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Simplified Empirical Method for Predicting Liquefaction Potential and Its Application to Kaohsiung Areas in Taiwan

Darn H. Hsiao, Zhu-Yun Zheng

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Abstract**—**Since Taiwan is located between the Eurasian and Filipino plates and earthquakes often thus occur. The coastal plains in western Taiwan are alluvial plains, and the soils of the alluvium are mostly from the Lao-Shan belt in the central mountainous area of southern Taiwan. It could come mostly from sand/shale and slate. The previous investigation found that the soils in the Kaohsiung area of southern Taiwan are mainly composed of slate, shale, quartz, low-plastic clay, silt, silty sand and so on. It can also be found from the past earthquakes that the soil in Kaohsiung is highly susceptible to soil subsidence due to liquefaction. Insufficient bearing capacity of building will cause soil liquefaction disasters. In this study, the boring drilling data from nine districts among the Love River Basin in the city center, and some factors affecting liquefaction include the content of fines (FC), standard penetration test N value (SPT N), the thickness of clay layer near ground-surface, and the thickness of possible liquefied soil were further discussed for liquefaction potential as well as groundwater level. The results show that the liquefaction potential is higher in the areas near the riverside, the backfill area, and the west area of the study area. This paper also uses the old paleo-geological map, soil particle distribution curve, compared with LPI map calculated from the analysis results. After all the parameters finally were studied for five sub zones in the Love River Basin by maximum-minimum method, it is found that both of standard penetration test N value and the thickness of the clay layer will be most influential.

Keywords**—**Liquefaction, western Taiwan, liquefaction potential map, factors influence high liquefaction potential areas, LPI analysis.

I. Introduction

IN recent years, with increasing in occurrence for large earthquakes all over the world, soil liquefaction has caused many serious damages, and thus related research on soil liquefaction has become more important [1]. In the meantime, the earthquake at the intersection of Taiwan's plates could be happening at any time, and the problem of liquefaction is indeed serious in Taiwan, including the 1999 Chi-Chi Earthquake, the 2010 Jiaxian Earthquake, and the 2016 Tainan 0206 Earthquake shown as Fig. 1. Due to the significant influence of soil liquefaction, the Kaohsiung City Government commissioned Sinotech Engineering Consulting Co., Ltd. [2] to identify high, medium and low soil liquefaction potential areas in various districts of Kaohsiung City. Therefore, this study desires to use these valuable data for further data analysis, and to explore the area around the old Kaohsiung City with a high population density and the Love River Basin. Most of South Taiwan is soil deposited by sand/shale and slate. The soil is fragile and brittle and susceptible to disturbance and softening. Most of the geology in Kaohsiung is mainly sedimentary soil [3]. There are eight major river basins in Kaohsiung City, from the north to the south, Er-ren Creek, Agongdian Creek, Dianbao Creek, Houjing Creek, Love River, Cianjhen (Fengshanxi) River, Saltwater Port Creek and Gaopoing Creek. Love River is a typical metropolitan river. It originates from the Bagua in Renwu District of Kaohsiung City. It flows into Kaohsiung Port after passing through the important administrative districts such as Zuoying, Gushan, Yancheng, Qianjin and Yuya. After long-term transformation, it has become important tourist attractions in Kaohsiung City. The length of Love River is 16 kilometers, which flows through the urban area of Kaohsiung about 10 kilometers. The width of the river course decreases from the 130 meters of the downstream estuary to the upstream to 14 meters. The source is the irrigation channel of the farmland. The drainage area is 5600 hectares. The number is about 1 million, and there are about 15 main tributaries. Fig. 2 shows the location of Love River.

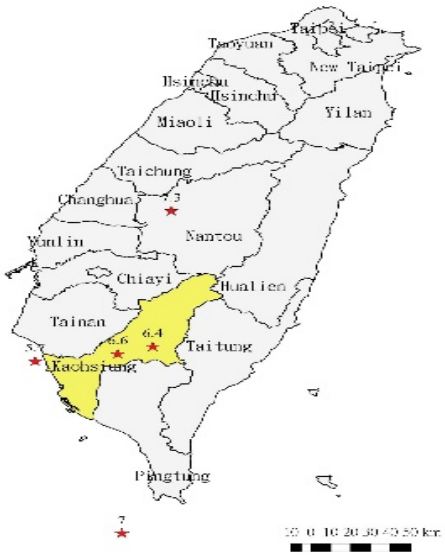
In order to understand the problem of soil liquefaction in the Love River Basin of Kaohsiung City, this paper first collects the boring drilling data of Sinotech Consulting Co., Ltd., and then uses the Geographic Information System (ArcGIS) to analyze the Liquefaction Potential Index (LPI) of Kaohsiung's administrative regions, and uses Kaohsiung Love River. Parameters such as water table groundwater level, surface acceleration, thickness of sand layer, thickness of clay layer and LPI value, to find out whether each administrative area will be liquefied, and then use various parameters to compare with LPI values to find out which parameters affect the LPI value. It is larger, and finally use the ancient map to compare with the current satellite photos to understand the changes of the Love River Basin from the past to the present.

II. Literature Review

Soil liquefaction is happened owing to that sandy soils are combined with high groundwater levels, and they are shaken by strong earthquakes, resulting in a decrease of effective stress between the particles, resulting in a phenomenon such as suspension soils in water or boiled sands. Once the liquefied soil layer loses the bearing capacity to carry the building, thus causing the building or house into sink or tilt.

D. H. Hsiao is with the National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan (phone: 886-7-381-4526ext.15259; fax: 886-7-383-1371; e-mail: hsiaodh@nkust.edu.tw)

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EQ	year	N	E	depth	Mag.	Liq. Y/No
1	1999	23.9	120.8	8.0	7.3	Y
2	2006	21.69	120.56	44.1	7.0	No
3	2010	22.97	120.71	22.6	6.4	Y
4	2016	22.92	120.54	14.6	6.6	Y
5	2017	22.87	120.14	16.2	5.7	Y

Fig. 1 Catastrophic earthquake on southern Taiwan after 1999 Chi-Chi Earthquake

The three conditions for soil liquefaction are: (1) loose sandy soil (2) high groundwater level (3) strong earthquake. Based on sandy soil and groundwater, which constitute two of the elements of soil liquefaction, soil liquefaction is more likely to occur within the alluvial plains downstream of the river and the soil near the sandy coast.



Fig. 2 Location of Love River

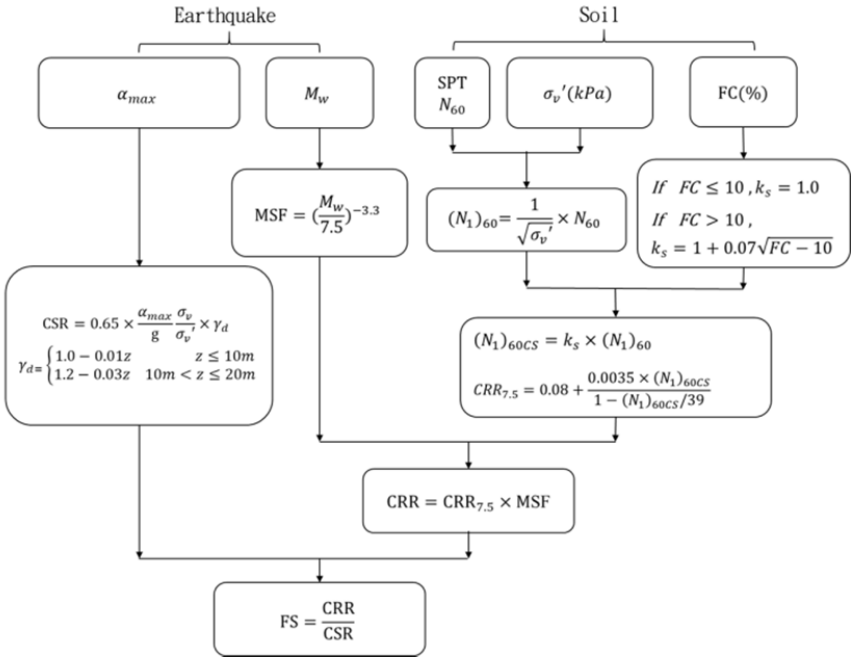


Fig. 3 Analytical flowchart for HBF method (After [5])

The HBF method popular in Taiwan is a method proposed by Huang et al. [4], [5]. Based on the simple empirical method proposed by Seed et al. [6], the analysis of the liquefaction and non-liquefaction case data collected in previous Taiwan earthquakes is performed by hyperbolic function regression. The method builds up the critical liquefaction intensity curve, the formula of the curve is simple, and its parameters have also obvious physical meaning. The HBF method mainly analyzes sandy soil, but for the cohesive soil (e.g. CH, CL, MH, SC and ML (PI>7)) from their judgements that liquefaction does not occur, so it is necessary to make use of uniform soil

classification system (USCS) for proper judgment, and a flowchart for HBF method as shown in Fig. 3.

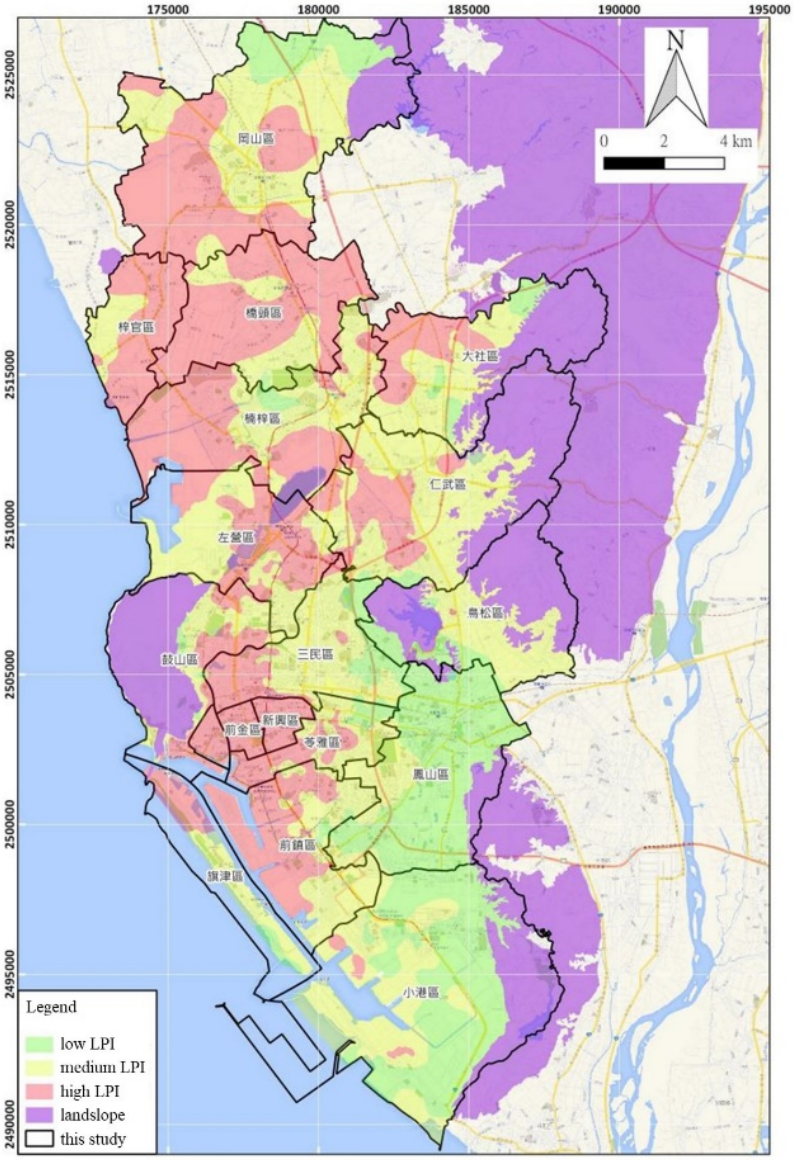


Fig. 4 Soil liquefaction potential assessment of the Kaohsiung Metropolitan Area (Cited from [2])

Iwasaki et al. [1] proposed the LPI shown as (1), which can deemed as a reference for the risk assessment of site liquefaction disasters, considering the degree of liquefaction of the soil layer from ground level to the depth of 20 m, and suggested that the liquefaction potential indices 5 and 15 can be used as low, medium, and high liquefaction risk, certainly this parameter is also an important basis for the preparation of soil liquefaction disaster potential map.

$$LPI=\int_0^{20} F_L \cdot W(z)dz \quad (1)$$

Safety factor against liquefaction FS ≦ 1.0, liquefaction degree parameter F_L=1-FS, however liquefaction safety factor FS > 1.0, F_L=0, and W(z) denotes depth weighting coefficient, W(z)=10-0.5z, z is the depth (m) from the ground surface. The safety factor (FS) can be calculated by the Japanese road bridge liquefaction evaluation method of SPT-N on the developable beginning period.

After careful geological survey and lots of experiments in the fields and laboratory, Sinotech Engineering Consulting Co., Ltd. (2018), by local HBF method and the Iwasaki depth weighting method, for the soil liquefaction potential assessment of the Kaohsiung Metropolitan Area, their analysis results are shown in Fig. 4, which indicates the concentration of highly liquefaction potential areas. In the central and northern coastal areas of Kaohsiung, the moderate liquefaction potential area is located in the margin of the coastal area. The low liquefaction potential area is dominated by Shoushan area,

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Banpingshan area and some hilly areas such as Dashe- zone and Renwu-zone.

Orense [7] performed the soil liquefaction potential assessment for a soil liquefaction region during the 2010 Darfield and 1990 Luzon earthquakes by using LPI. Wotherspoon et al. [8] investigated successfully the relationship between observed liquefaction at Kaiapoi City following the 2010 Darfield earthquake in New Zealand and old channels of the Waimakariri River.

III. Research Methods

Geographic Information System (GIS) is a comprehensive discipline that combines geography and cartography and has been widely used in different fields. It is a computer for inputting, storing, querying, analyzing and displaying geographic data system. This study uses ESRI's geographic information system - ArcGIS, then loading the boring drilling database into ArcGIS software, and again use IDW interpolation and Kriging interpolation to analyze and draw the hierarchical color map and contour map of each condition.

The IDW algorithm estimates each unknown value and uses its value near the known point to perform the weighting operation. The weight given is calculated based on the distance. The concept is an unknown point. The degree of influence of the surrounding known points is inversely proportional to the distance. The farther the distance is, the smaller the degree of influence is. The influence degree is expressed as the power of the distance between the unknown point and the known point.

Kriging method, also known as spatial local estimation or spatial local interpolation, is one of the two main contents of geo-statistics. This method is based on the theory of variogram function and the theory of structural analysis. It is a method to optimize the value of regionalized variables in a finite region.

This article used the boring drilling data of Sinotech Engineering Consulting Co., Ltd. (2018) for analysis, and sorted related useful data of each hole into Excel software and subsequently put them into the Geographic Information System (ArcGIS) to draw the location of the hole, with the LPI of each point. The calculated value can be to find the high liquefaction potential area, or then through the groundwater level, sand layer, clay layer and other parameters to compare with LPI value is really accurate. Furtherly the ancient map was tried to compare the location of the ancient river with those of the current Love River.

TABLE I
Boring Number Used in the Study for Each Administration District

District	Boring no.
Yancheng	56
Sanmin	163
Sinsing	95
Yuya	163
Qianjin	58
Gushan	147
Cianjhen	244
Renwu	233
Zuoying	220
Total	1379

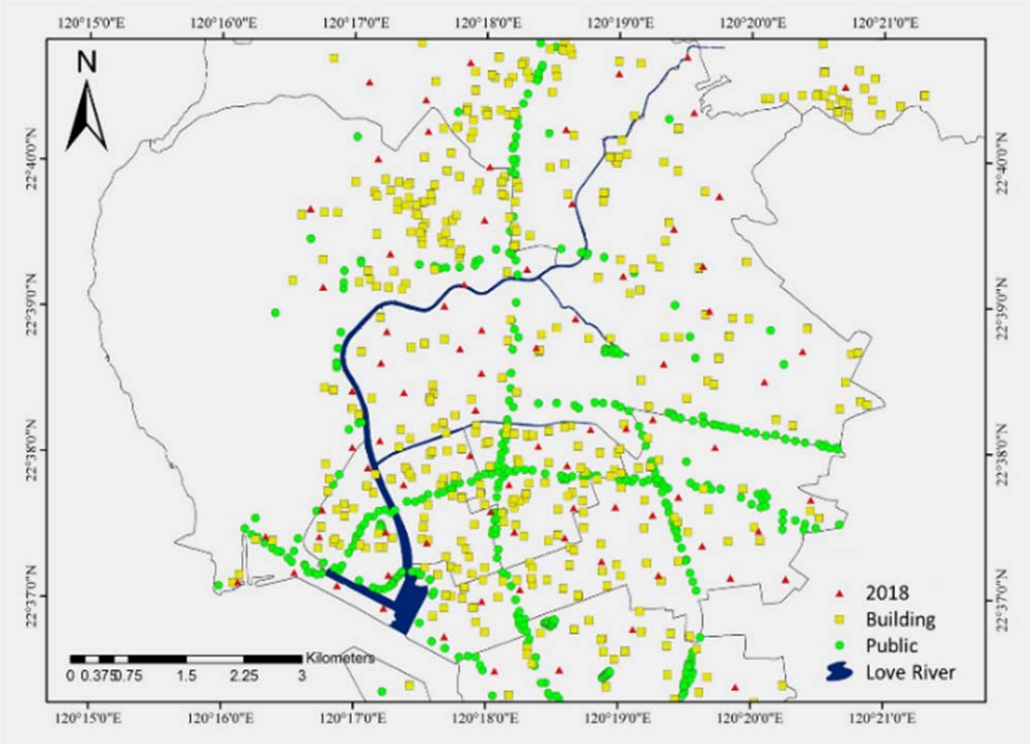


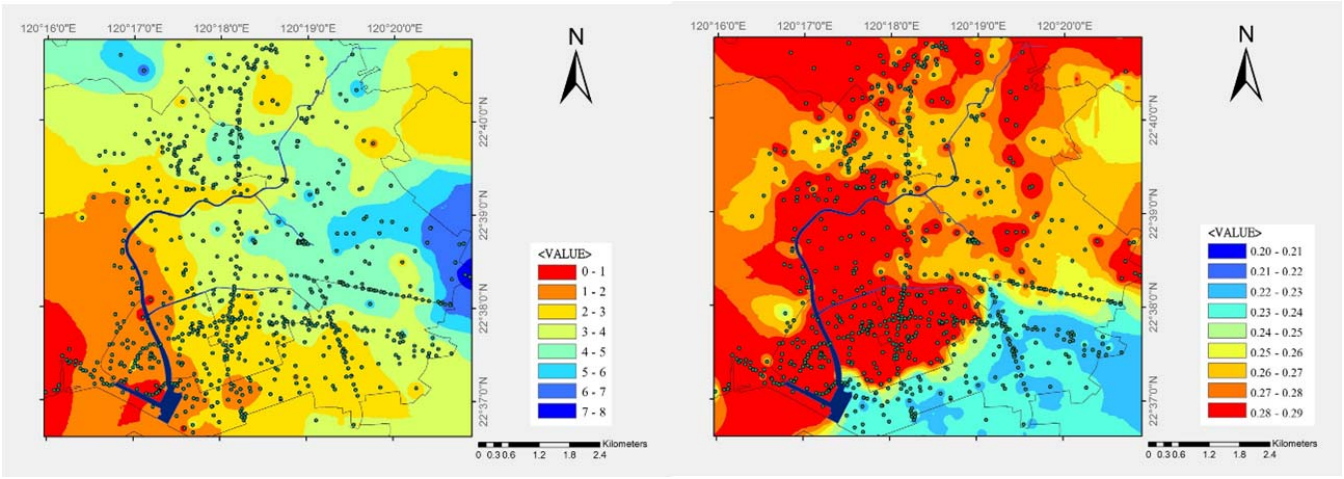
Fig. 5 Boring lots lies distribution location

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This study analyzes the drilling data of the old Kaohsiung administrative district including the Yancheng District, Qianjin District, Sanmin District and Gushan District of Zhongxing Engineering Consulting Co., Ltd., and collects 563 holes drilling data of high-rising building and 696 holes from public works drilling data. If adding geological drilling data 120 holes supplemented in 2018 by Kaohsiung City Government, a total of 1,379 holes was chosen after deleting improper data by man-power. The statistical information of each administrative district is shown in Table I, and the drilling lots distribution map is shown in Fig. 5.

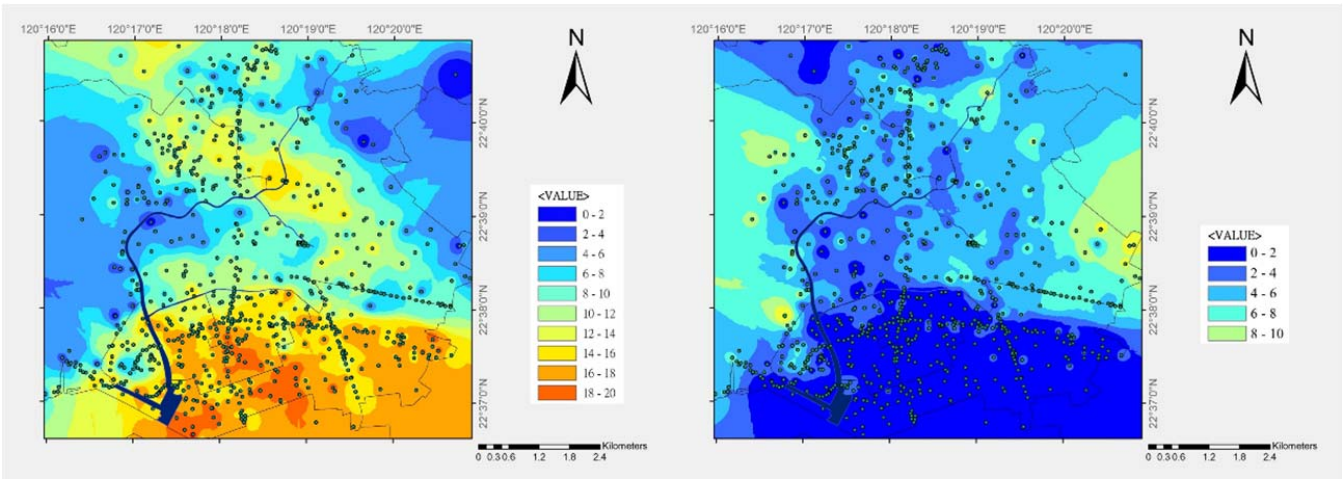
After surveying the first phase of Kaohsiung City's soil liquefaction potential map produced by Sinotech Engineering Consulting Co., Ltd., parameters such as the depth of the groundwater table H_w, the surface acceleration A_{max}, the thickness of the sand layer within 20 meters below the surface H_s, and the depth of the surface within 10 meters were taken. Besides them, the thickness of the clay layer H_c, the thickness of the soil layer calculated by the HBF method of less than 1 $H_{FC<1.0}$, the thickness of the soil layer of the liquefied soil layer having an SPT-N value of less than 10 $H_{s,N<10}$, the thickness of the soil layer having an SPT-N value of less than 8 $H_{c,N<8}$, The liquefaction layer fine particles of more than 35% of the soil layer thickness $H_{liquefied,FC<35\%}$ and LPI and other nine parameters were analyzed. We next created a data table established by Excel program, that then it can be calculated easily. In the meantime we can arrange the preceding statement above as an Equation (2), in which LPI may be functioned by these eight parameters. Zhang [9] tried to Predict Seismic Liquefaction Potential of Sands by Optimum Seeking Method, but the direct method to find maximum and minimum value will be used in the paper owing to consider the soil layers to be too complicated.

$$LPI=f\,(H_w, A_{max}, H_s, H_c, H_{FC<1.0}, H_{s,N<10}, H_{c,N<8}, H_{liquefied,FC<35\%}) \quad (2)$$



(a) Groundwater level H_w

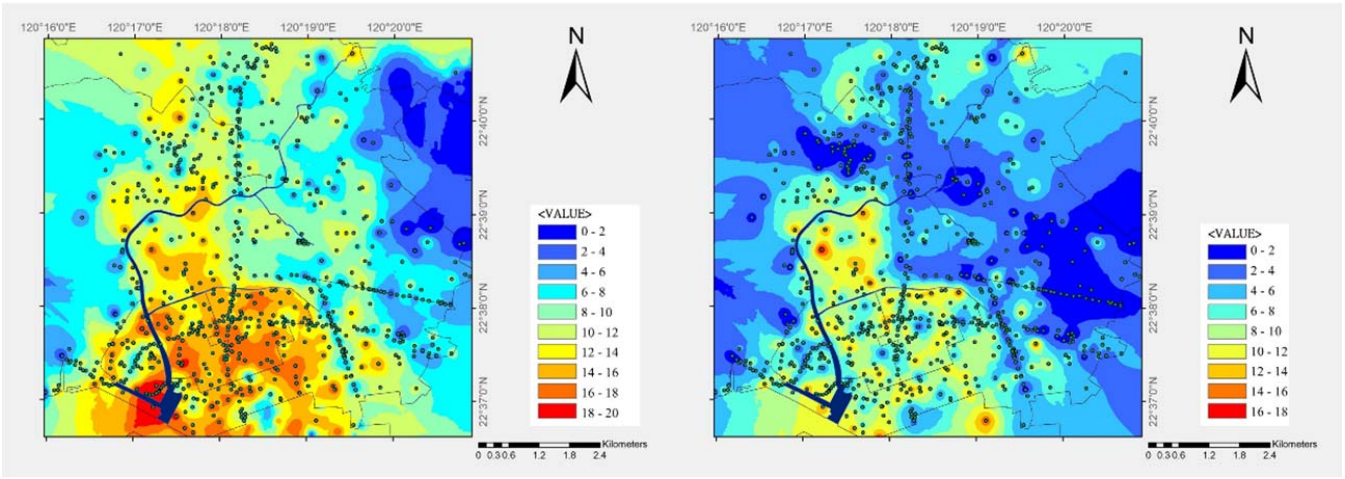
(b) Ground surface acceleration A_{max}



(c) Thickness of sand layers H_s

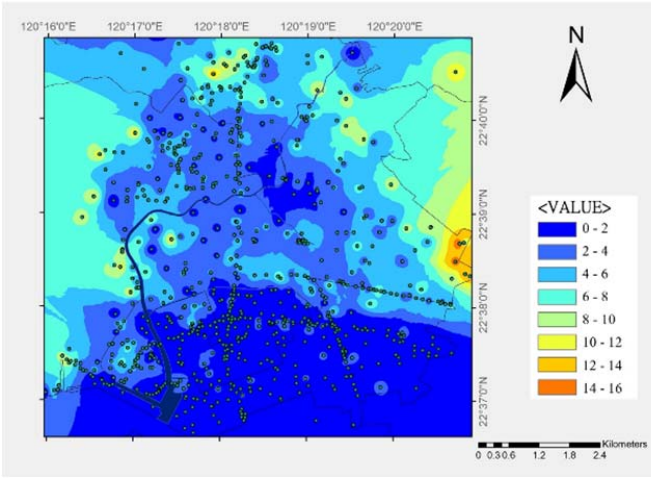
(d) Thickness of clay layers H_c

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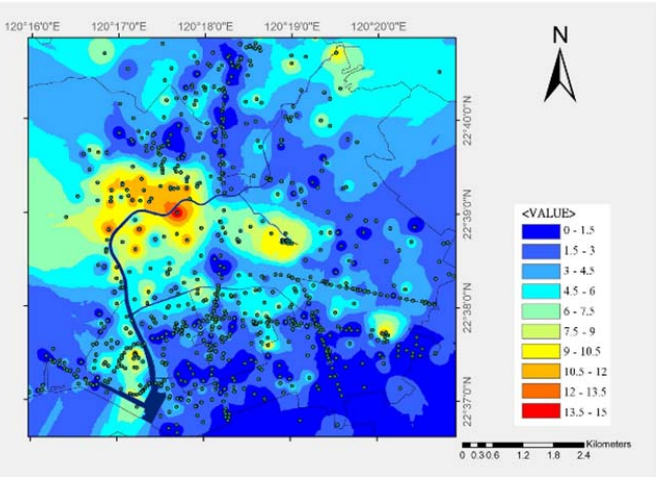


(e) Layer thickness when FS lower than 1 $H_{FC<1.0}$

(f) Thickness of sand layer liquefied when N lower than 10 $H_{s,N<10}$



(g) Thickness of clay layer when N lower than 8 $H_{c,N<8}$



(h) Thickness of layer liquefied when FC lower than 35% $H_{liquefied,FC<35\%}$

Fig. 6 The hierarchical color map in Love River Basin by ArcGIS software for eight parameters

IV. Results and Discussion

Fig. 6 is the hierarchical color map in Love River Basin by ArcGIS software for eight parameters. From the investigation in the past literatures, the groundwater level is also an important factor affecting liquefaction potential. Based on groundwater level distribution in Kaohsiung City, with using drilling data and using ArcGIS mapping analysis, Fig. 6 (a) is the groundwater level depth map, the map shows that the higher the water table is, the closer it is to the west of Kaohsiung City.

The surface acceleration is based on the seismic design specifications and coding explanations of a building structure of the National Earthquake Center (2011). The seismic size of each administrative area is calculated using the drilling data to calculate if the site earthquake magnitude is as 7.1, can be shown in Fig. 6 (b).

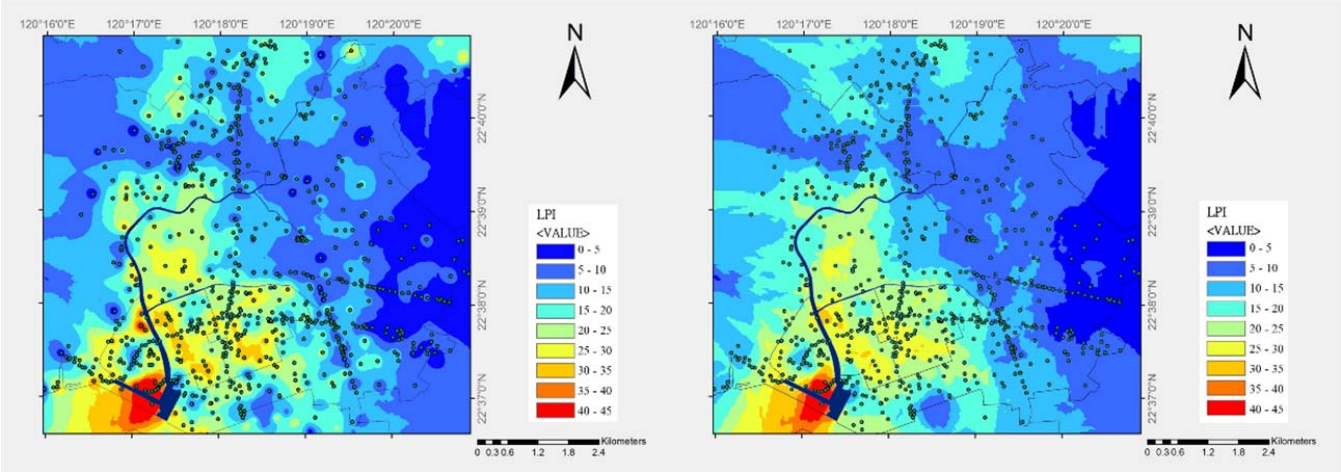
Using the drilling data to sort out the distribution of the underground soil layer in Kaohsiung City, we find the thickness of the sand layer within 20 meters below the ground surface, the thickness of the clay layer within 10 meters below the surface, the thickness of the soil layer with a safety factor less than 1, SPT- N value with fine content particles. The thickness of the sand layer is the sand layer within 20 meters below the ground surface. After finding the thickness of the sand layer, the distribution map is drawn, as shown in Fig. 6 (c). The figure shows that the thickness of the sand layer in the study area is quite high. It is also decided to use the clay layer within 10 meters below the surface because the LPI value is very important for the Iwasaki depth weighting method. The closer the weight value is to the surface, the lower the ground. The clay layer within 10 meters is used for analysis, as shown in Fig. 6 (d). The figure also shows that the thickness of the clay layer in all areas of the Love River Basin is very low.

Using the drilling data to find out the soil layer with the safety factor less than 1 within the liquefaction 20 m soil, and then we calculate the soil layer thickness. The analysis results are shown in Fig. 6 (e). The figure shows the soil layer with the safety factor less than 1 is very thick near the downstream of the Love River basin. The thickness of the soil layer with the N value of less than 10 in the liquefied soil layer is as shown in

Fig. 6 (f), and the soil layer with the N value of the clay layer is less than 8. The result is shown in Fig. 6 (g). Finally, it is found that the fine particles of the liquefied soil layer are more than 35%. In the soil layer, most of the fine aggregates were found to be concentrated in the middle of the river. The result is shown in Fig. 6 (h).

The LPI values calculated by the HBF method of the National Earthquake Center were used for analysis, and the IDW method and Kriging method in ArcGIS were used to draw out the two different distribution maps of soil liquefaction potential areas. It can be found from Figs. 7 (a) and (b) that the area calculated by the two calculation methods is slightly different, but the difference is not large, and the LPI value near the mouth of the river is the highest in the urban area of Kaohsiung. Fig. 7 is the contours of their two methods.

Fig. 8 indicates the locations of five sub-geological sections were further studied to investigate which factor most influence LPI. According to (2), five parameters including groundwater table H_w, the surface acceleration A_{max}, SPT-N value, liquefaction layer fine particles of more than 35% of the soil layer thickness $H_{liquefied,FC<35\%}$, and the thickness of the soil layer having an SPT-N value of less than 8 $H_{c,N<8}$ were discussed without considering others because of their minor effect. Apparently zone (d) is dominated by the thickness of the soil layer having an SPT-N value of less than 8 $H_{c,N<8}$ in Fig. 9, but SPT-N value will be most important for other zones. As the statement above, most soils are covered with the clays in the zone (d).



(a) IDW method (b) Kriging method

Fig. 7 Two different distribution maps of soil liquefaction potential areas for Love River Basin

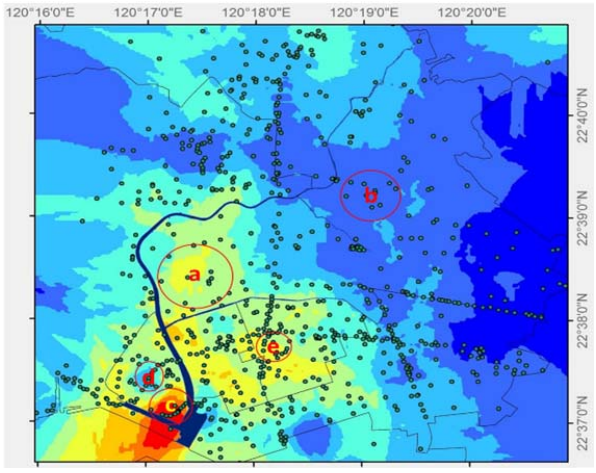
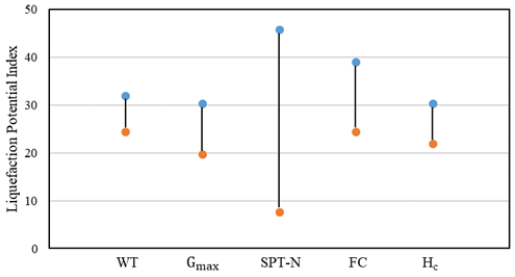


Fig. 8 Five sub-geological sections were further studied to investigate which factor most influence LPI

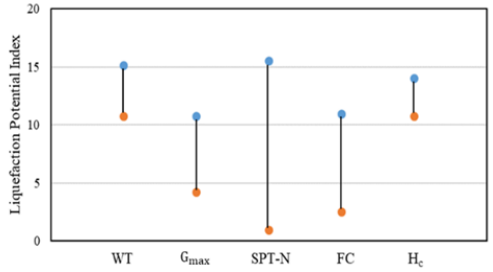
After comparing various liquefaction conditions, it was found that the liquefied area was very easy to be distributed near the Love River Estuary. Therefore, the ancient maps of 1904 (Fig. 10 (a)) and 1944 (Fig. 10 (b)) were compared with the current satellite photos, and the comparison results was found. In 1904, when Love River could flow out from the east and west side of Yan-Cheng District, it was discovered that the Yan-Cheng District began to implement land reclamation after 1904. The area is about 130,000 square meters, probably because of the backfill used at that time. Lots of evidences show that the sands come from excavated in Kaohsiung Port, which causes the LPI values of these backfill areas to become quite high. Finally, in the case of the high LPI of the soil layer at the mouth of the river, the ancient map can be compared with the current satellite photos. It is found that the landscape near the mouth of the river has changed greatly, and the small tributaries of the river have already passed. Remediation, so the map from 1904 to the 1944 found that there is not much change in the middle and upper reaches of the Love River. It is especially mentioned that there are three known disaster cases happened in Yan-Cheng District, even tunneling method in MRT construction, due to soft/loose soil condition [10], [11].

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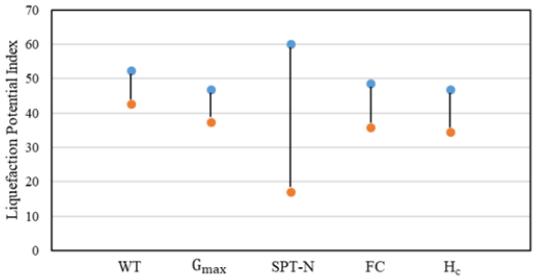
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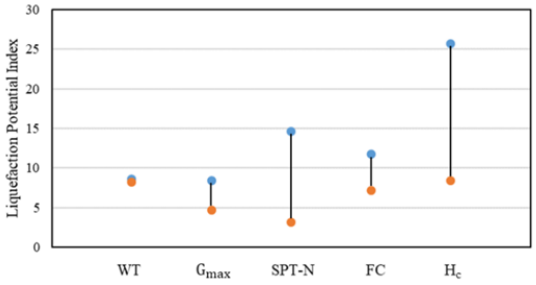
(a) a zone



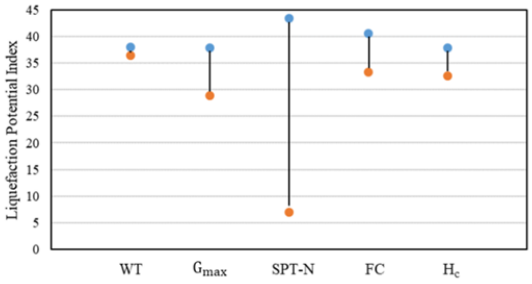
(b) b zone



(c) c zone



(d) d zone



(e) e zone

Fig. 9 LPI varied from five related parameter for every interested zone



(a) In 1904



(b) in 1944



(c) Satellite picture now (Google Map)

Fig. 10 Topography variance of Yancheng district and river estuary of Love River

V. Conclusions

[1] With response to the first phase of the analysis of soil liquefaction potential in Kaohsiung City by Sinotech Engineering Co., Ltd., nine parameters were taken from the drilling database, and the largest factor affecting LPI was the thickness of the sand layer and ground water level.

[2] Based on the analysis of each administrative region, it will be found that the middle area of Yan-Cheng District belongs to the lower LPI value, and it is inferred that it may be caused by the thicker clay layer in the middle area, and the area with higher LPI value in other administrative areas. It is believed that the soil layers on the two sides of the river are most susceptible to liquefaction. In the case of the Love River Basin, the area with an LPI value of 15 or

higher is concentrated in the middle-stream and downstream of the river.

[3] In order to explain the LPI of the soil layer in the Love River Estuary is relatively high, the ancient map was used to compare with the current satellite photos. It is found that the landform near the mouth of the Love River has changed greatly, and the small tributaries of the Love River have changed, however the maps from 1904 to the present found that there was not much changed in the middle and upper stream of the Love River.

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