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Exploring the Physical Environment and Building Features in Earthquake Disaster Areas

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Abstract**—**Earthquake is an unpredictable natural disaster and intensive earthquakes have caused serious impacts on social-economic system, environmental and social resilience. Conventional ways to mitigate earthquake disaster are to enhance building codes and advance structural engineering measures. However, earthquake-induced ground damage such as liquefaction, land subsidence, landslide happen on places nearby earthquake prone or poor soil condition areas. Therefore, this study uses spatial statistical analysis to explore the spatial pattern of damaged buildings. Afterwards, principle components analysis (PCA) is applied to categorize the similar features in different kinds of clustered patterns. The results show that serious landslide prone area, close to fault, vegetated ground surface and mudslide prone area are common in those highly damaged buildings. In addition, the oldest building might not be directly referred to the most vulnerable one. In fact, it seems that buildings built between 1974 and 1989 become more fragile during the earthquake. The incorporation of both spatial statistical analyses and PCA can provide more accurate information to subsidize retrofit programs to enhance earthquake resistance in particular areas.

Keywords**—**Earthquake disaster, spatial statistical analysis, principle components analysis, clustered patterns.

I. INTRODUCTION

ASIAN region has been regarded as most frequently hit by natural disasters. Earthquakes are infrequent hazards but unpredictable which result in higher fatalness [1]-[4]. Such earthquake disasters have an enormous impact on social-economic system, environmental and social resilience [5]. Asia is prone to earthquake and riddled with faults. Recently, large-scale earthquakes have inflicted severe damage on Sichuan in China (2008), Haiti (2010), Tōhoku earthquake in Japan (2011), Yunnan in China (2014). The Great Hanshin Earthquake in Japan in 1995 raised even serious issues that such advanced engineering country defeated. Over 6,000 people dead and over US$100 billion economic lost in the earthquake [6]. Again, the threat posed by even larger earthquakes has outpaced the ability to mitigate the impacts to acceptable levels.

Earthquakes do not kill people, buildings do [7]. Although cities are artificial environments shielding inhabitants against natural disasters, inadequate shield may result in secondary disaster on human live and property. When buildings located nearby earthquake-prone areas and constructed upon poorer soil areas might result in earthquake-induced ground damages such as fault rupture, landslides and liquefaction [8]. In addition, many existing buildings built before any improved seismic provisions required. And limited engineering structures are unable to resist earthquake induced ground damages. Inappropriate land usage and highly dense population with intensive earthquake disaster result in higher living environment risks. The security of urban areas confronting of natural extremes is no longer tenable.

Land use planning and zoning are two critical non-structural measures on controlling physical development within urban regions in earthquake-prone areas. However, it is difficult for zoning boards and planning committees to do further restriction on questionable lands for limited credible earthquake projection. Consequently, development continues in the potential path of earthquake prone areas and the existing built environment is lacking awareness for the possible risk [8]. The identification of sensitive geologic environment might help decision makers come up more compatible land use regulation for future development and retrofitting requirement for existing development.

Taiwan locates on the frequent convergence of the Philippine Sea Plate and the Eurasian Plate. There are forty-two active faults identified by geologists. The 921 Earthquake was a 7.3 MS earthquake, and it caused serious impacts on both social and economic system. In that day, we lost 2,500 people and over 10,000 people were injured [9]. Since then, a fault zone area of 15 meters on each side of fault trace has been regulated [10]. However, the earthquake damages were not only clustered along the fault. Therefore, this study attempts to explore potential similarities on those damaged buildings by using spatial statistical analyses and principal component analysis. The identification of potential sensitive physical environment might be some reference for future land use plan. Section II is the case study of land use management along the fault. Section III is the research design including conceptual model and methods. Section IV is the results and Section V is the contribution. This study concludes in the last section.

II. CASE STUDIES: LAND USE MANAGEMENT ALONG FAULT

Southern California lies on the boundary between the Pacific and North American plates and is riddled with faults and prone to earthquakes. One quarter of the earthquake risk for the U.S. lies in Southern California [11]. By understanding when and where earthquakes may occur might provide great help on mitigating loss. The U.S. Geological Survey incorporates detailed long-term forecasts into official National Seismic Hazard Map. Such map has been applied in public and private

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sector on evaluating insurance rate on buildings, risk assessment, disaster mitigation strategies [12]. Still, the earthquake prediction is a challenge because the accurate stop and begin time of rupture is hard to capture [13].

Alquist-Priolo (AP) Earthquake Fault Zonation Act has been passed in California afterwards in 1972, and geologic investigations are required to restrict housing construction across faults [12]. The AP Act is a state law designed to reduce the hazard from surface fault rupture during an earthquake for associated damage of houses, commercial buildings and other structures with extensive surface fault ruptures.

The law requires the State Geologist to establish regulatory zones (know as Earthquake Fault Zones) around the active fault traces. Such map will then be approved and distributed to planning bodies to control future development by regulating land divisions, buildings height, setback and others in those high surface rupture zones. Currently, there are 922 seismic hazard zone reports, 1,830 maps, and 671 GIS datasets are allowed people to download and check whether their property might be near or within an active fault [12].

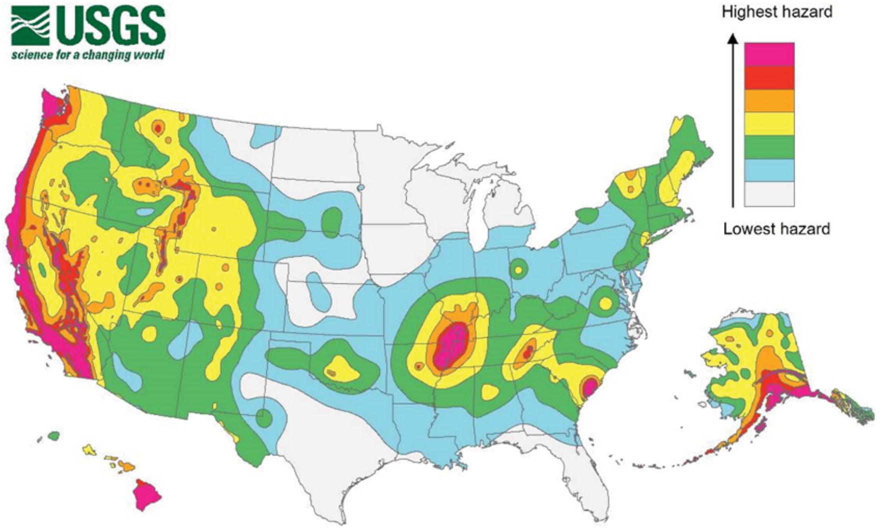


Fig. 1 Simplified 2014 Hazard Map (PGA, 2% in 50 years) [12]

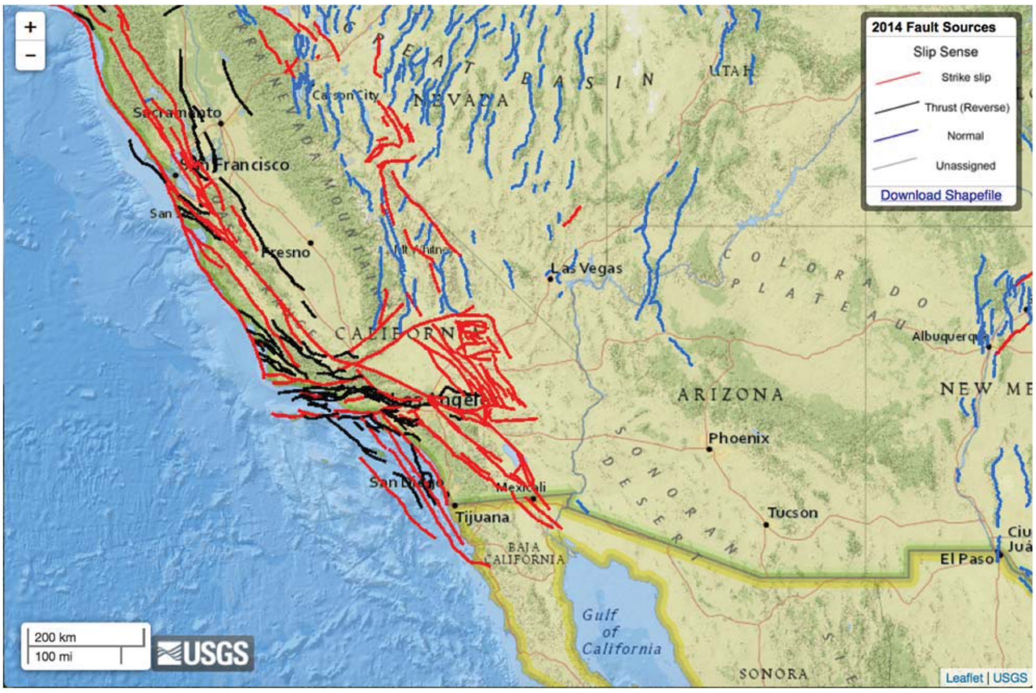


Fig. 2 Fault Source Map in the U.S. [12]

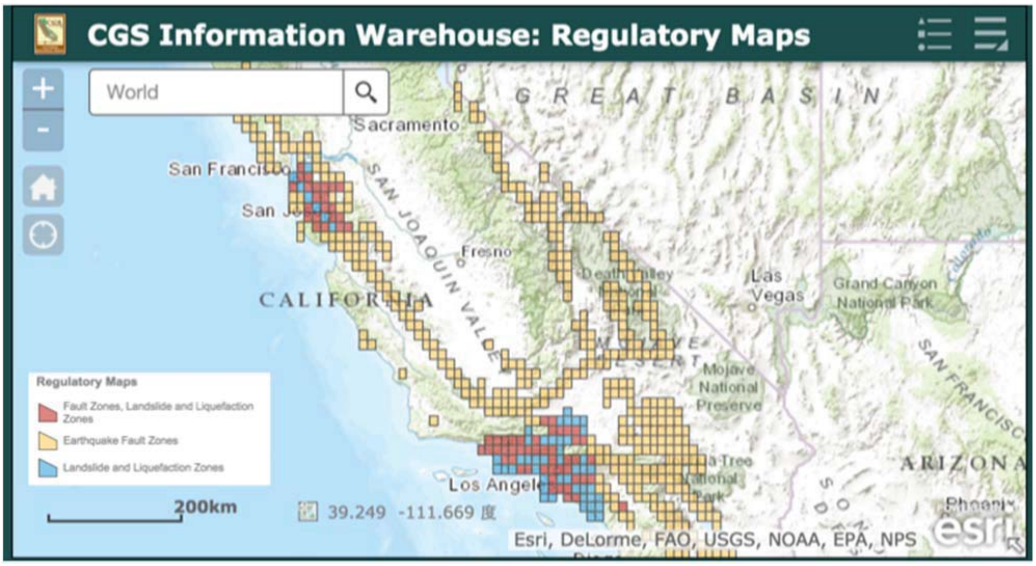


Fig. 3 AP Fault Zone and Seismic Hazard Zone maps [12]

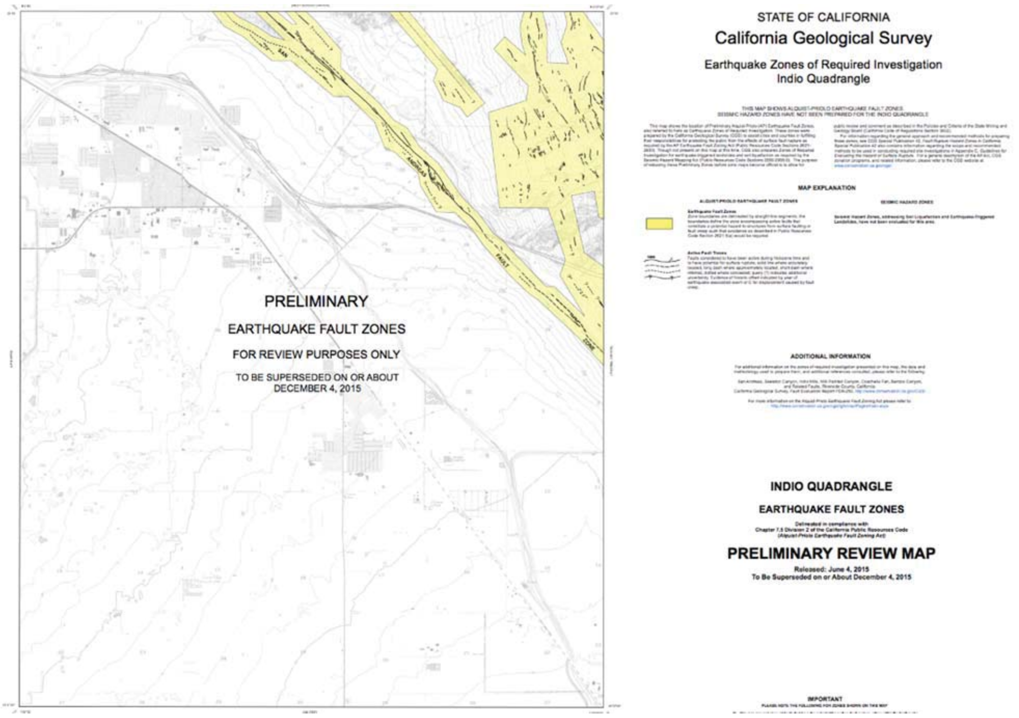


Fig. 4 Earthquake Zones of required investigation in Indio Quadrangle [12]

III. Research Design

Earthquake disaster is a joint product of nature and human society, and such can be revised by humans but is not ultimately reducible to a human construction. After 921 Chi-Chi Earthquake, over 2,400 people dead, 10,000 people injured, and 100,000 buildings damaged [9]. Due to the epicenter, fault dislocation and ground deformation, huge live and property losses were aggregated in the central Taiwan, and 5,213 damage buildings are used in this study [9]. The application of two spatial statistic analyses is to probe into if there is any significant cluster pattern on particular distance. Afterwards, principle component analysis (PCA) will be applied to categorize particular features of damage buildings.

A. Methodology

a. PCA

PCA, which was developed by Pearson in 1901 [14], has been commonly employed in the social and physical sciences, and the details of extracting components for a data matrix and their interpretation have been presented by Hotelling [15]. The basic theory behind PCA is to transform a set of correlated variables into a set of uncorrelated variables by linear transformation. PCA is independent of any hypothesis of data probability distribution and is generally applied to highlight patterns within multivariable data [16]. PCA has several advantages, such as flexibility in the data reduction process and the ability to retain important patterns among multivariate data.

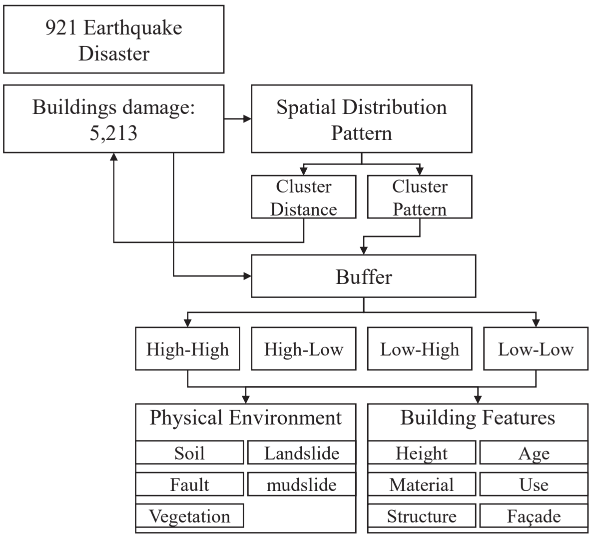


Fig. 5 Research design framework

The total variance is unchanged via orthogonal linear transformation. The first principle component (PC) is designed to have the largest variance, and the second principle component the second largest variance. The ranking of the PCs is based on the eigenvalues that are associated with each PC. This mathematical transformation identifies p variables that account for the total variability, which are divided into p PCs. The choice of the number of PCs is subjective and based on the extent that PCs are interpretative [17].

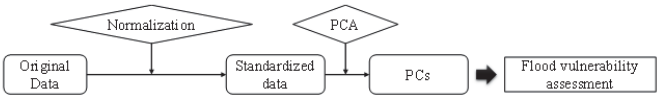


Fig. 6 Technical flow chart of flood vulnerability PCA

b. Spatial Autocorrelation Analysis

Spatial autocorrelation statistics detect the degree of similarity between objects occurring in nearby locations by measuring and testing the clustering/dispersal based on Tobler's statement in 1970 that everything is related but near things are more closely related [18]. This study applies Moran's I to test for the significance of spatial pattern. Moran's I can be defined as

$$I(d)=\frac{n\sum\sum w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{W\sum(x_i-\bar{x})^2} \qquad (1)$$

where x_i and x_j are the values of variables in areal unit i and unit j; $\bar{x}$ is the mean value of variables in all spatial units; w_{ij} is the spatial weights matrix; $(x_i-\bar{x})(x_j-\bar{x})$ is cross –product of the variances between neighboring values and the overall mean; W is the sum of all elements of the spatial weights matrix.

The value of Moran's I ranged from -1 to 1. -1 indicates an extremely negative spatial autocorrelation while 1 is extremely positive autocorrelation. In order to detect the spatial autocorrelation, it should be compared to the expected value of Moran's I:

$$E(I)=-(1)/(n-1) \qquad (2)$$

E(I) is always negative for *E(I)* is inversely related to the areal units. $I > E(I)$ indicates a clustered pattern for similar features in adjacent areal units; $I \cong E(I)$ indicates random pattern for no particular patterns or similarity; $I < E(I)$ indicates a dispersed pattern for different features in adjacent areal units.

IV. RESULTS

A. Study area

The interaction of the Eurasian and Philippine Sea plates causes the frequent rate of earthquakes. In Taiwan, there are 20 faults belonged to the Holocene active fault, and 13 faults belonged to the Late Pleistocene active fault, and 4 faults belonged to concealed or inferred. 90% of Taiwan's 23 million people live in the west island [19].

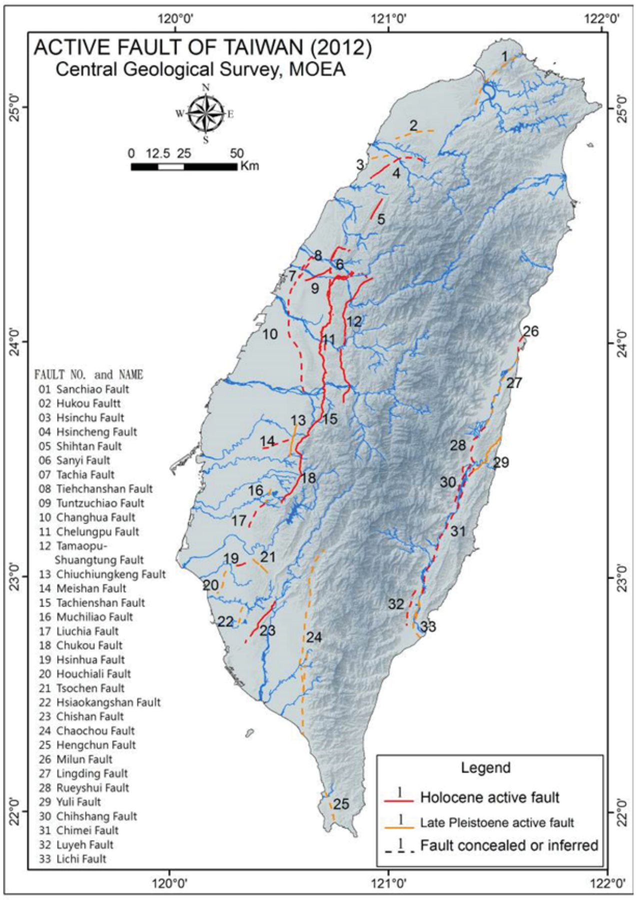


Fig. 7 Active fault of Taiwan [19]

B. Spatial Distribution of Damaged Buildings

The result of LISA shows that 470 spatial units are High-High (high values of damage clustered), 346 spatial units are High-Low (high values of damage surrounded by low values of damage), 152 spatial units are Low-High (low values of damage surrounded by high values of damage), and 833 spatial units are Low-Low (low values of damage clustered). Other damage buildings are distributed randomly in the study area.

TABLE I
THE SPATIAL DISTRIBUTION OF DAMAGE BUILDINGS ACCORDING TO LISA

	High-High	High-Low	Low-High	Low-Low
Serious damage	470	346	0	0
Moderate damage	0	0	46	262
Slight damage	0	0	106	571

C. PCA

a. Physical Environment

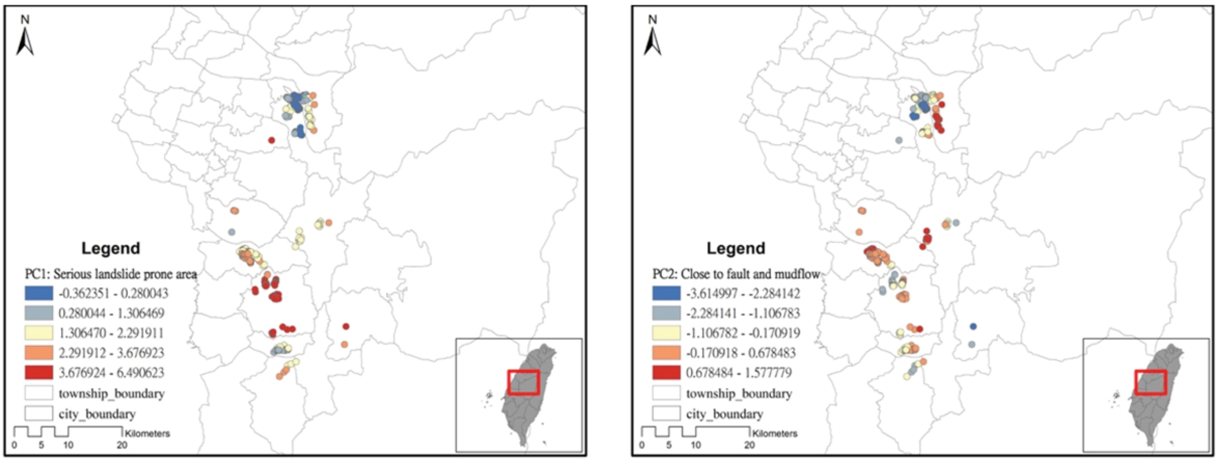
For the High-High category, the PCA of twelve indicators extracted four components that explained 69% of the variance and 0.678 of the KMO value in the data. The indicators "high landslide risk", "moderate landslide risk" and "colluvial" show high positive correlation in HH_PC1 and explained 32% of the variance. HH_PC1 is renamed "serious landslide prone area." The second principle component HH_PC2 explains 14% of the variance with the indicators "fault distance" and "mudslide stream distance." HH_PC2 is renamed "close to fault and mudflow." The indicators "vegetation" is highly positive in HH_PC2 and explained 12% of the variance. HH_PC3 is renamed "soft ground surface." The fourth principal component HH_PC4 explains 12% of the variance with the indicators "uncovered" and "mudslide stream distance." HH_PC4 is renamed "mudslide prone area."

b. Building Feature

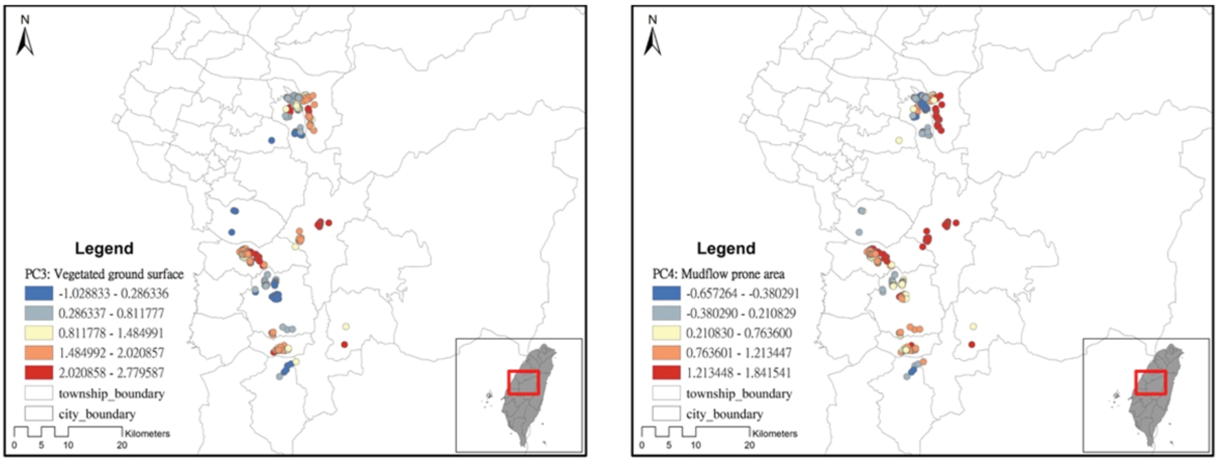
For the High-High category, the PCA of six indicators extracted two components that explained 47% of the variance and 0.640 of the KMO value in the data. HH_PC1 represents 29% of the total variance, and the indicators "year" and "anti-earthquake structure" show a high positive significance. In order to investigate how "year" affect High-High category, the PCA of five indicators extracted two components that explained 54% of the variance and 0.210 of the KMO value in the data. Although the KMO value is too low, the two components reveal the building feature in "1974-1982" and "1983-1989." HH_PC2 represents 17% of the total variance, and the indicator "material" is highly positive. In order to investigate how "material" affect High-High category, the PCA of three indicators extracted one component that explained 61% of total variance and 0.448 of the KMO value. Although the KMO value is not significant enough, the component reveals the building feature in "reinforced concrete."

V. CONTRIBUTION

Earthquake is infrequent but unpredictable disaster, and even larger magnitude has outpaced the ability of human beings to mitigate. Land use regulation and zoning have been discussed quite a while as nonstructural engineering measures, and they have been implemented mostly in fault zone area to prevent the surface rupture disaster. However, earthquake induced disaster are more than surface rupture such as liquefaction, landslide, land subsidence and so on. The results in this study show that there are similar physical environment features and way beyond the fault itself. Besides, the newest structure followed the newest Building Code and Regulations but defeated in the end. The continued allowed development in such sensitive geological or earthquake prone areas might result in another fatalness disaster in the future.

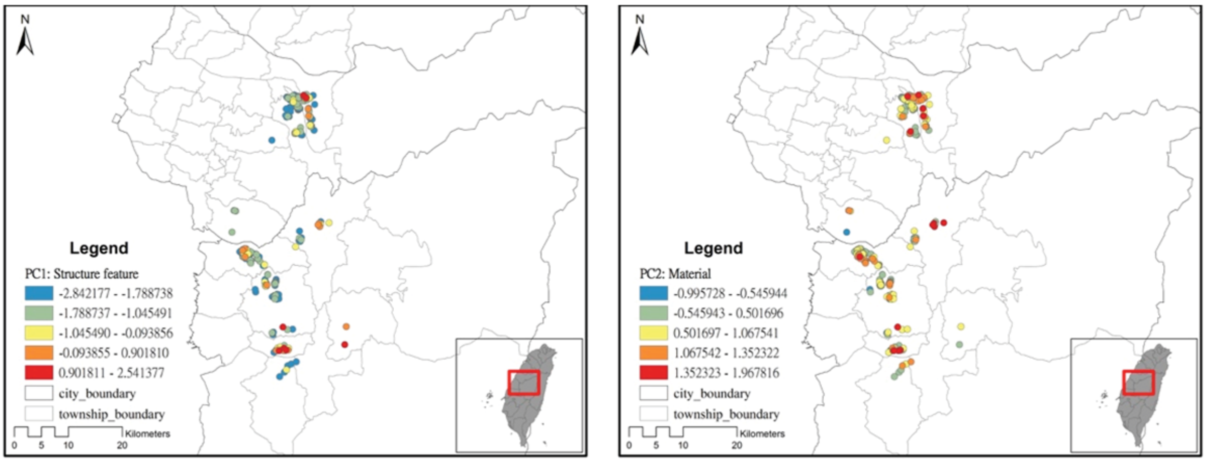


(a) HH_PC1: Serious landslide prone area (b) HH_PC2: Close to fault and mudflow



(c) HH_PC3: Vegetated ground surface (d) HH_PC4: Mudslide prone area

Fig. 8 Principle components of physical environment in High-High category



(a) HH_PC1: Structure features (b) HH_PC2: Material

Fig. 9 Principle components of building feature in High-High category

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