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MESH-BASED SOIL LIQUEFACTION ANALYSIS FOR EMERGENCY RESPONSE – CASE STUDY OF THE MEINONG EARTHQUAKE IN TAIWAN

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Abstract

Many urban areas in Taiwan are located in the alluvial deposit with high ground water level which is prone to soil liquefaction endangering buildings, transportation and lifeline systems under strong ground shaking. An extensive database of engineering boreholes from the governmental agency and private sectors is established for soil liquefaction analysis. An automatic processing module producing the shake map and soil liquefaction map in a 500m × 500m mesh is developed in this study. The Meinong earthquake (M_L=6.6) in 2016 caused 117 death and wide-range soil liquefaction was chosen as a case study to verified the performance of the methodology. Incorporated with the actual distribution of ground motion and the borehole data in corresponding grids is capable of providing a superior evaluation of liquefaction potential comparing to traditional approach subjected to a uniform excitation. The analytical results of liquefaction potential and induced settlement are generally consistent with the field observations except for some areas without borehole data. Majority of the buildings settled obviously as a result of soil liquefaction are seated in the medium liquefaction potential region as the analysis disclosed. This study provided the prompt and reliable information to the commander for decision making in the practical emergency operation.

Keywords: earthquake, soil liquefaction, emergency response, disaster

1. Introduction

As located on the subduction zone between the Philippine Sea Plate and the Eurasia Plate, the people of Taiwan have suffered from more than a dozen of disastrous earthquakes. The most three devastating events are the Meishan earthquake (M_L=7.3, 1,258 death), the Hsinchu-Taichung earthquake (M_L=7.1, 3,276 death), and the Chi-Chi earthquake (M_L=7.3, 2,405 death), which are all in the western part of Taiwan. The epicenter of these earthquakes and the distribution of population are displayed in Figure 1. Approximately 70% of the population (23 million in total) is concentrated in 6 metropolitan cities in the western plan areas of Taiwan. In recent decades, the disaster vulnerability in urban areas has increased because of population concentration and complex infrastructures constructed in Taiwan. A major earthquake (M_L=6.6) occurred in Meinong, Kaohsiung city on February 6, 2016, which caused tens of buildings collapsed or tilted, 117 death, 551 insured, and wide-range soil liquefaction in Tainan city. If a large-scale earthquake like the Chi-Chi event occurred in urban areas again, the casualties and losses may become several times of those in 1999.

To analysis the liquefaction potential in urban areas, some geological databases of engineering boreholes were established by the government agencies and research institutions. After the Meinong earthquake, the Central Geological Survey (CGS) published the soil liquefaction potential maps covering 8 cities/counties for homeland planning or disaster prevention planning. However, the soil liquefaction potential maps generally are under a scenario of a uniform acceleration equal to the design earthquake which is different from the practical acceleration distribution in an earthquake event. Therefore, a rapid and reliable analysis of soil liquefaction using the magnitude and acceleration distribution from an earthquake event is required to provide in-time information to the commander for emergency response. In this study, an automatic analysis procedure of soil liquefaction is build using the focal parameter of an earthquake event and updated borehole data from various institutions. The analytical result is compared with the field observation in the Meinong earthquake.

No.	Earthquake	Date	Magnitude (M_L)	Depth (km)	Casualty	
					Decease	Injured
1	Douliou	1904/11/06	6.1	7.0	145	158
2	Meishan	1906/03/17	7.1	6.0	1,258	2,385
3	Nantou Series	1916/08/28	6.8	45.0	71	285
		1916/11/15	6.2	3.0		
		1917/01/05	6.2	0.0		
		1917/01/07	5.5	0.0		
4	Hsinchu-Taichung	1935/04/21	7.1	5.0	3,276	12,053
5	Chungpu	1941/12/17	7.1	12.0	358	766
6	Shinhua	1946/12/05	6.1	5.0	74	182
7	Longitudinal Valley Series	1951/10/22	7.3	4.0	>85	>1,000
		1951/10/22	7.1	1.0		
		1951/10/22	7.1	18.0		
		1951/11/25	6.1	16.0		
		1951/11/25	7.3	36.0		
8	Hengchun	1959/08/15	7.1	20.0	17	85
9	Paiho	1964/01/18	6.3	18.0	106	653
10	Hualien	1986/11/15	6.5	15.0	13	45
11	Chi-Chi	1999/09/21	7.3	8.0	2,405	11,305
12	Taoyuan	2010/03/04	6.4	5.0	0	96
13	Meinong	2016/02/06	6.6	14.6	117	551

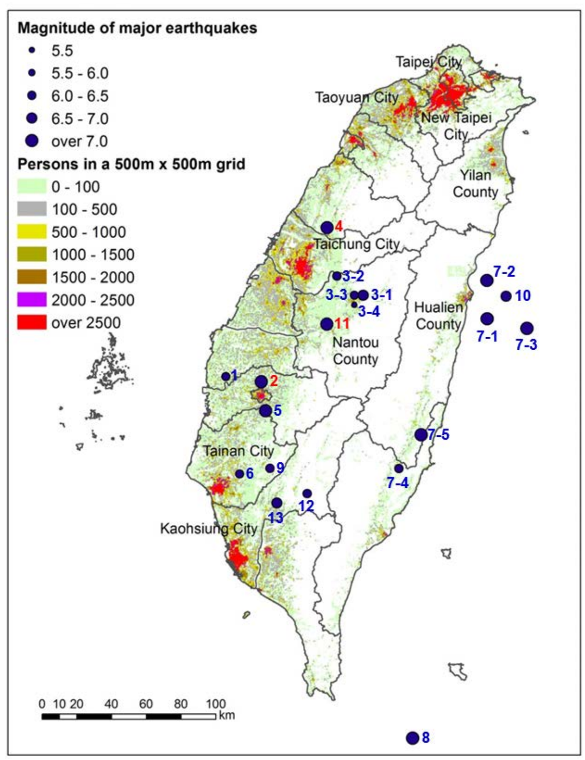

Fig. 1 – Location of disastrous earthquakes and population distribution in Taiwan

2. Methodology

2.1 Borehole database

Many simplified evaluation methods of soil liquefaction potential have been proposed by researchers based on the SPT-N value and other soil parameters retrieving from boreholes [1, 2, 3]. A thorough borehole database with good quality and adequate coverage in a region is essential to obtain the superior analytical result. Totally 16,156 sets of borehole data were included in this study comprising the following sources: (1) The Geo2010 database established by the CGS which is mainly from the construction projects of infrastructures; (2) The engineering geological database of the strong-motion stations from the Central Weather Bureau (CWB); (3) The borehole data from the field investigation of liquefaction sites in the Chi-Chi earthquake; (4) The borehole data in Tainan city from the Sino Geotechnology, Inc. As exhibited in Fig. 2, the digital topography map in grey levels indicates the elevation ranging from sea level to 3,890m in the island. The distribution of boreholes covered most of the alluvia plain displayed in white color.

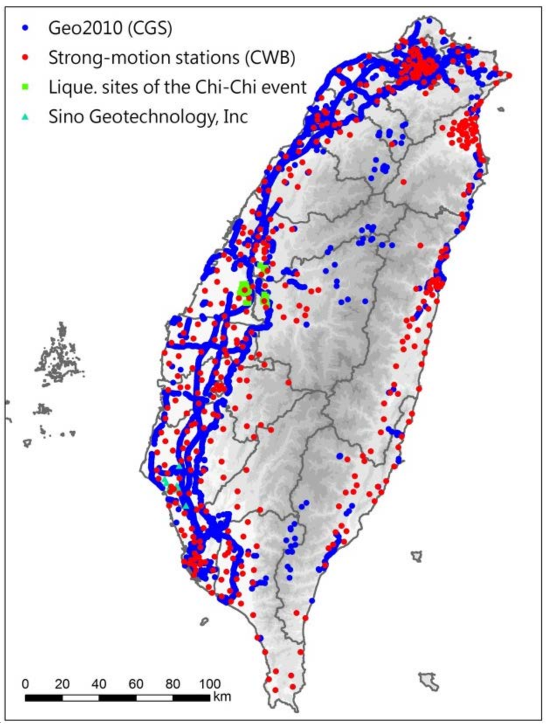

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Fig. 2 – Borehole database used in this study

2.2 Ground motion distribution

The earthquake information, including the magnitude, location of epicenter, measured peak ground acceleration (PGA) at triggered real-time monitoring stations, can be received from the CWB after an earthquake. Thereafter, a shake map in a 500m $\times$ 500m mesh is produced as the input excitation for the analysis of soil liquefaction.

2.3 Automatic processing module of soil liquefaction

The evaluation method of soil liquefaction suggested in the seismic design code of buildings in Taiwan [5] is adopted in this study, which is equivalent to the JRA(1996) method [2] as shown in Fig. 3. The SPT-N value, bulk unit weight, percentage of fine content, classification of soil type, plastic index, depth of soil sample, and depth of water table are retrieved from the database and assembled in a transition file for the automatic process of soil liquefaction analysis.

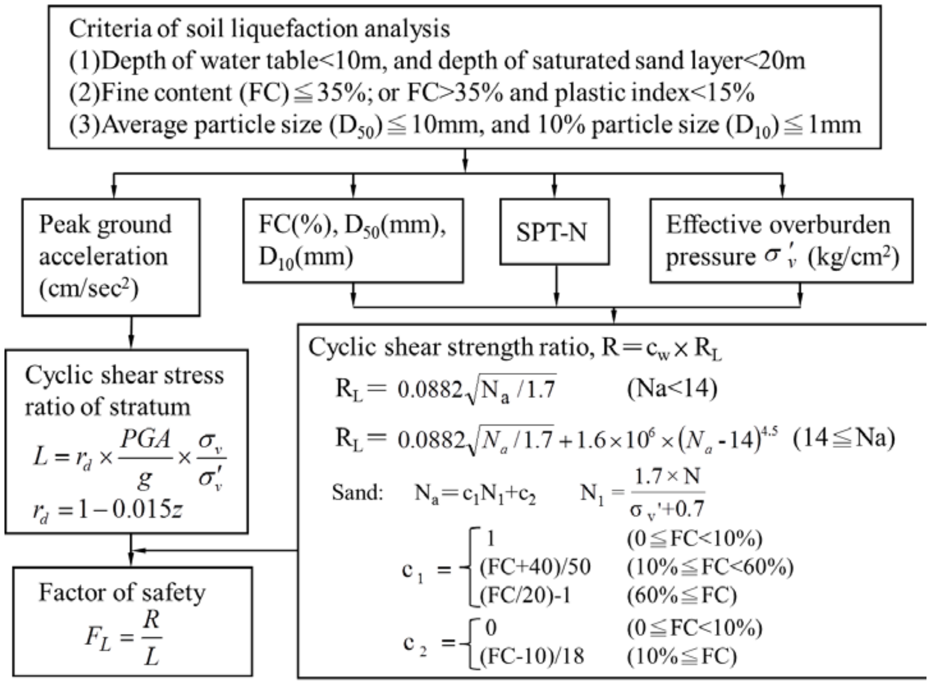


Fig.3 – Analysis method of soil liquefaction

An index of liquefaction potential (P_L) can be used to classify the potential of liquefaction [6]:

$$P_L = \int_0^{20} F(z)w(z)dz \tag{2}$$

where z is the depth of soil sample, F_L is the factor of safety against liquefaction

F_L ≦ 1.0, $F(z)$=1- F_L

F_L > 1.0, $F(z)$=0.

$w(z)$=10-0.5z

According to field investigation from earthquake events, the potential of soil liquefaction can be classified in three categories:

0 ≦ P_L < 5: low potential of soil liquefaction; slight liquefaction.

5 ≦ P_L < 15: medium potential of soil liquefaction; settlement or liquefaction feature is not obvious on the ground surface; some liquefaction may be existed in deep layer of stratum.

P_L > 15：high potential of soil liquefaction; serious liquefaction; settlement or sand boiling is obvious on the ground surface

The empirical method proposed by Ishihara and Yoshimine (1992) [7] can be used to estimate the settlement induced by liquefaction using the P_L value. Furthermore, Yi (2010) [8] presented detailed formula to predict the settlement following the liquefaction.

$$\epsilon_v = 1.5 \times exp\{-0.449[(V_{s1})_{cs}/100]^{1.976}\} \times \min(0.08, \gamma_{max}) \tag{3}$$

where ε_v is the volumetric strain, $(V_{s1})_{cs}$ is the overburden stress-corrected shear wave velocity which can be interpreted by the STP-N value, and γ_{max} is the maximum shear strain which can be expressed in a hyperbolic relation with the F_L value. Integration of the volumetric strain at various depths derives the total deformation of the ground.

The scheme of an automatic processing module elaborating ground motion prediction and soil liquefaction analysis is illustrated in Fig. 4. After an E-mail for an earthquake was received from the CWB, this module will be triggered to estimate the ground motion in each grid using the focal parameters and attenuation relation. Subsequently, the P_L value is calculated for each borehole using the soil parameters from the database. The P_L value at a grid having boreholes is given by averaging all the values inside this grid. Afterward, the P_L value at each grid is determined by the inverse distance weighting interpolation approach using the values from neighboring grids. The settlement caused by soil liquefaction can be predicted for each borehole then transformed to the values in grids by means of the same interpolation method. Finally, the analytical result is interpreted in a 500m × 500m mesh using a Geographic Information System (GIS) software.

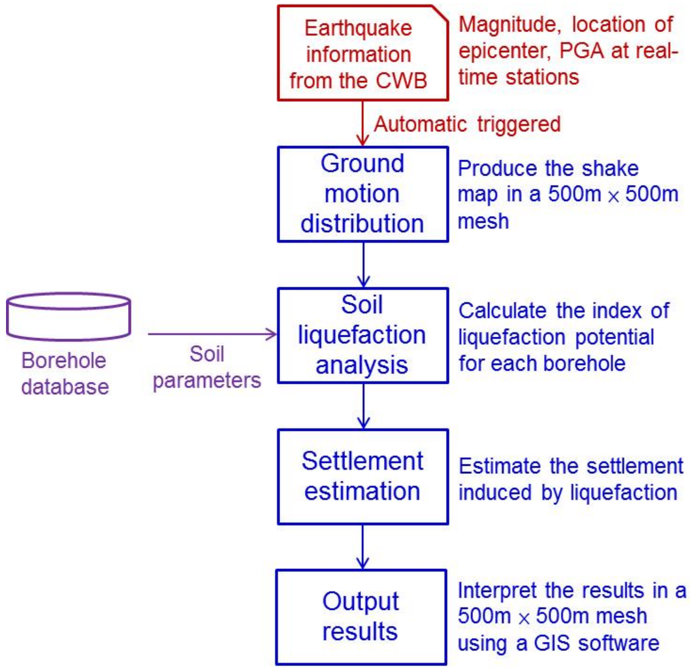


Fig. 4 – The automatic processing module producing shake map and soil liquefaction map

3. Case study of the Meinong earthquake

3.1 Ground motion of the earthquake

A major earthquake (M_L=6.6, depth=14.6km) occurred at AM3:57 on February 6, 2016 in the Meinong district, Kaohsiung city. According to the modified earthquake report and measured PGA from the CWB, the shake map in a 500m × 500m mesh was produced as Fig. 5. The intensities in Tainan city and Yunlin county are Level 6 (PGA=250 ~ 400gal). The average PGA in the some districts of Tainan city is illustrated in Table 1. The intensive excitation is the main reason for the building collapse and soil liquefaction.

Table 1 – The average PGA in some districts of Tainan city

District	PGA(gal)
Shanshang	342
Sinhua	276
Shanhua	243
Sinshih	231
Guanmiao	214
Yongkang	204
Annan	179

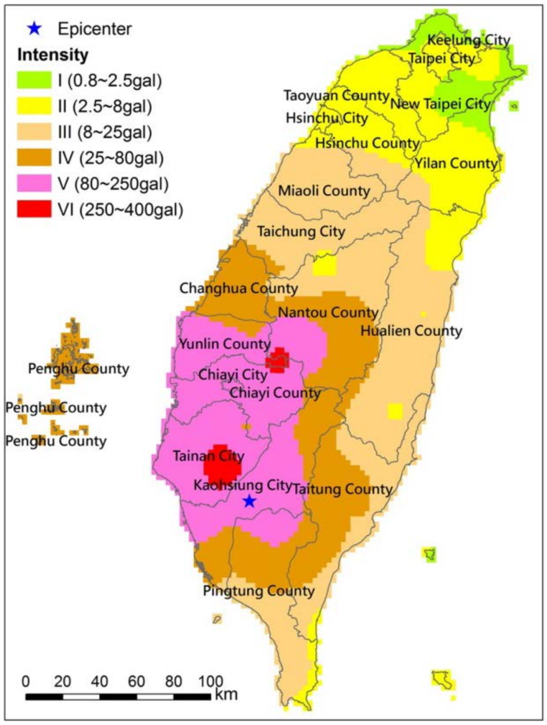


Fig. 5 – Shake map of the Meinong earthquake

3.2 Liquefaction features observed in the earthquake

Under the strong shaking in the Meinong earthquake, some typical liquefaction features were observed in Tainan city. According to the report from the Central Emergency Operation Center (CEOC) and the field investigation by the CGS (Fig. 6), large portion of the sand boiling spots were found on the farms along the Yanshuei River in the Sinhua district. In the same areas, some sand boiling spots were also observed after the Shihua earthquake (M_L=6.1, Tainan city) in 1946 and the Taoyuan earthquake (M_L=6.4, Kaohsiung city) in 2010. Tens of residential buildings settled or tilted due to soil liquefaction in the Annan district, Sinshih district, and Guanmiao district which drew considerable attention of Taiwanese people. The embankment of the Freeway #3 in the Shanhua District was sliding failure because of soil liquefaction.

3.3 Analysis results of soil liquefaction compared with field observations

Using the corresponding PGA distribution from the earthquake, the liquefaction potential was analyzed and provided to the CEOC as a reference of decision making in the emergency operation. The potential of soil liquefaction in each borehole is depicted in Fig. 7(a). Large extent of areas in the Anan district is high to medium liquefaction potential, where is a wide alluvial fan between the Tsengwen River and Yanshuei River. It was a lagoon in the 17th century and lots of fish ponds existed in last century. In addition, the low liquefaction potential areas are not presented in this map since it is trivial to influence the safety of structures.

The residential buildings in the Annan district and Sinshih district having serious settlement are both located in the medium liquefaction potential zone as interpreted in Fig. 7(b), which demonstrates a high correlation between the building damage and the liquefaction potential from the evaluation. However, some cracks on the ground floor caused by liquefaction in the Guanmiao district positioned in the region of low potential liquefaction. The discrepancy may be derived from insufficient borehole data in these areas. More borehole data in the areas neighboring river bank and other soft alluvia deposits is necessary for more detailed and precise assessment of liquefaction. The analytical procedure [9] based on the deposit type, age, distribution of cohesionless sediments in a geological map could be a preliminary tool to understand the possibility of liquefaction in the regions without borehole data. Further study on the integration of these approaches in terms of borehole data and geological map may be an option to overcome the shortcoming of both approaches.

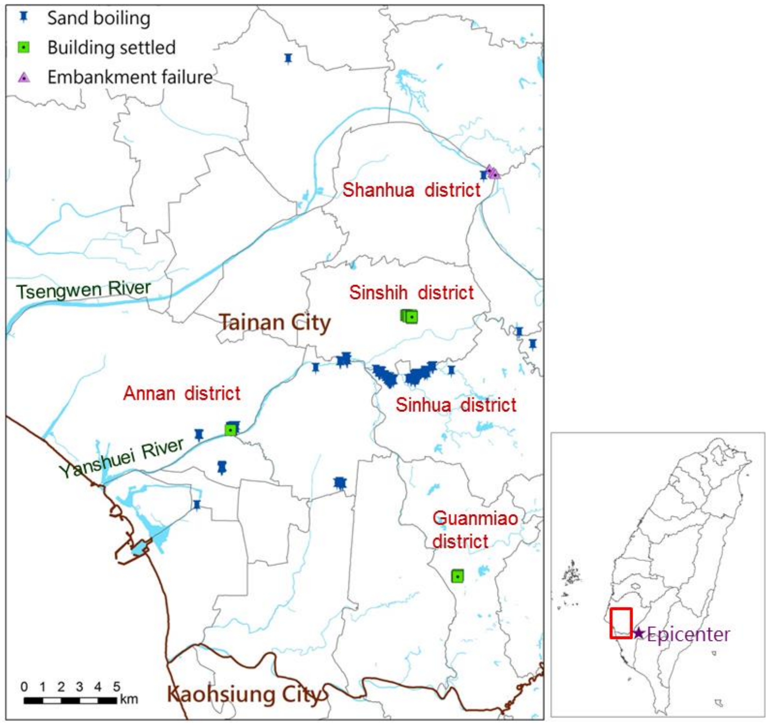
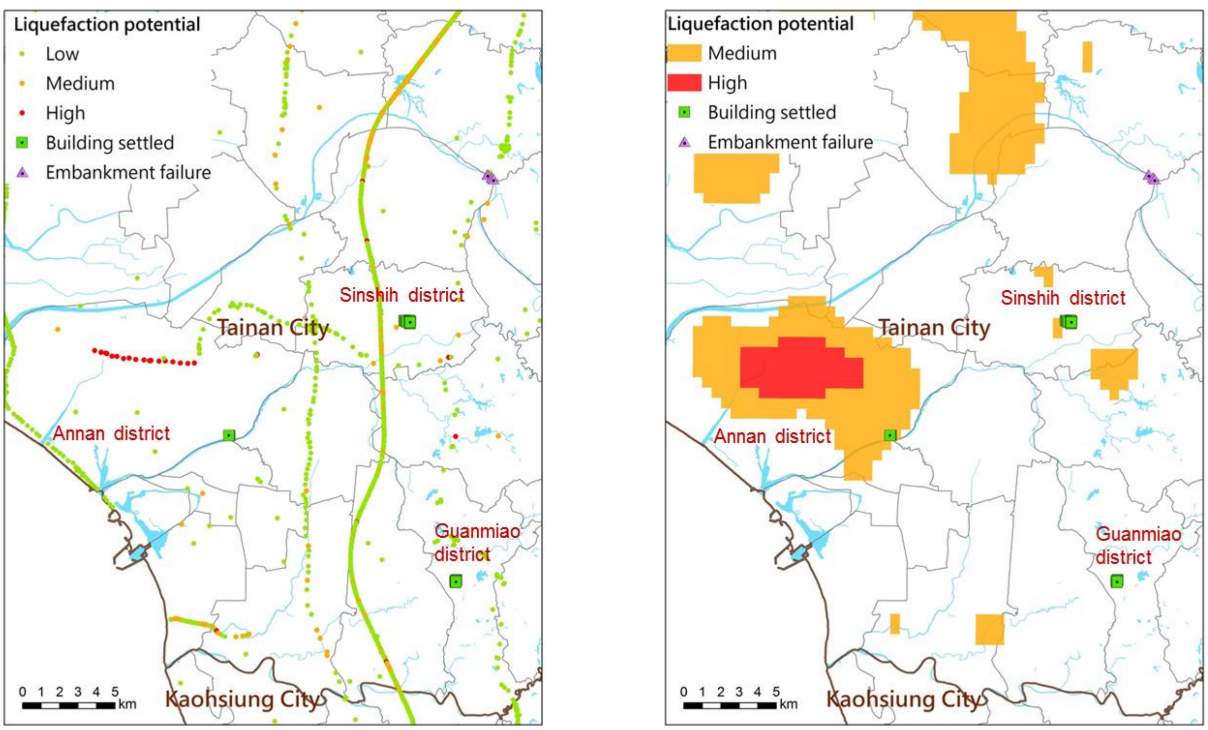


Fig. 6 – Soil liquefaction features and induced damages in the Meinong earthquake



(a)Analysis result in each hole (b)Analysis result in the mesh

Fig. 7 – Liquefaction analysis result compared with structure damages in the field

The settlement induced by soil liquefaction on the free field in each grid is estimated as Fig. 8. The excessive settlement is concentrated in the Annan district which is consistent with the evaluation of liquefaction potential. The estimated settlement in the Annan district is almost 30cm while the measured settlement on the building sites is more than 1m. The predicted settlement in the Shinshih district is approximately 25cm whereas the measured settlement is greater than 45cm. These deviations may result from the basic assumption of free field in the theoretical approach. The self-weight of buildings could increase the settlement under strong motion. In an overall picture, the methodology proposed in this study enables providing rapid and useful information identifying the vulnerable zone of liquefaction and following settlement endangering the safety of buildings after an earthquake.

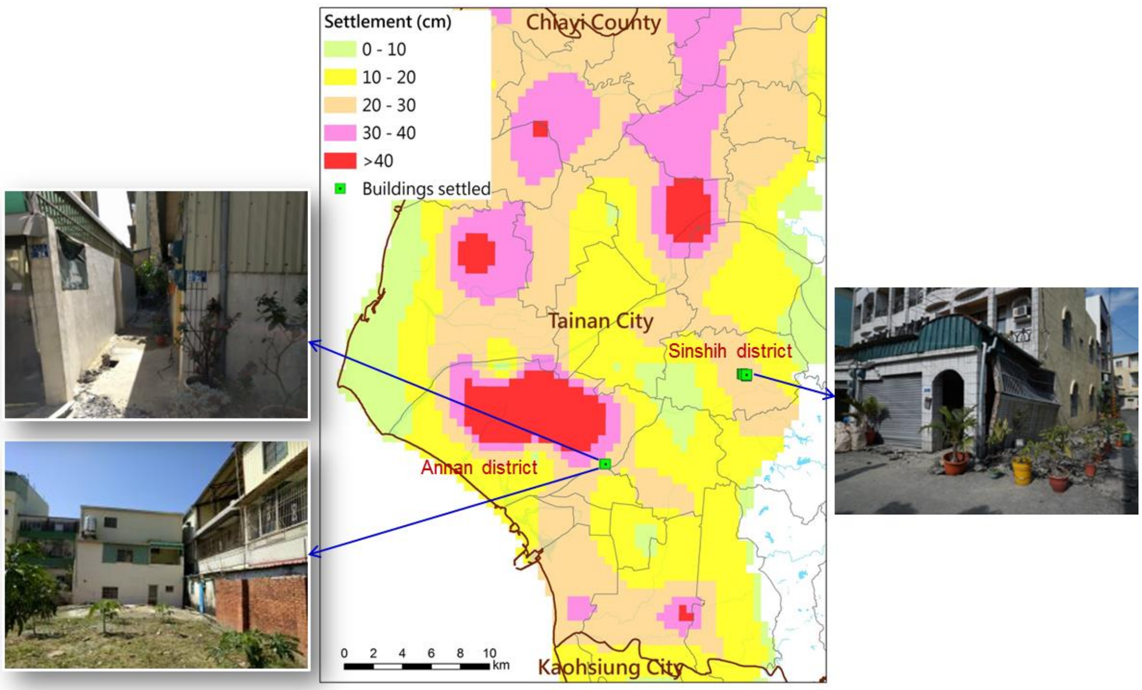


Fig. 8 – Distribution of estimated settlement and building damages due to soil liquefaction

4. Conclusions remarks

An automatic processing procedure for evaluating the liquefaction potential and the induced settlement interpreted in a 500m × 500m mesh is organized in this study. The mesh-based methodology by means of borehole data in conjunction with the actual PGA in corresponding grids provides superior understanding of liquefaction potential in details, comparing to the traditional approach using the uniform acceleration equal to the design earthquake. In the case study of the Meinong earthquake, the buildings with serious settlement are located in the medium potential zones as this study reveals. In general, the analytical results of liquefaction potential and induced settlement in comparison with the field observations demonstrate acceptable agreement. Through the earthquake event, the performance of this procedure was validated for conveying real-time valuable information for emergency operation. Further efforts on collecting respectable borehole data are undergoing in order to obtain a more precise prediction.

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