Chapter

The Study of Risk Assessment of Soil Liquefaction on Land Development and Utilization by GIS in Taiwan

Lien-Kwei Chien, Jing-Ping Wu and Wen-Chien Tseng

Abstract

The issue of soil liquefaction has been investigated widely in the past 50 years. However, there is no an integrated method have been considered for the factors between regions' vulnerability of soil liquefaction and resilience capacity to perform the risk assessment of soil liquefaction hazard. This study selects Yunlin and Chiayi County as a demonstration area, and uses Model Builder of geo-processing models to connect multiple analysis processes, the liquefaction risk distribution in Yun-Chia Plain's area is carried out in 100 × 100 m grid map scale by GIS. The study results could provide the reference of land development and management in Taiwan.

Keywords: soil liquefaction, hazard risk assessment, pareto ranking method, land utilization management, GIS

1. Introduction

For global environmental changing, the change of land use cause severe and straightforward impact [1]. The form of land use is determined by several of complex factors, such as politics, economics, society, culture, and natural environment. However, if the change of land use is based on those complex factors, it will easily bring huge impact to the environment [2].

Reference [3] indicated that in hazard-prone areas worldwide, cyclones, flooding, landslides, earthquakes, and volcanoes are the most common natural hazards. The report showed that 73% of Taiwan's citizens are exposed in the three or more hazards; 99% of people are exposed in two or more hazards. This analysis reveals is the extent to which, at global and regional scales, there is substantial overlap between different types of hazards and population concentrations. The result shows that large percentages of the population in Taiwan reside in hazard-prone areas.

Reference [4] raises a new concept about three essential factors to cause a disaster such as Hazard, Exposure, and Vulnerability. In other words, risk management will rise to the top priority if we cannot predict or control the natural disaster. Mastering exposure and vulnerability is the first step. Reference [5] had pointed out that some of the researches that will consider Exposure as a part of Vulnerability analysis. For instance, United Nations Development Program (UNDP) presented a brand new concept to explain how the risk be assessed, in which risk = Hazard × Exposure × Vulnerability. Report from [6] shows how Vulnerability and Exposure can be decided and the potential disaster happened under climate change.

Kaohsiung, Taiwan Meinong earthquake measuring 6.6 on the Richter scale happened in February 6, 2015; and became one of the most harmful disaster, which caused serious damage to the society. The damages are restricted in causing building failure and also make tons of people in suffer. Central Geological Survey (CGS) of MOEA has also started to do large-scale national geological drilling survey to set up Taiwan's own soil liquefaction potential inquiry system.

As high speed growth of Taiwan's population and rapid economic development, land use is becoming more and more diversity. Disaster impact will be changed in accordance to dissimilar regions, environments, and soil types. In summary, the main principle of this study is to use the Geographic Information Systems (GIS) tool, Chiayi and Yunlin plain survey result done by National Land Surveying and Mapping Center, Ministry of the Interior (NLSC); and combine with hazard, vulnerability, and resilience maps to do the soil liquefaction risk mapping. Based on the soil liquefaction risk map, proper development, and utilization strategy of the region will be established. This study also could become a reference of a general land protection strategy and regional development licensing and risk assessment and management.

2. Research methodology

This study takes the risk of soil liquefaction in Chiayi and Yunlin plains, adopt those soil liquefaction potential index assessment which is commonly used in Taiwan and worldwide as the basic reference. United Nations Disaster Relief Organization (UNDRO) [7] proposed an operability definition for disaster risk: R(Risk) = H(Hazard) × V(Vulnerability), which is the most commonly used method of disaster risk assessment The study also uses this definition as a basis for assessing soil liquefaction risks. In order to fully realize the effect of land use, this study changes the past boundaries of risk, such as townships, towns, cities, and districts as the boundaries of risk allocation and takes the 100 × 100 m grid as the regional space unit.

2.1 Risk matrix

This study takes resilience as an indicator that represented how the region recovers from the disaster. Therefore, the risk assessment method used in this study is as Eq. (1) and the concept of risk matrix is shown in **Figure 1**.

$$\text{Risk} = \text{H}(\text{hazard}) \times \text{V}(\text{vulnerability}) \times \text{R}(\text{resilience}) \qquad (1)$$

This study considered soil liquefaction as a cause of disaster, which is defined as hazard, the different phases of Taiwan society developments are named as Vulnerability and how Taiwan's response to upcoming disaster as Resilience. Taiwan soil liquefaction risk assessment will be done by combining hazard, vulnerability, and resilience into risk matrix.

In this study, CGS's drilling investigation result is selected as our database. Therefore, the assessment methodology used in this study is the same as CGS, which is called NJRA method [8]. This study adopts the soil liquefaction potential

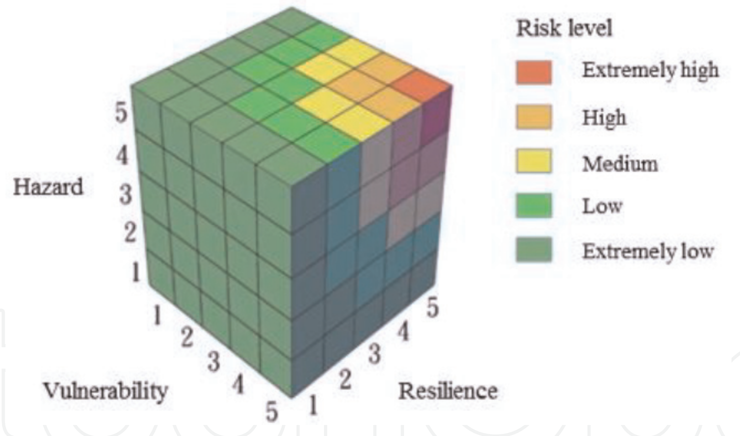

Figure 1.
The concept of the three-dimensional risk matrix.

mentioned in NJRA method, and considers different earthquake force designs as our hazard level grading. By comparing this study's result and CGS's result, people can figure out the difference between using normal soil liquefaction potential and our research's soil liquefaction potential that considers hazard, vulnerability, and resilience.

Second, vulnerability is based on the vulnerability indicators established by [9, 10]. To ensure that the database is correct, this study generally reviews the integrity of the indicators' data; ensures the indicators are selected appropriately and reflects the true development of the regions. Resilience indicators used in this study refer to [11, 12] for using the resilience indicators at all levels to consider the data integrity, the appropriateness of indicators which could showed the real condition of representative regions' development, and recovery. What is more, there is neither direct correlation nor the preference between the indicators. Therefore, the Pareto ranking (PR) method is used to standardize all the grading and abandon indicator weighing in order to establish the vulnerability and resilience.

This study seeks to simplify the mapping of potentially liquefiable areas by using Geographical Information Systems (GIS), and compared with the assessment method by the UNDRO to produce a map that could be used to evaluate potential damage in high risk areas of the county.

Cone penetration tests are used by the CGS in order to create GIS maps, but this is costly and not every county can afford to fund such studies on land. Geologic GIS layers are available due to the soil mapping of most counties by the CGS. Using the databank of social-economy and humanities in the county, along with other available data layers to narrow down the liquefaction risk of areas within the counties using ArcGIS and liquefaction criteria, the GIS layers for the Yun-Chia plain areas were modeled to select out the most liquefiable areas. These data layers were then combined to create a liquefaction risk map for Yunlin County and Chiayi County. This research can easily represent results straight forwardly.

2.2 Pareto ranking (PR) analysis

Before using PR analysis, those factors have to be standardized by Eq. (2). After getting a standardized grade, this study sums each region's vulnerability indicators total grade (grades of each factor vulnerability indicators are 1–5) and integrates those hazard indicators into six degrees. Hazard indicators are mean sea level rising, land subsidence, and storm surge flooding. And finally, use Pareto ranking (PR) analysis to evaluate general risk in coastal areas; and give each region a hazard risk level; the highest risk region gets level 9 and the lowest gets level 1, based on the principle to do PR analysis and evaluate each regional vulnerability.

Pareto ranking is a method for ordering cases on multiple criteria that has become popular in the context of genetic algorithms, where it is particularly valued because it often gives high rankings to those cases that only score heavily on one factor [13]. PR analysis is based on the principle of Pareto optimality. "Pareto optimality" is a formally defined concept used to determine when an allocation is optimal. An allocation is not Pareto optimal if there is an alternative allocation where improvements can be made to at least one participant's well-being without reducing any other participant's well-being. When no further Pareto improvements are possible, the allocation is a "Pareto optimum." A primary factor is selected from each vulnerability indicator. As shown in **Figure 2**, each point represents a grade of factor 1 and factor 2. If there is no point staying in the first quadrant, and there is no point ranked as high vulnerability degree. By taking same grade range region as a degree and following up the same step, this study can show each region's vulnerability distribution.

$$\text{z-score} = (X_i - M)/S \quad (2)$$

where *Xi* is the different indicators' data; *M* is the average grade, *S* is the standard deviation, $S = \sqrt{\left(\Sigma(X_i - M)^2/(N-1)\right)}$, and *N* is the number of data

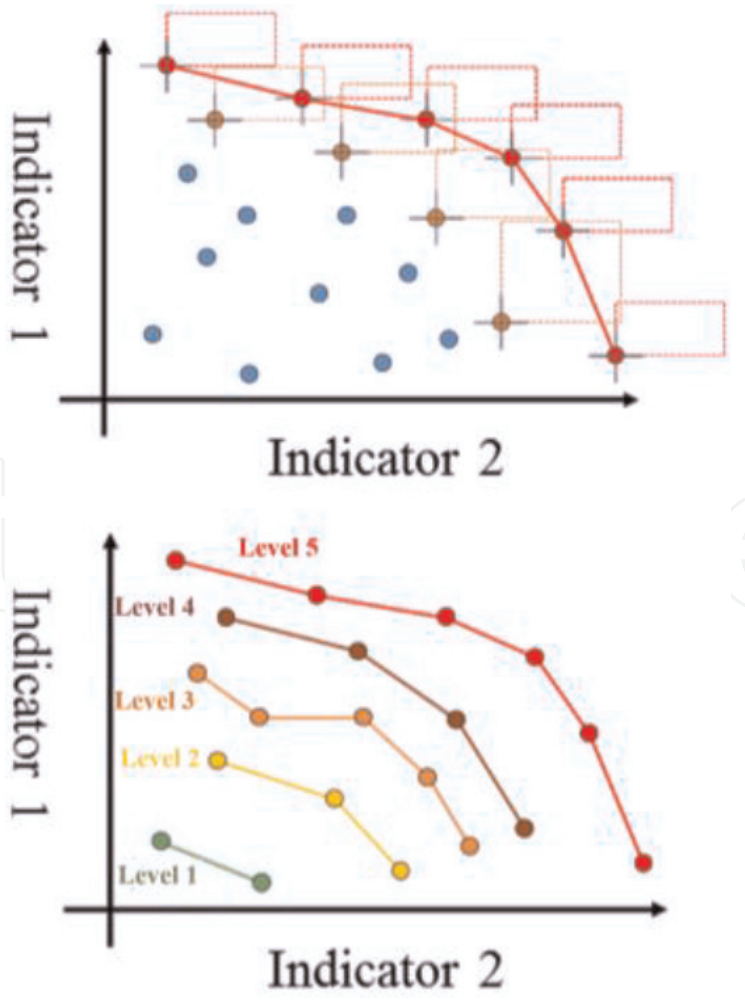

Figure 2.
Concept of PR analysis.

3. Analysis resources of database

3.1 General introduction of study area

According to the CGS disclosed geological drilling database, the Yunlin and Chiayi areas have relatively complete drilling data and complicated geographical environment. The area of environmental sensitive areas in Chiayi area of Yunlin is as high as 57%.

The strata along the western coast of Taiwan, especially the Chiayi area of Yunlin, are mostly modern alluvial strata. Because of their unconsolidated strata, the soil layers are mostly interbedded layers of sand and clay. In the past, soil liquefaction took place in sites containing particles with a diameter of about 0.01-cm loose fine sand-based and high groundwater level characteristics of the soil. Therefore, this study focuses on the Yushe River alluvial fan plain in Yunlin County, Chiayi County in the Chia-Nan Plain, the grid scale is 100 × 100 m, as shown in **Figure 3**.

Figure 3.
Study area—the plate area in Yunlin and Chiayi.

3.2 Drilling data selection

According to the data of soil parameters for soil liquefaction assessment according to the NJRA method, there are eight items of data, including the Peak ground acceleration (PGA), fines content (FC), clay content (Pc), 10% particle diameter (D_{10}), average particle diameter (D_{50}), SPT-N value, depth of groundwater level (D_w), soil depth (D), and other parameters, which can be used as parameters that affect the liquefaction judgment as follows.

According to [14], three seismic forces of different peak ground acceleration (PGA) are designed in this study:

(I) Small and medium-sized earthquakes: the regression period of 30 years, the 50-year surpassing probability is about 80%, 0.067 g.

(II) Earthquake design: in the 475 years of regression, the probability of surpassing in 50 years is about 10%, 0.28 g.

(III) The biggest consideration earthquake: the regression period of 2500 years, 50 years beyond the probability of about 2%, 0.36 g.

Reference [15], based on the present soil data from the Niigata earthquake liquefaction area of Japan in 1964, concluded that liquefaction is less likely to occur when the soil fines content (FC) is greater than 35%; the selected liquefaction range: FC $\leq$ 35%.

Reference [16] showed that clay content (Pc) will exceed 20% and soil will not liquefy. Selected influence liquefaction range: Pc $<$ 20%.

Reference [17] proposed the average particle diameter D_{50} less than 10 mm and D_{10} less than 1 mm of sandy soil, liquefaction may occur; selected impact liquefaction range: $D_{50} \leq 10$ mm and $D_{10} \leq 1$ mm.

Reference [18] used the SPT-N value to determine that the sandy soil with N value of less than 10 for weak sites and N value less than 4 for clay. Selected influence liquefaction range: SPT-N $\leq$ 10.

Reference [19] pointed out that shallow soils tend to liquefy, studies have shown that liquefaction mostly occurs within a depth of 20 m of the soil, so a more conservative impact on liquefaction range is used: Groundwater depth (D_w) $<$ 10 m.

According to a study by Japan's Niigata earthquake in 1964, Ref. [20] found that liquefaction did not occur when the casing pressure in the area was greater than 2 kg/cm^2. Therefore, we set the depth of liquefaction: Soil depth (D) $\leq$ 20 m.

According to the above criteria of soil parameter selection, this study selected Yun-Chia area as the research area, excluding the borehole with incomplete data. Based on the calculation of the soil liquefaction potential, it was 850 in Yunlin area and 880 in Chiayi area, as shown in **Figure 4**.

3.3 Vulnerability

In order to investigate how vulnerability of soil liquefaction impact the urban and rural areas development in Yun-Chia Plain, this study considers the vulnerability references, data integrity, and the indicators of representative vulnerable areas. There are four indicators that represent factors such as population

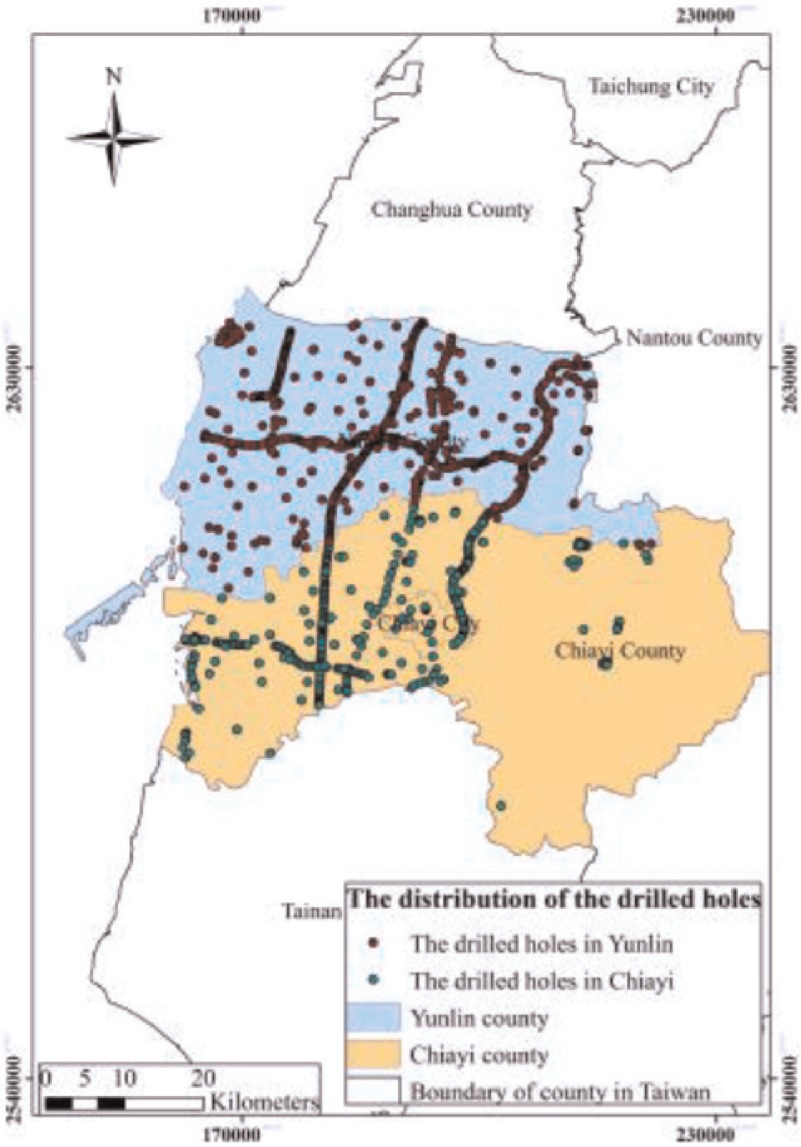

Figure 4.
The distribution of drilled holes in Yunlin and Chiayi (drew by this study).

density, gross industrial output, environmentally sensitive areas, and land use, which, respectively, representing the population distribution, economic development, urban and rural environmental development, and other indicators. Vulnerability included four indicators from the land surveys conducted by the National Land Surveying and Mapping Center in 2015.

3.4 Resilience

In order to investigate the resilience indicator which can show the make Yun-Chia plain areas recover from disasters. This study considers the resilience references, data integrity and the indicators of representative fragility areas. There are five representative indicators such as human development index, county budget, insurance coverage rate, social welfare workers, and communal participation rate, which represent social development, community development, government resources, property protection, and social assistance, respectively.

4. Analysis results

4.1 Hazard analysis in Yun-Chia plain areas

In this study, soil liquefaction is adopted as hazard. Referring to the maximum PGA of the three different design earthquakes force aforementioned for the NJRA method to assess soil liquefaction potential, also considering the effect of depth presented by [21], anti-liquefaction coefficient of different ground layers and the depth weighting factor are combined to obtain liquefaction potential index P_L of each drilling.

Previously, soil liquefaction potentials and different return periods of earthquake forces were usually discussed separately. This research takes different soil liquefaction potential indices PL induced by three different return periods of earthquake forces to separate the level of hazard, such as high, medium, and low. The three different return periods of earthquake forces are 30, 475, and 2500 years (**Figure 5a–c**), respectively. The basis classification of hazard degree is shown in **Table 1**. Hazard distribution condition is shown in **Figure 5d**.

4.2 Vulnerability analysis in Yun-Chia plain areas

The definition of vulnerability in this study is "the degree to which the area may be damaged." Vulnerability indicator introduction and calculation method are shown below.

Population density is a commonly used quantitative indicator reflecting the density of population distribution, which is the ratio of the total number of inhabitants under the unit area, as shown in Eq. (3). The density of grid units can reflect the seriousness of the people casualties in disaster-hit areas.

$$\text{Population density} = \left(\frac{\textit{village population}}{\textit{village area}}\right) \tag{3}$$

Gross industrial output is critical to measure the economic status and regions development level. It is the total output value of various industries in a unit area, as shown in Eq. (4). The level of the total industrial output within a grid of units can reflect the degree of economic loss that may be caused when a disaster strikes the area.

$$\text{Grid industrial total output} = \sum\left(\frac{\textit{gross industrial output}}{\textit{total industrial area}} \times \textit{industrial area in grid}\right) \tag{4}$$

Environmentally sensitive areas are basically equipped with special biological value or highly vulnerable to environmental impacts due to improper development activities. Based on the database platform established by the Construction and Planning Agency, Ministry of the Interior (http://60.248.163.236/SEPortal/), this study sets first-grade and second-grade environmentally sensitive area as the most vulnerable area, and non-environmentally sensitive areas are considered as low vulnerability.

Natural Breaks (Jenks) is used to speed up by dividing different PR scores into five different levels of vulnerability. The classification is shown in **Table 2**. The research of the result shows that the most vulnerable level is the Yunlin Industrial and Commercial Zone, the south of Koch Township, the Dongshih Township of Chiayi County, the coastal areas of Budai Township, and the residential areas in the center of Chiayi City. Yun-Chia plain area's vulnerability distribution and grading chart is shown in **Figure 6**.

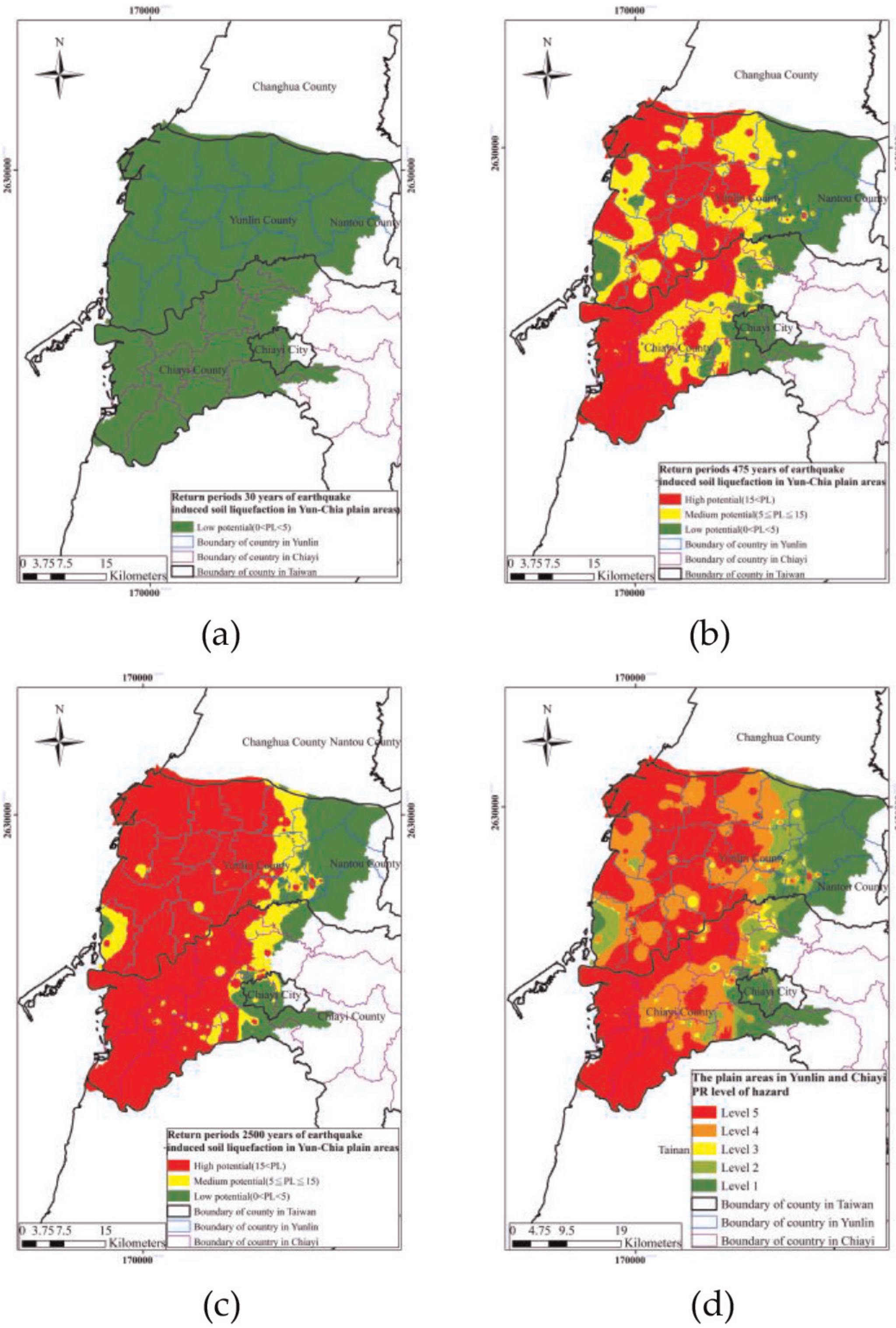

Figure 5.
Three different return periods of earthquake forces and Hazard distribution condition. (a) Soil liquefaction for earthquakes with a 30-year return period, (b) Soil liquefaction for earthquakes with a 475-year return period, (c) Soil liquefaction for earthquakes with a 2500-year return period, and (d) Hazard level induced by soil liquefaction.

4.3 Resilience analysis in Yun-Chia plain areas

The definition of resilience in this study is "the ability of the region to adapt frequent disasters, the ability of the plains to rebuild and improve after the disaster." Resilience indicator introduction and calculation method are shown below.

Due to the fact that this indicator is country scale, this study refers to the concept presented by [22], which took mortality, the proportion of higher

Level	The classification of hazard
5	The areas are high potential when the seismic design made by guideline happens ($15 < P_L$).
4	The areas are medium potential when the seismic design made by guideline happens ($5 \le P_L \le 15$). However, the areas are high potential when the maximum considered earthquake happens ($15 < P_L$).
3	The areas are medium potential when the seismic design made by guideline happens ($5 \le P_L \le 15$). In addition, the areas are medium potential when the maximum considered earthquake happens ($5 \le P_L \le 15$).
2	The areas are low potential when the seismic design made by guideline happens ($P_L < 5$). However, the areas are medium potential when the maximum considered earthquake happens ($5 \le P_L \le 15$).
1	The areas are low potential when the seismic design made by guideline happens ($P_L < 5$). In addition, the areas are low potential when the maximum considered earthquake happens ($P_L < 5$).

Table 1.
Classification of hazard.

	Classification	Level 1	Level 2	Level 3	Level 4	Level 5
PR score of distribution	Natural Breaks(Jenks)	0~2.14	2.14~4.06	4.06~7.21	7.21~9.80	9.80~14.18

Table 2.
The classification of vulnerability based on PR score.

education population, and the average individual income tax as alternatives to health, knowledge, and living standard. The higher the indicator, the better is its ability to cover from upcoming disasters. The data of this study are based on the report published by the Directorate-General of Budget, Accounting and Statistics, Executive Yuan, R.O.C. (Taiwan) in 2015. And its formula is calculated as shown in Eqs. (5)–(7). The Human development index (HDI) value is the geometric mean of the three basic indicators in Eq. (8).

$$\text{Life expectation index} = 1 - \left[\frac{(death\ rate - 5)}{maximum\ mortality\ rate}\right] \tag{5}$$

$$\text{Education index} = \frac{2}{3}\left(\frac{percentage\ of\ the\ population\ of\ higher\ education}{45\%}\right) + \frac{1}{3}\left(\frac{literacy\ rate\ of\ population\ over\ 15\,yrs}{100\%}\right) \tag{6}$$

$$\text{Living standard index} = \frac{\left[\log\left(\frac{average\ household\ disposable\ income}{US\ dollar}\right) - \log(100)\right]}{[\log(75000) - \log(100)]} \tag{7}$$

$$\text{HDI} = \sqrt[3]{(life\ expectancy \times education\ index \times standard\ of\ living\ index)} \tag{8}$$

The counties and counties' financial budgets are related to the recovery potential after the counties and cities encountered disaster. The data of this study are based on the report published by Directorate-General of Budget, Accounting and Statistics, Executive Yuan, R.O.C. (Taiwan) in 2015. And its formula is calculated as shown in Eq. (9).

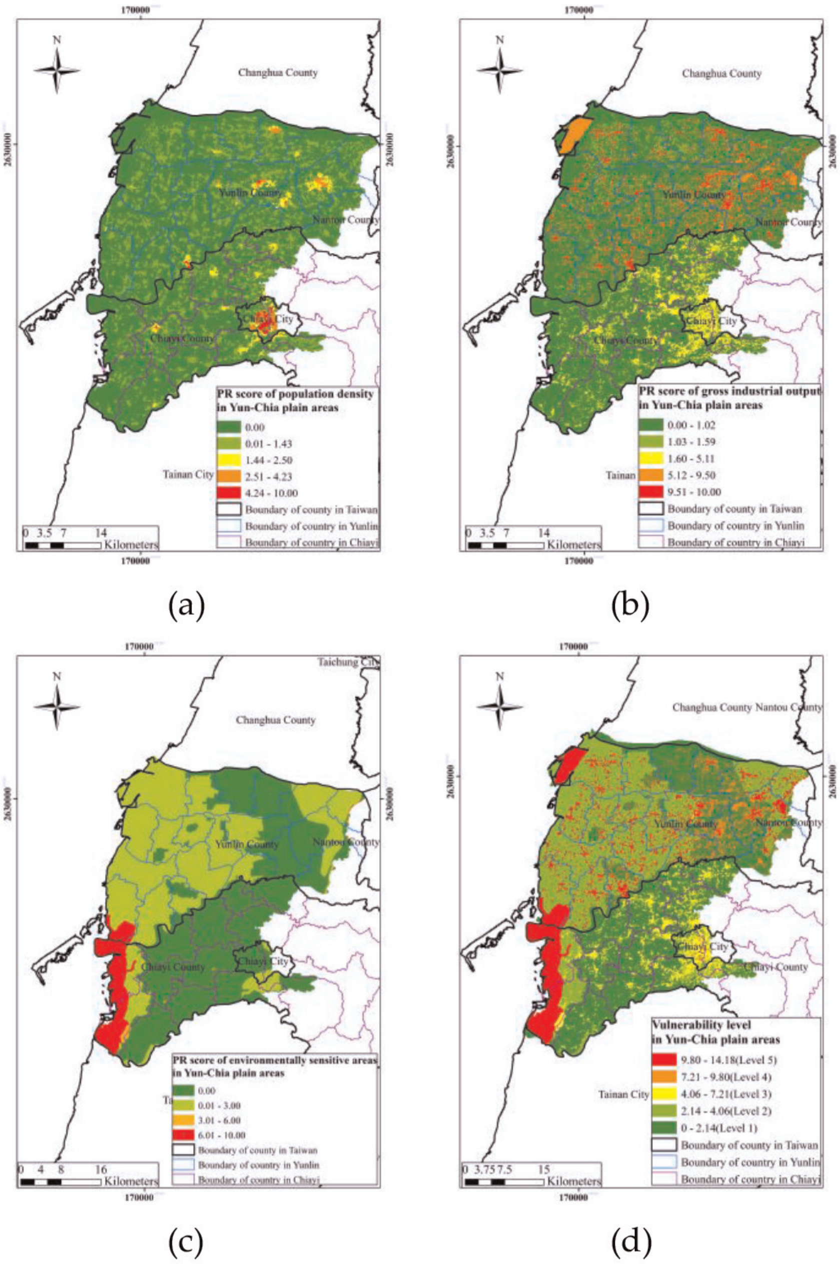

Figure 6.
Yun-Chia plain area's vulnerability distribution and grading chart. (a) Population density, (b) Gross industrial output, (c) Environmentally sensitive areas, and (d) Vulnerability distribution.

$$\text{County financial budget} = \left(\frac{county\ budget}{county\ population}\right) \times village\ population \quad (9)$$

Insurance coverage rate is the percentage given by the amount of earthquake insurance divided by the number of households in counties. The more insurance coverage rate, the more citizen can be recovered by the insurance after the disaster, and the higher the resilience.

Social welfare workers aim to prevent or relieve social problems by assisting individuals, families, groups, and communities in adapting their social functions, enhancing or restoring the energy of their social functions, and creating social conditions that achieve goals. The more staff members, the higher the resilience.

Communal participation rate reflects the local populace's income and preference for leisure. It is influenced by individual labor supply choices, which are affected by personal and social factors. Communal participation rate is the percentage given by the number of people willing to participate in community affairs divided by the number of people in a community. The higher the community participation rate, the higher the resilience.

Natural Breaks (Jenks) is used to speed up dividing different PR scores into five different levels of resilience. The classification is shown in **Table 3**. The research of the result shows that the highest resilience area is Maifeng Village, Yunlin County, HsinJei Village, Chiayi County, Ping Lin Lane, and Chiayi City District. Yun-Chia plain area's resilience distribution and grading chart is shown in **Figure 7**.

4.4 Risk assessment of soil liquefaction

This study sets the definition of disaster risk as a result of disasters caused by soil liquefaction such as structure failure, property loss, and even casualties. And hazard was defined as the earthquake-induced soil liquefaction; vulnerability is dined as population distribution, economic development, and environmental development; resilience is for social development, community development, government resources, property protection, and social assistance showing the recovery from disaster.

Taking the above definition as main principle, hazard, vulnerability and resilience are cross calculated and graded accordingly and divide the disaster risk levels into 1–5 points. The grading index standard of each factor given in this study is shown in **Table 4**. The risk analysis procedure showed how the combination among hazard, vulnerability, and resilience is shown in **Figure 8**.

Based on the report published in [23], dividing risk levels as five parts help the decision maker to make the optimized decision. This study followed the guide and divided risk into five categories: "extremely high," "high," "medium," "low," and "extremely low." The categories could easily show the risk when different area encountered the disaster. The risk of soil liquefaction distribution condition is shown as **Figure 9**. The risk assessment result assessed by UNDRO method (Risk = Hazard*Vulnerability) is shown in **Figure 10**.

By comparing the degree of vulnerability, resilience, and resilience used in this study, we can find that the risk analysis of joining resilience factor in this study is more effective than the risk analysis of two factors of degree of vulnerability and vulnerability in the past. When it comes to considering the resilience factor, the resilience of areas such as Mailiao Township, Lunbei Township, and Chiayi County of Yunlin City is better, and the degree of risk exposure in the event of a disaster is effectively reduced.

In this study, the soil liquefaction potential chart and the liquefaction risk chart obtained in 475 years of the return period of Yun-Chia plain and the soil liquefaction potential map in Yun-Chia area published by the CGS are analyzed and compared, as shown in **Figure 11**. It is found that the distribution of soil liquefaction potential obtained in 475 years (**Figure 5b**) of the study area of Yun-Chia Plain is similar to the distribution of soil liquefaction potential in Yun-Chia area published by the CGS. However, the risk analysis shows that most of the areas are high soil liquefaction potential area. But if we take the region's resilience into consideration, the risk level it faces in the event of soil liquefaction-induced disaster is not as severe as imagined.

	Classification	Level 1	Level 2	Level 3	Level 4	Level 5
PR score of distance	Natural breaks(Jenks)	0~5.24	5.24~6.10	6.10~7.33	7.33~9.36	9.36~13.41

Table 3.
Classification of resilience based on PR score.

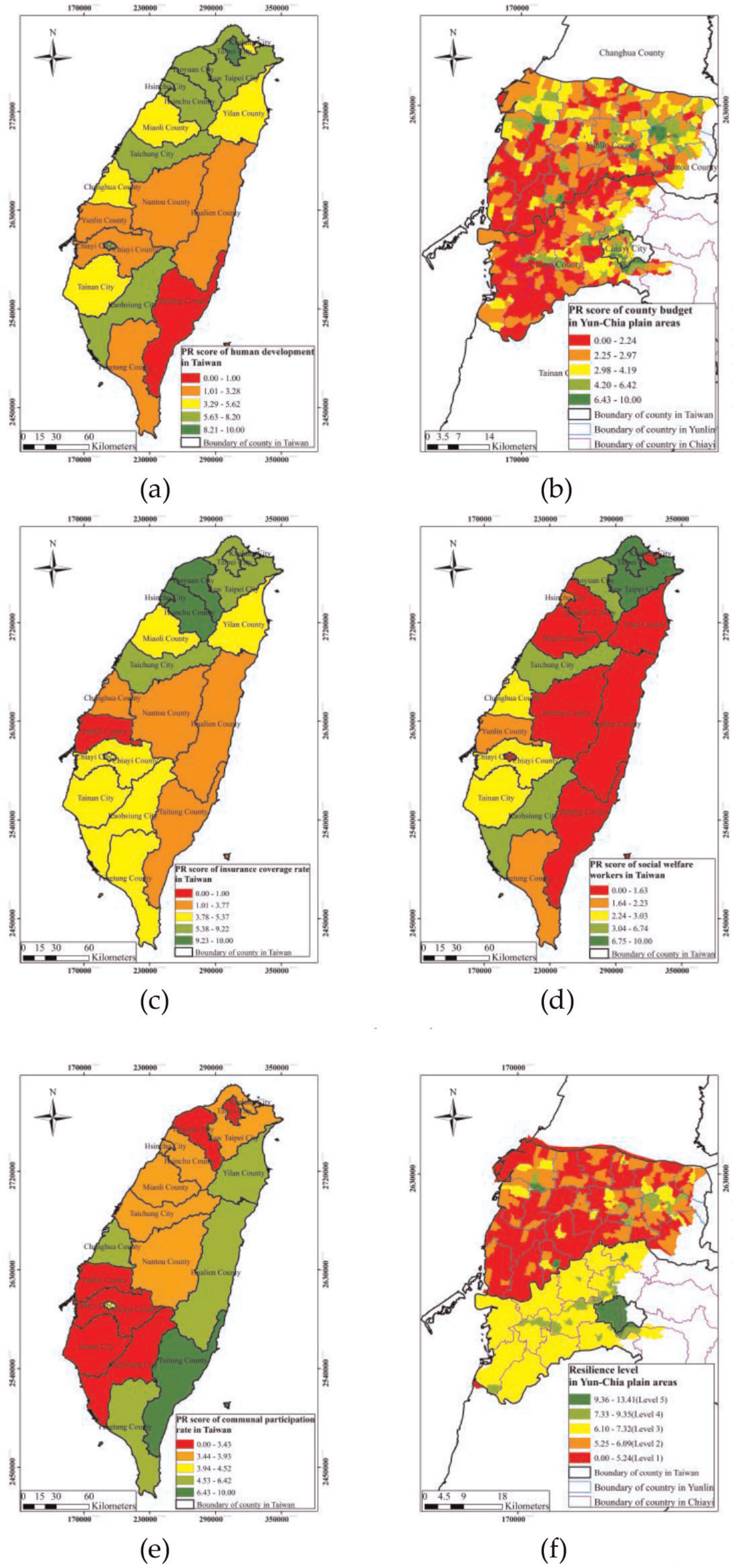

Figure 7.
Yun-Chia plain area's resilience distribution condition. (a) HDI distribution, (b) County budgetdistribution, (c) Insurance coverage rate distribution, (d) Social welfare workers distribution, (e) Communal participation rate distribution, and (f) Resilience distribution.

In formulating national strategy for disaster prevention, local governments can adjust and control the overall high soil liquefaction area and low potential in the event of soil liquefaction. The "Extremely High" and "High" risk region in this study should be the top priority improvements targets.

Indicator grading	Risk level 1	Risk level 2	Risk level 3	Risk level 4	Risk level 5
Hazard	1	2	3	4	5
Vulnerability	1	2	3	4	5
Resilience	5	4	3	2	1

Table 4.
Indicator grading and risk level.

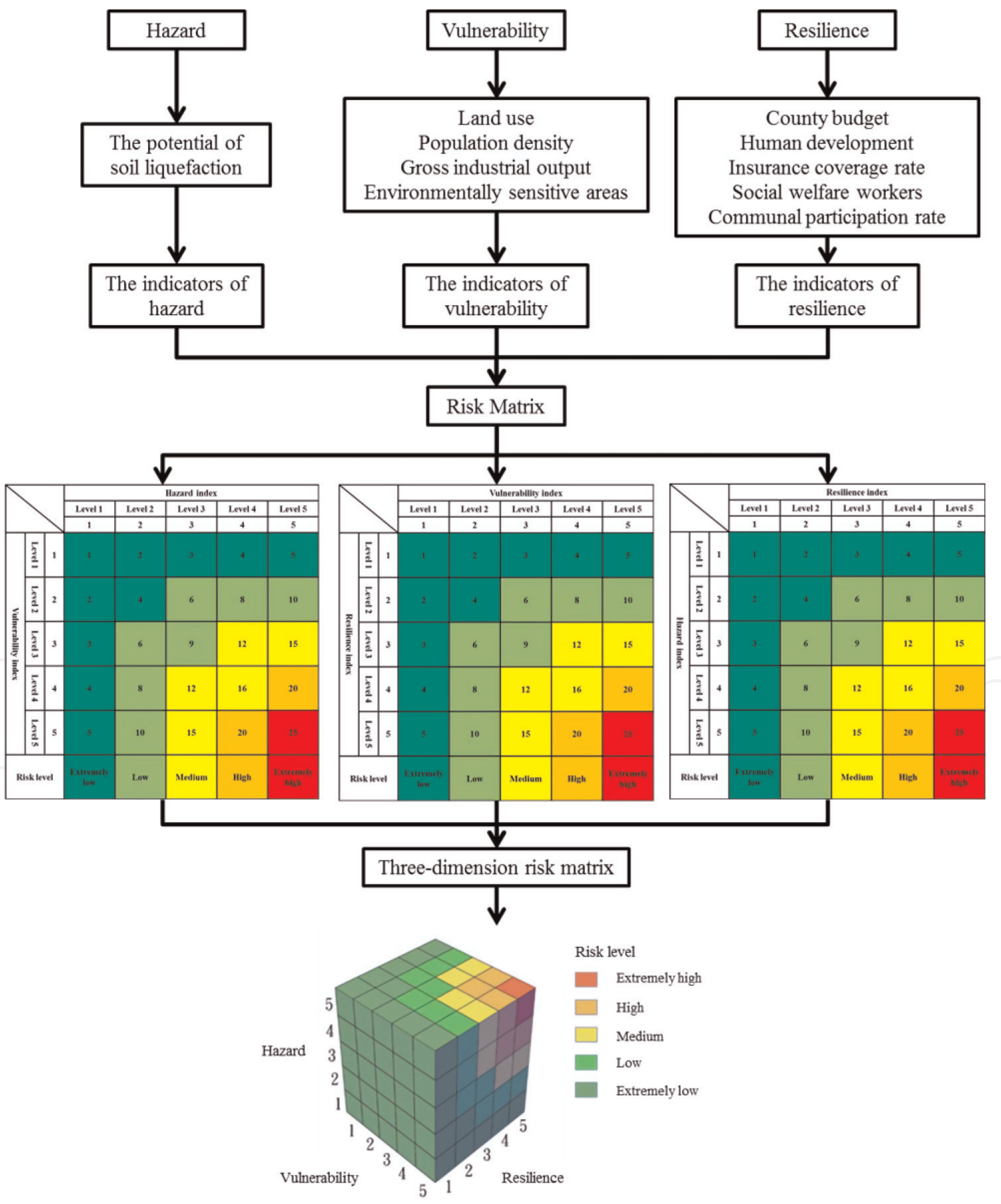

Figure 8.
Procedure of the risk level analysis.

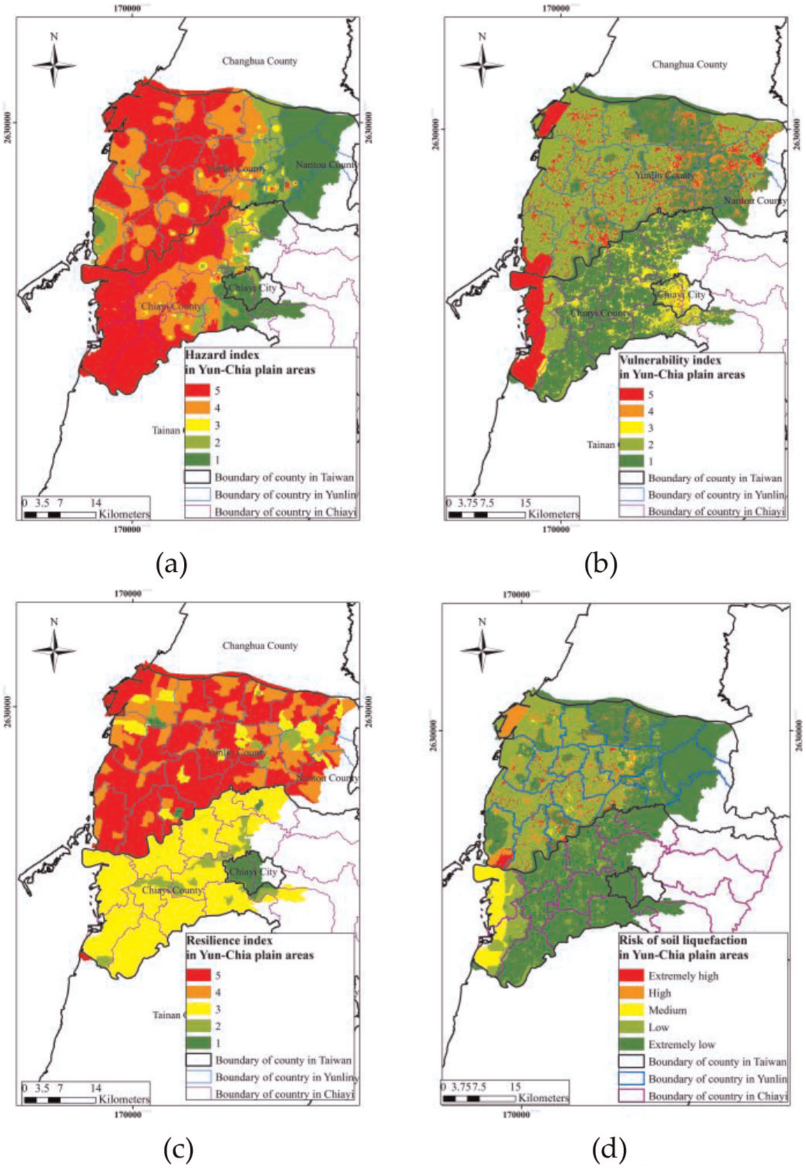

Figure 9.
Risk of soil liquefaction distribution condition. (a) Hazard index grading, (b) Vulnerability index grading, (c) Resilience index grading, and (d) Risk of soil liquefaction.

5. Conclusions

This study takes the risk of soil liquefaction in Chiayi and Yunlin Plains, adopt those soil liquefaction potential index assessment which commonly used in Taiwan and worldwide as the basic reference. This study also uses the definition proposed by UNDRO as a basis for assessing soil liquefaction risks but resilience was added into this study's risk assessment method, and considers risk as the combination of hazard, vulnerability, and resilience.

This research took different soil liquefaction potential index P_L induced by three different return periods of earthquake forces such as 30, 475, and 2500 years as Hazard. Vulnerability took four indicators representing factors such as population density, gross industrial output and environmentally sensitive areas, and land use. Resilience took social development, government resources, property protection, social assistance, and community development as the main points to show how the county recovers from the disaster.

According to the results of vulnerability analysis and resilience analysis, the vulnerability and resilience of Yunlin County are weaker than those of Chiayi

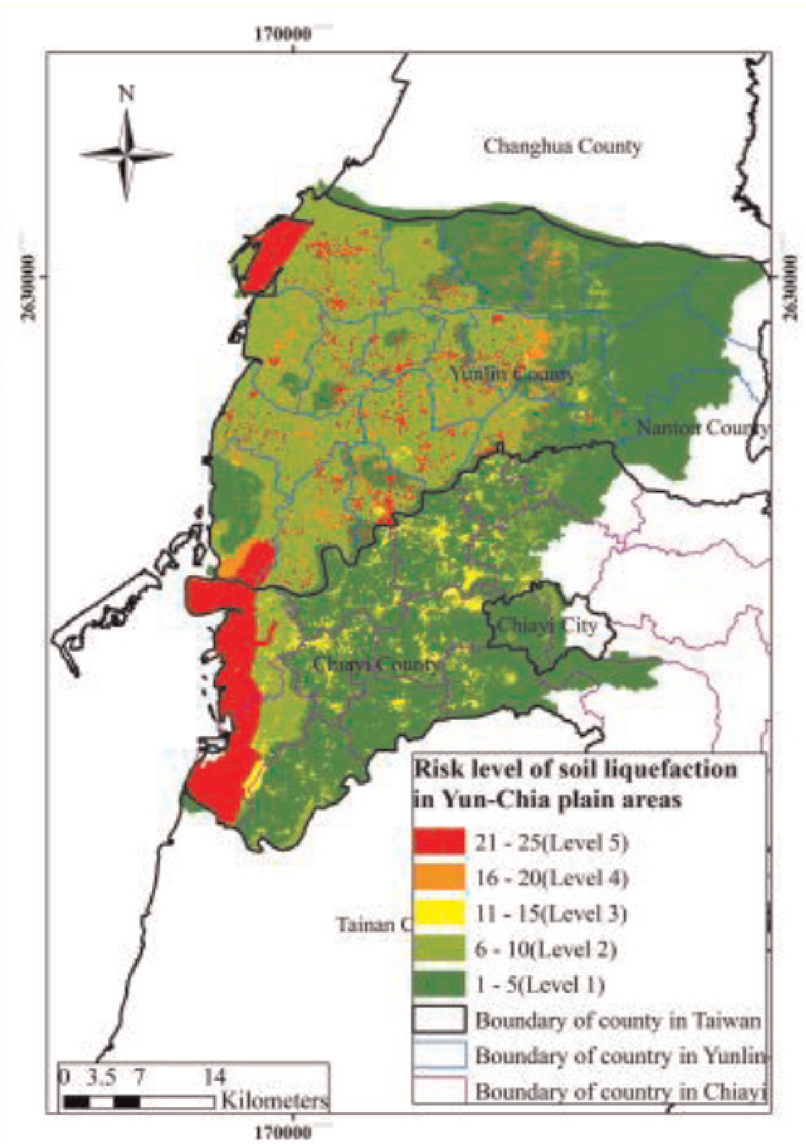

Figure 10.
The risk assessment result assessed by UNDRO method.

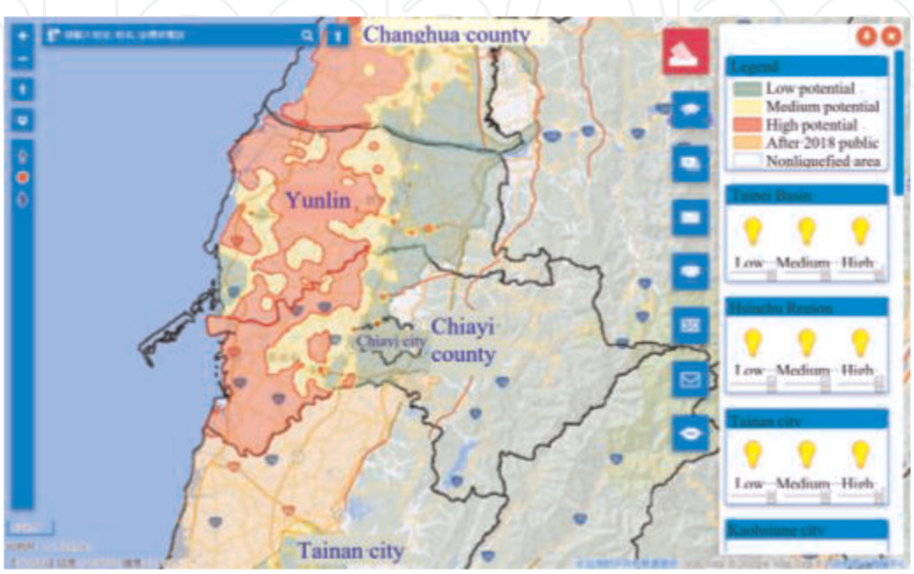

Figure 11.
Soil liquefaction potential map in Yun-Chia area published by the CGS.

County in the general areas, so in the event of a disaster, Yunlin County will likely face more serious losses in densely populated areas and high-output-value industries.

From the risk analysis results, we can see that in the face of the impact of soil liquefaction disasters, the population in Kouhu Township, Beigang Township, Tucu Town, Shui Lin Township, Dapi Township, Yuanchang Township, Dongsiang Township, and Baozhong Township of Yunlin County, was significantly lower than that of other large areas and low resilience led to these townships being over 10% at risk "extremely high" and "high," of which Kwuchu Township (26%) was the worst, followed by Beigang Town (16%) and Turku Town (14%).

This study discussed soil liquefaction from the perspective of risk. Compared with the CGS, "Soil liquefaction potential" can better reflect the relative risk among different regions and is more effective in concentrating decision makers in regional risk management.

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