd et al. 2001), Tokimatsu and Yoshimi (T-Y) method (Tokimatsu et al. 1983), and the new version of Japanese Roadway Authority (NJRA) method (JRA 1996) to evaluate the liquefaction potential and post-liquefaction settlement in the Tzuoswei River Alluvial Plain.

Liquefaction potential. Based on 64 liquefaction incidents and 23 non-liquefaction incidents from the previous 6 earthquakes, Iwasaki et al. (1982) had defined an index for the evaluation of liquefaction damages (i.e., Liquefaction Potential Index, P_L) with the consideration of depth-weighting. The index can be divided into the following categories: P_L = 0, for very low liquefaction risk; 0 < P_L ≤ 5, for low liquefaction risk; 5 < P_L ≤ 15, for high liquefaction risk; and P_L > 15, for very high liquefaction risk.

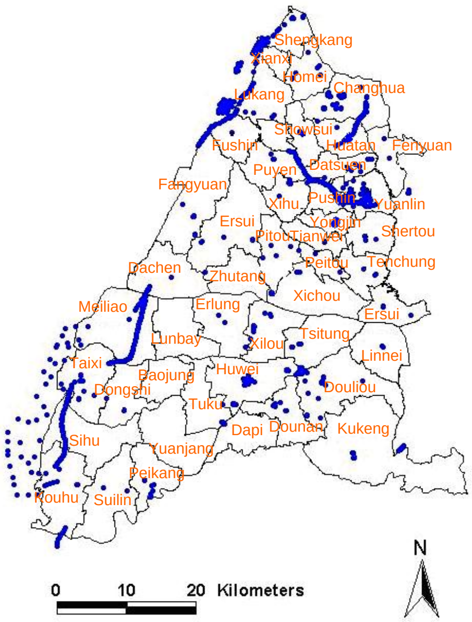

Fig.1. Effective borehole locations.

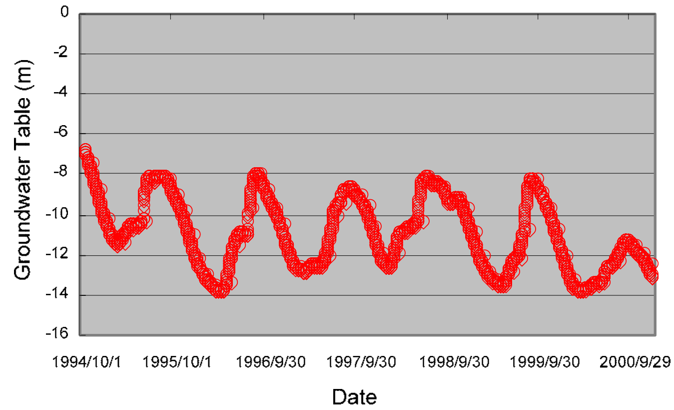

Fig. 2. Results of groundwater monitoring in the study area (Tenchung Station, WRA 1994-2000).

<u>Post-liquefaction settlement</u>. The post-liquefaction settlement was computed based on results of the above-mentioned liquefaction analysis and the Ishihara's methodology (Ishihara and Yoshimi 1992).

<u>EQ Magnitude and PGA</u>

According to the current seismic zonation in Taiwan (NCREE 1999), the design earthquake magnitude (*M*) and the peak ground acceleration (PGA) in Changhua and Yunlin Counties are 7.3 and 0.33g, respectively. For conservative reasons, a magnitude of 7.5 was adopted in this study. In consideration of the PGA distribution (i.e., 0.05~0.40g) in the area during 1999 Chi-chi Earthquake and the seismic design code for Taiwan High Speed Railway (NCREE 1992), a value of 0.33g was selected for analysis in this study.

<u>Groundwater Table</u>

The groundwater data in the effective borehole logs were used for contouring the groundwater level, which was also assumed as the average datum in the study area. The groundwater level was found ranging between 0.2m and 30m below the ground surface. By considering the seasonal effect, the fluctuation in the groundwater level was assumed to be ±3m in the area, as per the results of a long-term monitoring program by WRA from 1994 to 2000 (Fig.2). Accordingly, a groundwater table of the above average datum plus 3m up, but should be lower than the ground surface by at least 1m, was conservatively adopted for analysis in this study.

<u>SPT Energy Ratio</u>

According to Wu (1997), Hong (1997), and Huang (1996), energy ratios (*ER*) of the SPT hammer used in Taiwan were about 77.16% and 78%, for the rope-pulley and the free fall methods, respectively. A value of 73.5% was conservatively adopted in the current study, which was different from the value of 60% as suggested by Seed et al. (1985).

GEOLOGIC PROFILE

<u>Shallow Geology</u>

Tzuoswei River has been very serious in eroding its river sides, with the most sand-carrying capacity than the other rivers in Taiwan. When the river approached the flat land, alluvial deposits were formed and finally became the largest alluvial fan in the island. It has been the most abundance in the groundwater storage and a major agriculture region in Taiwan. The materials of the alluvial fan mainly consist of saturated loose sands (Ho 1986), with a USCS classification as SM and ML.

<u>Fault</u>

According to the latest active fault map by Central Geology Survey of Taiwan, primary faults of the area include: Changhua Fault (to the east of Changhua County), and Dajanshang, Jiucheonkeng, and Meishan Faults (to the east of Yunlin County). Dajanshang Fault is the south portion of Chelungpu Fault, which was the causative fault in the 1999 Chi-chi Earthquake (CGS 2000).

LIQUEFACTION AND SETTLEMENTS ANALYSES

Evaluation of liquefaction potential was performed based on the aforementioned three empirical approaches (i.e., Seed, T-Y, and NJRA methods) for individual depth intervals and a depth-weighting technique (Iwasaki) for averaging the entire potential of the borehole. Post-liquefaction settlement analysis was also conducted based on the three empirical approaches and a procedure provided by Ishihara for the entire borehole. Results of each suite of the analysis are discussed as follows.

Table 1. Results of Seed + Iwasaki / Ishihara analysis.

	Liquefaction Potential, P_L			Post-Liquefaction Settlement, S (cm)		
Category	<5	5~15	>15	<10	10~30	>30
No. of Boreholes	346	292	511	348	398	403
Percentage	30	25	45	30	35	35

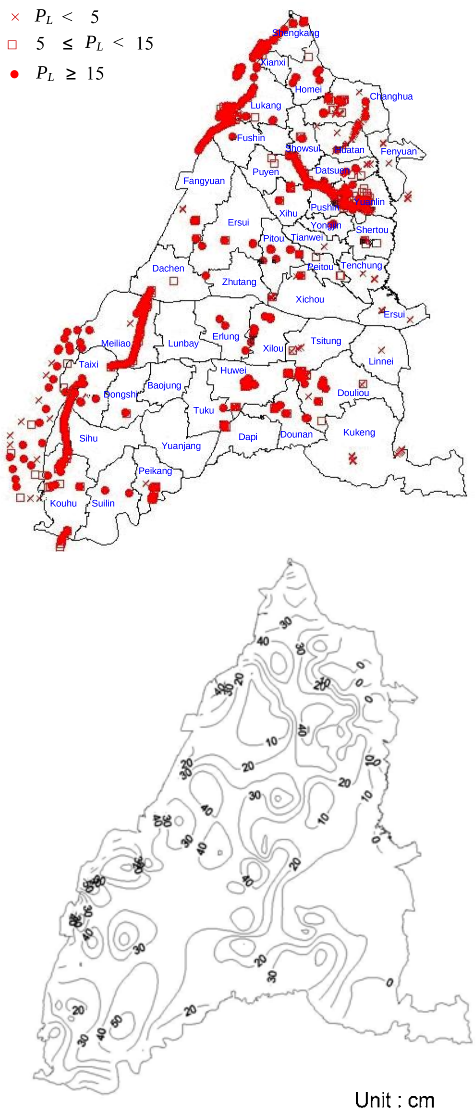

Fig.3. Results of Seed + Iwasaki / Ishihara analysis.

<u>Seed + Iwasaki / Ishihara Analysis Results</u>

Results of this suite of analysis are shown in Table 1 and Fig.3. Results indicated that around 45% of the effective boreholes were computed with $P_L > 15$, suggesting a very high liquefaction risk. The area with a high risk potential encompasses the mid-plain and the coastland of the counties, approximately 3/4 of the entire study area. The analysis also showed the computed maximum settlement was 72cm, and the average settlement for entire area was 22.7cm with a standard deviation of 17.6cm. As shown in Fig.3, locations with greater post-liquefaction settlements were generally consistent with those with higher liquefaction potentials.

Table 2. Results of Tokimatsu & Yoshimi + Iwasaki / Ishihara analysis.

	Liquefaction Potential, P_L			Post-Liquefaction Settlement, S (cm)		
Category	<5	5~15	>15	<10	10~30	>30
No. of Boreholes	287	304	558	301	412	436
Percentage	25	26	49	26	36	38

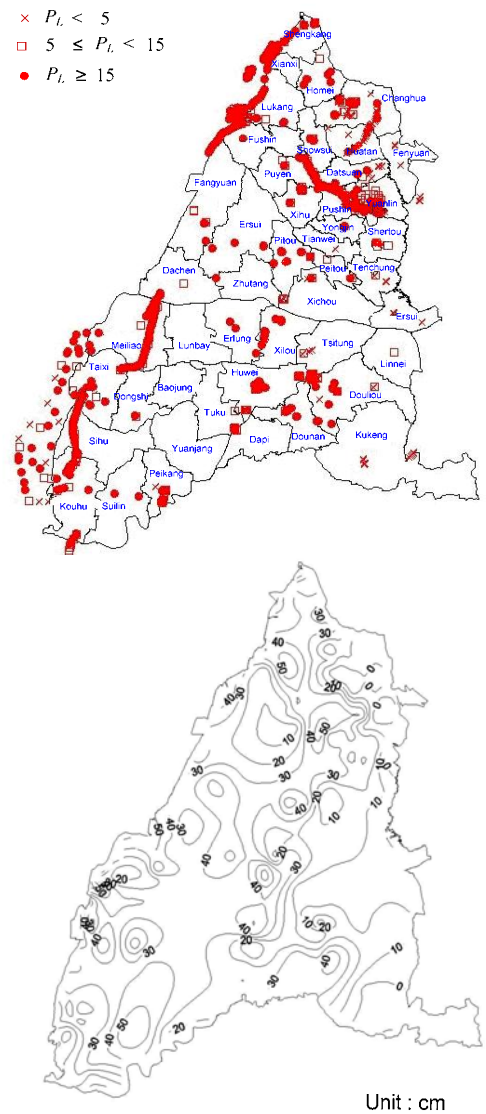

Fig.4. Results of Tokimatsu & Yoshimi + Iwasaki / Ishihara analysis.

<u>Tokimatsu & Yoshimi + Iwasaki / Ishihara Analysis Results</u>

Results of this suite of analysis are shown in Table 2 and Fig.4. Results indicated that around 49% of the effective boreholes were computed with $P_L > 15$, suggesting a very high liquefaction risk. The area with a high risk potential also encompasses the mid-plain and the coastland of the counties, with an area slightly larger than the previous suite of analysis (Seed's method). The analysis also showed the computed maximum settlement was 75cm, and the average settlement for entire area was 24.7cm with a standard deviation of 18.1cm, all slightly greater than the previous analysis.

Table 3. Results of NJRA + Iwasaki / Ishihara analysis.

	Liquefaction Potential, P_L			Post-Liquefaction Settlement, S (cm)		
Category	<5	5~15	>15	<10	10~30	>30
No. of Boreholes	242	288	619	289	411	449
Percentage	21	25	54	25	36	39

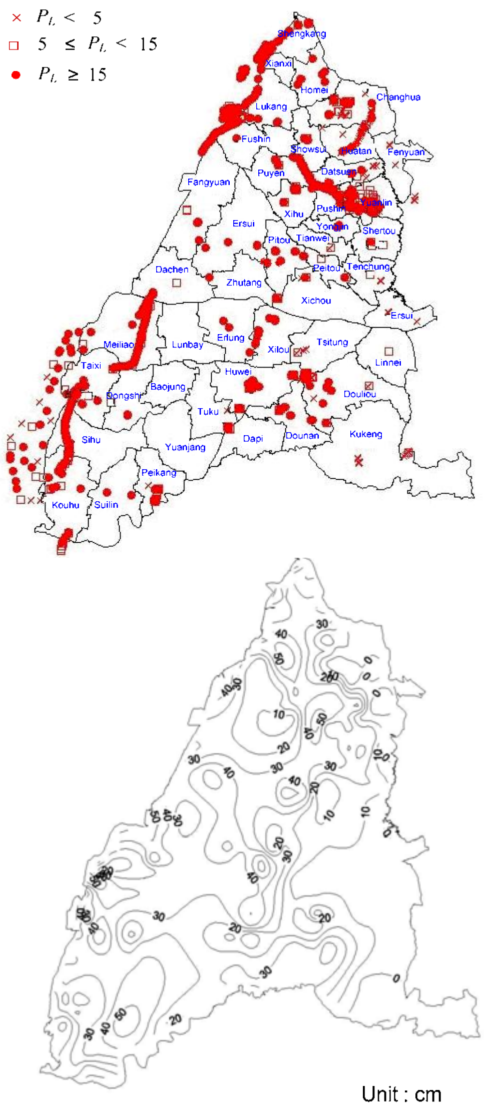

Fig.5. Results of NJRA + Iwasaki / Ishihara analysis.

NJRA + Iwasaki / Ishihara Analysis Results

Results of this suite of analysis are shown in Table 3 and Fig.5. Results indicated that around 54% of the effective boreholes were computed with $P_L > 15$, suggesting a very high liquefaction risk. The area with a high risk potential also encompasses the mid-plain and the coastland of the counties, with an area larger than the previous two suites of analysis (Seed's method, Tokimatsu & Yoshimi's method). The analysis also showed the computed maximum settlement was 75cm, and the average settlement for entire area was 25.1cm with a standard deviation of 18.0cm, approximately the same values as the Tokimatsu & Yoshimi's analysis.

DISCUSSION OF ANALYSIS RESULTS

Results of the above analyses were further compared with the topography, abandoned river channel locations, groundwater regime, and critical construction projects of the study area. Due to non-uniform distribution of the borehole locations, the contouring of liquefaction potential index, P_L, was estimated by interpolation from the finite computed values of the boreholes. Accordingly, the potential error in analysis plots should be put in mind during the interpretation of the results.

Liquefaction Potential and Topography

The terrain contour map of the Tzuoswei River Alluvial Plain was plotted based on surface elevations of the observation wells by WRA (1994~2000). The map was overlapped with liquefaction potential distributions computed by the aforementioned analysis suites as shown in Fig.6 to Fig.8. Results generally show a high liquefaction risk in the mid-plain and the coastland (i.e., surface elevations less than about 30m) due to the design PGA of 0.33g, with the results of NJRA-analysis suite somewhat higher than those of the Seed-analysis suite.

Liquefaction Potential and Abandoned River Channels

According to Chang (1985), the main channel of Tzuoswei River has been changed several times in the history. Figures 9 to 11 show the existing and abandoned river channels overlapped with the computed liquefaction potentials from the three analysis suites. Results indicate high liquefaction risks exist in most of the downstream area of the existing and abandoned river channels, where loose and saturated sandy materials are deposited. The grain size of sandy deposits and the associated computed liquefaction potential were plotted along the current Tzuoswei River, as shown in Fig.12. The grain size of alluvial deposits is decreasing, associated with an increase in the computed liquefaction potential, as the river approaches its estuary. For the liquefaction potential index less than 5 (low liquefaction risk), the mean grain size (D_{50}) of deposits would be greater than 80mm. On the contrary, for the mean grain size of 1mm or less, the liquefaction potential index would be greater than 15 (very high liquefaction potential).

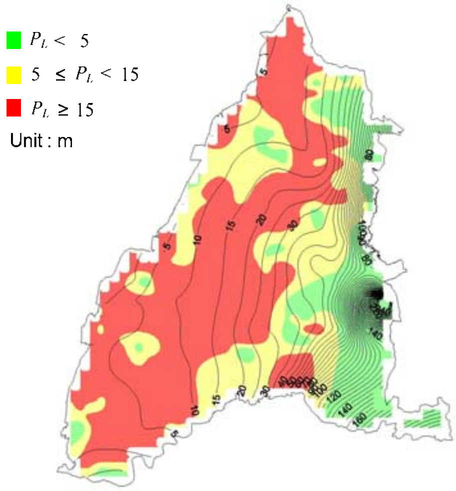

Fig.6. Topography and computed liquefaction potential by Seed + Iwasaki method.

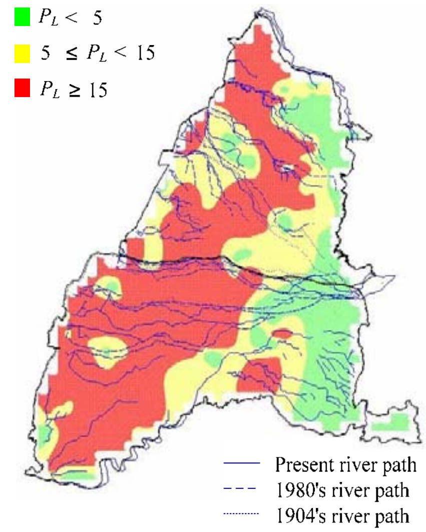

Fig.9. River channels and computed liquefaction potential by Seed + Iwasaki method.

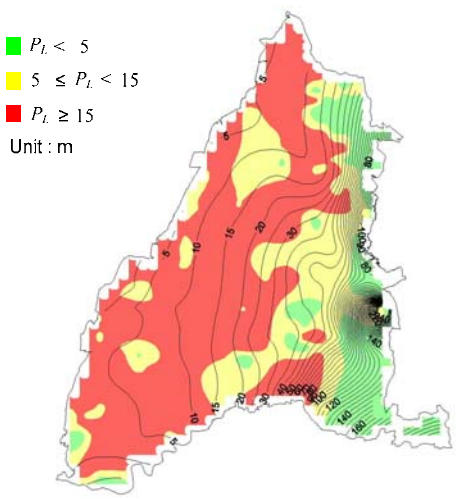

Fig.7. Topography and computed liquefaction potential by Tokimatsu & Yoshimi + Iwasaki method.

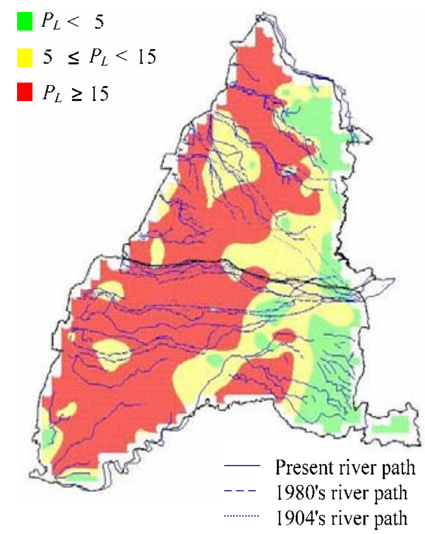

Fig. 10. River channels and computed liquefaction potential by Tokimatsu & Yoshimi + Iwasaki method.

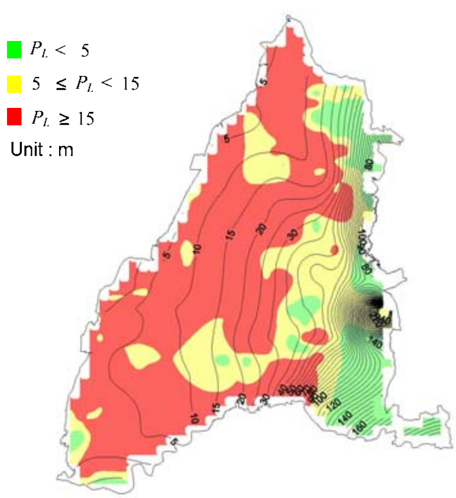

Fig.8. Topography and computed liquefaction potential by NJRA + Iwasaki method.

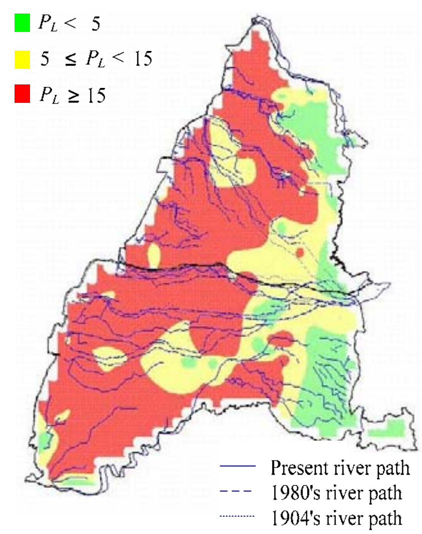

Fig. 11. River channels and computed liquefaction potential by NJRA + Iwasaki method.

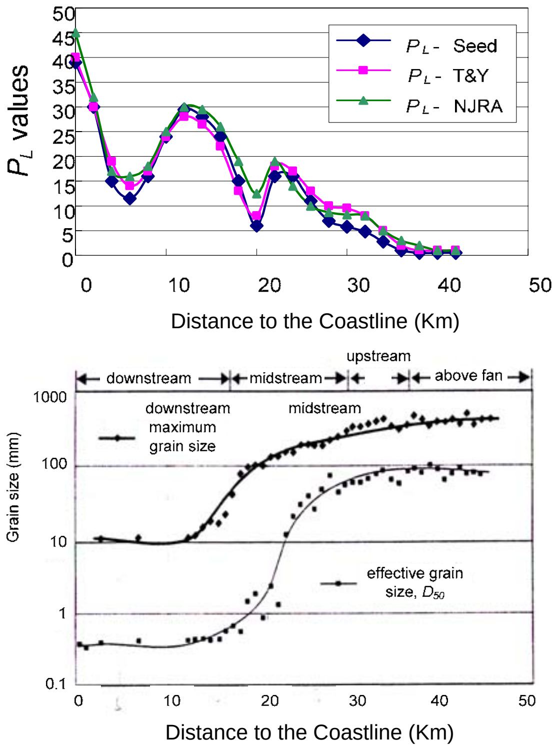

Fig.12. Liquefaction potential and grain-size distribution of alluvial deposits.

<u>Liquefaction Potential and Groundwater Level</u>

The average groundwater level of the study area was based on the groundwater data of the borehole logs. Figures 13 to 15 indicate the groundwater level contours overlapped with the computed liquefaction potentials from the three analysis suites. Results show the relationship between groundwater level and liquefaction potential was not obvious, partly because of the non-uniformity of borehole locations and the accuracy of groundwater data. Nonetheless, the liquefaction risk would appear to be high for the groundwater depth of less than 2m below the ground surface.

<u>Liquefaction Potential and Critical Construction Projects</u>

Tzuoswei River Alluvial Plain is the most important agriculture region in Taiwan. Due to rapid economic growth in the past decade, several critical construction projects have been constructed or under construction in this area. The projects include: Mailiao Industrial Park of Formosa Plastic Co., Yunlin Off-Shore Industrial Park, Changbin Industrial Park, High Speed Railway, the 3rd Freeway, No.76 and 78 Expressways, etc. In order to examine the potential impact on the projects due to liquefaction by the design earthquake, the study herein was therefore carried out. As shown in Figures 16 to 18, all of the off-shore industrial parks and some of the transportation projects would apparently be affected by liquefaction of the sandy deposits during the design earthquake.

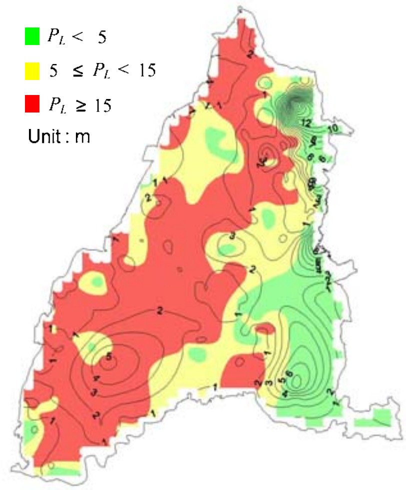

Fig.13. Groundwater level and computed liquefaction potential by Seed + Iwasaki method.

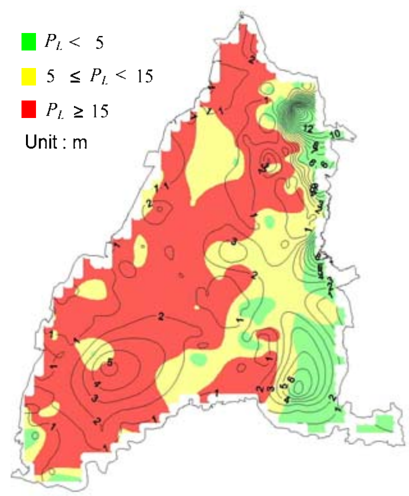

Fig.14. Groundwater level and computed liquefaction potential by Tokimatsu & Yoshimi + Iwasaki method.

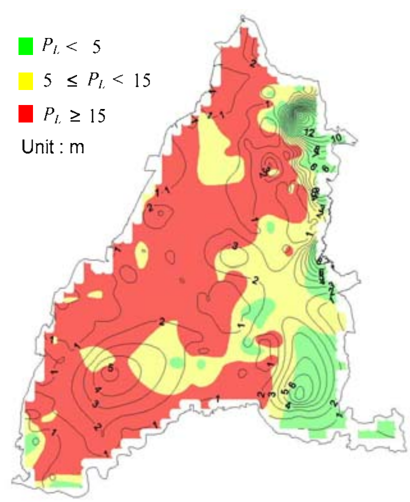

Fig.15. Groundwater level and computed liquefaction potential by NJRA + Iwasaki method.

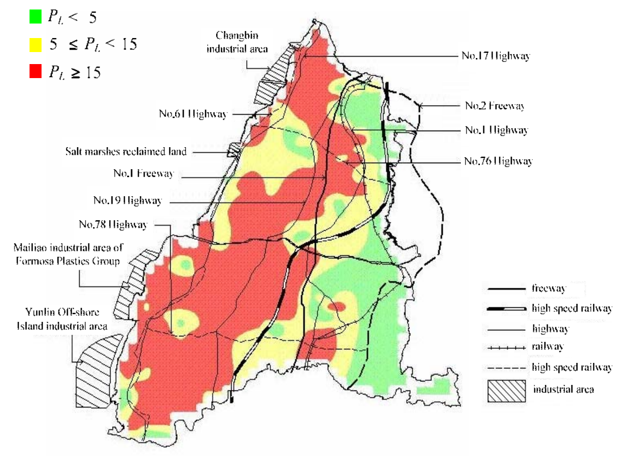

Fig.16. Critical construction projects and computed liquefaction potential by Seed + Iwasaki method.

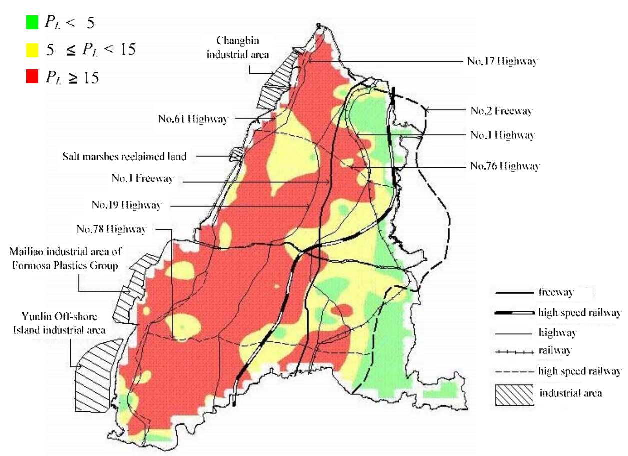

Fig.17. Critical construction projects and computed liquefaction potential by Tokimatsu & Yoshimi + Iwasaki method.

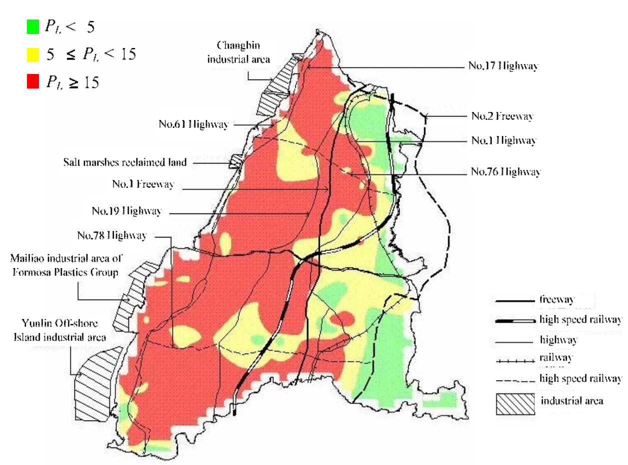

Fig.18. Critical construction projects and computed liquefaction potential by NJRA + Iwasaki method.

It should be noted, however, the current evaluations were based upon the design earthquake with a PGA of 0.33g in this area. For the causative faults, which are located to the east boundary of the area, the ground shaking would be expected to attenuate with distance (from east to west), and possibly decrease to a much smaller value when reaches the coastline.

CONCLUDING REMARKS

The study herein was conducted to assess the potential of liquefaction and the associated post-liquefaction settlement in the sandy deposits of Tzuoswei River Alluvial Plain, which had been suffered significant liquefaction damages during the 1999 Chi-chi Earthquake. Three types of liquefaction analysis procedures were adopted, including Seed, Tokimatsu & Yoshimi, and the new version of Japanese Roadway Authority (NJRA) methods. Results of the major findings in this study are listed as follows:

1. The alluvial deposits of Tzuoswei River mainly consist of saturated loose sands, which are susceptible to liquefy during earthquakes;
2. Differences in the liquefaction potential and the post-liquefaction settlement analyses are generally small for the three empirical liquefaction analysis procedures adopted in the current study;
3. NJRA + Iwasaki method appears to be more conservative than others, and provides lower liquefaction safety factors and higher liquefaction potential indices;
4. Seed + Iwasaki method appears to be the least conservative and generally results in higher liquefaction safety factors and lower liquefaction potential indices;
5. For the post-liquefaction settlement analysis, NJRA + Ishihara method is more conservative than others, and provides greater settlement estimations;
6. Seed + Ishihara method is the least conservative in post-liquefaction settlement estimation, and generally computes smaller settlement values;
7. Under the design earthquake with a PGA of 0.33g, all analysis methods predict a high liquefaction risk in the mid-plain and the coastland of study area, with computed liquefaction potential indices (P_L) greater than 15;
8. The average computed post-liquefaction settlement of the area ranges from 22 to 26cm during the design earthquake condition;
9. As the average effective grain size (D_{50}) less than about 1mm, the computed liquefaction potential would be greater than 15, indicating a very high liquefaction risk in the alluvial deposit under the design earthquake;
10. For the groundwater level shallower than 2m below the ground surface, the computed liquefaction potential would normally indicate a very high liquefaction risk for the sandy deposits in the area during the design earthquake;

11. All of the off-shore industrial parks (Mailiao Industrial Park of Formosa Plastic Co., Yunlin Off-Shore Industrial Park, Changbin Industrial Park,) and some of the transportation projects would apparently be affected by liquefaction of the sandy deposits during the design earthquake with a PGA of 0.33g;
12. It should be noted that the current evaluations were based upon the design earthquake, which tended to provide more conservative predictions in liquefaction potential and post-liquefaction settlement. For the causative faults, which are located to the east boundary of the area, the ground shaking would be expected to attenuate with distance (from east to west), and possibly decrease to a much smaller value when reaches the coastline.

ACKOWLEDGEMENT

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