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The application of seismic risk-benefit analysis to land use planning in Taipei City

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In the developing countries of Asia local authorities rarely use risk analysis instruments as a decision-making support mechanism during planning and development procedures. The main purpose of this paper is to provide a methodology to enable planners to undertake such analyses. We illustrate a case study of seismic risk-benefit analysis for the city of Taipei, Taiwan, using available land use maps and surveys as well as a new tool developed by the National Science Council in Taiwan—the HAZ-Taiwan earthquake loss estimation system. We use three hypothetical earthquakes to estimate casualties and total and annualised direct economic losses, and to show their spatial distribution. We also characterise the distribution of vulnerability over the study area using cluster analysis. A risk-benefit ratio is calculated to express the levels of seismic risk attached to alternative land use plans. This paper suggests ways to perform earthquake risk evaluations and the authors intend to assist city planners to evaluate the appropriateness of their planning decisions.

Keywords: disaster reduction, earthquake, HAZ-Taiwan, land use planning, risk-benefit analysis, Taipei

Introduction

In the developing countries of Asia local authorities rarely use land use planning or zoning regulations to prevent or to mitigate losses caused by seismic disaster. This is because local governments lack appropriate tools to support risk analysis,[1] the most sophisticated level of hazard and vulnerability assessment, to inform their land use planning and development decision-making. In particular, a failure to provide a factual basis for the assessment of seismic hazards exposes many locally planned land uses to high levels of seismic hazard (Olshansky and Wu, 2001; Nelson and French, 2002).[2] This increases the vulnerability of new development to earthquake hazards.

Consequently, new tools must be developed to support hazard assessment or risk analysis in the processes of local land use planning and regulation and in reviews of land use plans. These tools should create seismic risk maps in order to improve implementation (Shinozuka, 1996). It is not only the data required in the land use planning process, but also information about the possible impacts of each land use decision that should be provided in seismic risk maps (Berke, 1994; Mader, 1997; Olshansky and Wu, 2001; Chen and Hung, 2003; Chen at al., 2003). Thus, seismic risk maps have to

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help planners to identify earthquake hazard and to assess vulnerability. Risk maps also play an important role in increasing public awareness of earthquake risk (Burby and Dalton, 1994; Deyle et al., 1998). The issues of how to use risk maps appropriately and how to avoid disproportionate development controls or inappropriate development behaviour in highly hazardous locations are essential to community planning and local land use planning as well as to the review of new development.

The main purpose of this paper is to provide a methodology for risk-benefit analysis that can be applied to land use planning. It illustrates a metropolitan-based risk-benefit analysis used to evaluate various land use plans in Taipei City. This analysis was made possible by a new earthquake loss estimation model (HAZ-Taiwan) developed by the National Science Council (NSC), Taiwan (Yeh et al., 2003). This paper briefly reviews recent studies of land use planning and earthquake risk analysis. The earthquake hazard model of the National Center for Research on Earthquake Engineering (NCREE), Taiwan, is applied to the HAZ-Taiwan model in order to assess earthquake hazard. We estimated the expected direct economic losses, injuries and damage based on three hypothetical earthquakes and their spatial heterogeneity. We then used the outputs of HAZ-Taiwan as inputs in order to conduct a risk-benefit analysis, and made a comparative analysis in a case study.

Land use planning and risk analysis

One objective of land use planning is to use the limited information and resources available to achieve safer growth for communities (Kunreuther, 2000; Olshansky, 2001). Seismic hazards were apparently given little consideration in city planning throughout Taiwan before the Chi-Chi earthquake hit central Taiwan in 1999.[3] However, the 2000 Disaster Prevention and Protection Act introduced the idea of appropriately addressing seismic safety implications and risk analysis in local land use planning, and this became a key issue for local development decision-making in Taiwan. Meulbroek (2002) proposes integrated risk management, that is, that risk management in planning should proceed from detailed hazard assessment and flexibly adopt appropriate measures to face potential risks rather than pursue absolute risk control. This is similar to the concept of 'comprehensive vulnerability management', or sustainable development that reduces the impact of disasters, suggested by Mileti (1999) and McEntire et al. (2002).[4]

There is a growing consensus that local planning authorities should consider both the risk implications and the potential benefits of their development decisions. The major factors that determine the risks and benefits consistent with city growth are attributed to the conditions placed on land uses and the socio-economic attributes of residents in the planned area. Hence the intensity and type of development, and the scale of exposure of property and the population to seismic hazard not only make up the social capital but also determine the level of vulnerability in development locations (Chen et al., 2002). It therefore follows that the assessment of land use, and the population growth characteristics that result from a development decision, will both be important factors in the process of land use planning (Kartez and Lindell, 1987; Davidson and Rivera, 2003).

There is strong evidence that a high quality planning process can reduce seismic damage (Burby et al., 1998; Olshansky, 2001). In order to mitigate seismic damage and implement risk management, the essential information requirements about seismic hazards include the:

a) expected earthquake sources and their likelihood;
b) areas with the potential for earthquake hazard amplification or ground failure;
c) expected levels of ground-shaking and its expected effects; and
d) potential for direct and indirect economic losses (Olshansky, 1997; Olshansky, 2001).

Furthermore, there should be a sophisticated assessment of such information, which should be made easier to apply. In other words, to reduce seismic risk and avoid disproportionate restrictions on land use, planners should have to create risk maps to inform their land use planning, and to set out mechanisms by which the information can be applied (Burby et al., 1998; Kijko et al., 2002).

New tools for hazard assessment are available that estimate levels of ground shaking, ground failure, building damage, lifeline damage, casualties and displaced households, as well as economic and social losses and the need for temporary shelter. The methods, components or modules of the hazard assessment tools are described and discussed in detail in several articles (Whitman et al., 1997; Kircher et al., 1997; Uitto, 1998; Bendimerad, 2001; Olshansky and Wu, 2001; Yeh et al., 2003). The primary purpose of developing these tools was to create and make available seismic risk maps to inform land use decisions. The applications include: a) seismic risk and vulnerability analysis; b) evaluation of disaster mitigation measures; c) zoning and related land use regulation; and d) implementation of emergency, recovery and hazard abatement plans (Kircher et al., 1997; Olshansky, 2001). A pioneering study by French and Isaacson (1984) provides general guidance on applying earthquake risk analysis techniques to land use planning. Several metropolitan areas in Italy, Japan and the United States have also developed maps of earthquake hazards, and have applied the information to case studies in order to undertake comparative risk analyses to evaluate different land use plans (Bendimerad, 2001; Meletti et al., 2000; Olshansky and Wu, 2001; Chen et al., 2002).

This article differs from previous work in two key ways. First, we employed the HAZ-Taiwan software to create seismic risk maps. This process used HAZ-Taiwan to estimate the possible effects of a variety of potential earthquake sources. The outputs of HAZ-Taiwan allow us to assess profiles related to the spatial distribution of seismic risks in a given area, which previous studies have found difficult to do. This is an important support for land use planning and decision-making. Second, we developed a method of risk-benefit analysis that considers the key factors that determine vulnerability to earthquake hazard. We assessed vulnerability in terms of the exposed population, and the types of building use and its development density rather than simple land use types. Seismic risk analysis processes based on input data involving building inventories and demography may provide a more comprehensive assessment of earthquake losses and vulnerability in the given areas (Davidson and Rivera, 2003).

Risk-benefit analysis

Earthquake risk analysis incorporates estimates of the probability of various levels of injury, damage or loss to provide a more sophisticated description of the risk from the full range of possible earthquake hazard outcomes in a given area (Deyle et al., 1998). Risk-benefit analysis, by contrast, places special emphasis on the value of risk-reduction measures. Thus, when considering whether a policy or land use plan reduces seismic risk, the risk-benefit analysis assesses the value of the benefits and/or the costs of risk change (Freeman, 1994).

The primary methods of risk-benefit analysis fall into two categories according to the way they identify value. The first approach is based on its foundation on the neo-classical welfare economic theory. It argues that the basis for measuring the economic value of changes in natural disaster systems (or risk) is its effects on human welfare (Freeman, 1994). The second approach emphasises assessing the value changes caused by a given policy or land use plan in a given area. This approach simply tries to assess the value of the direct impact on social capital of disaster risk reduction (Wilson and Crouch, 2001; Bateman et al., 2003).

Like the application of risk-benefit analysis to evaluating land use policy, the factors that should be taken into account include the characteristics of the disaster risk and the impacts that result from the land use change. To make the observation of the relationship between land use change and its effects on risk easier, we focus on an assessment of the differences in the direct impacts on social capital associated with various land use plans. The detailed assessment of changes in human welfare is beyond the scope of this paper. The second of the approaches mentioned above is therefore more appropriate for this study (Burby et al., 1998; Olshansky, 1997; Olshansky and Wu, 2001).

Earthquake damage can be considered as a function of land use types, seismic hazard and the socio-economic attributes of residents. Thus, the extent of earthquake damage or losses can be described using a damage function thus:

$$D = f(E, B_i, S) \quad (1)$$

where L represents earthquake economic losses or damage linked to a given earthquake event; E is expected earthquake hazard; B_i represents the development density of land use types i, and S represents the socio-economic characteristics of residents in a given area. On the other hand, both the density and the type of land use and socio-economic conditions can affect the benefits of urban development. The benefit function, thus, can be shown by the following expression:

$$R = f(B_i, S) \quad (2)$$

where R represents the urbanisation benefit. The methods of estimating expected earthquake hazard E can be divided into two types: a) a probabilistic sum of the expected cumulative shaking hazard at each point; and b) a calculation of the expected effects of individual earthquakes (a deterministic calculation). HAZ-Taiwan calculates the expected effects of earthquakes by using the second approach.

To design a convenient method of risk-benefit analysis, a risk-benefit ratio can be calculated comparing the predicted value of earthquake-related economic losses with the total predicted benefits derived from urbanisation. This ratio, independent of the economic conditions or size of area, expresses expected damage as a proportion of the economic value of the proposed development of the area. Alternative land use policies can be evaluated by measuring the changes to the ratio.

The HAZ-Taiwan system

HAZ-Taiwan was developed, based on the framework of modules in HAZUS,[5] by the NSC and the Department of Industrial Technology, Ministry of Economic Affairs, Taiwan.[6] The framework of HAZ-Taiwan is made up of several modules that measure hazards and losses in various ways, including potential earthquake hazards, direct physical damage, induced physical damage, direct economic and social losses and indirect losses (Loh et al., 2002).

The existing literature on HAZ-Taiwan mainly focuses on the HAZ-Taiwan development process rather than its application (Chen et al., 2003). In terms of earthquake hazard-reduction, using a risk analysis tool to provide information on the types and levels of potential earthquake hazards and risks is the basis for deploying land use planning and for allocating public facilities in a particular geographical area. HAZ-Taiwan should be regarded seriously as a tool for providing the necessary information to assist such risk analyses and land use planning.

For our illustrative case study, earthquake risk is expressed using two elements: direct economic losses and casualties. These can indicate effectively the spatial heterogeneity of risk, and provide multiple quantitative ways to compare the risks associated with various land use decisions. The use of two indicators to assess risk provides a more comprehensive measure of vulnerability than using a single indicator. A significant number of authors have computed earthquake risk using only dollar values (Olshansky and Wu, 2001; Davidson and Rivera, 2003). This indicator is probably a reasonable proxy for urban development, but it also introduces bias and underestimates risk in densely populated locations.

Direct economic loss usually includes structural damage and non-structural damage as well as damage caused to buildings, loss of business incomes and wage losses. In the case study, only structural and nonstructural damage were considered when calculating direct economic loss. Estimates of development (or urbanisation) benefit should probably also be broader to encompass real estate development values that include anticipated property appreciation and related market benefits in a given area. However, the detailed measurement of development benefit is not dealt with in this study. We used the replacement costs of all existing or planned building stock as an approximation of development benefit.[7] This gives a conservative estimate of both development benefit and the total economic value of an area's structures as 'dollar exposure'. Replacement costs have the advantage of being easy to use but this measure may undervalue the benefits of land development in fast growing areas (William, 1991).

Case study

Inputs

The case study applies an illustration of risk-benefit analysis to the Shihlin District of Taipei. Three types of input are required for the HAZ-Taiwan. The inputs required to estimate the potential earthquake hazard include the scenario basis, attenuation relationship and soil map. We used the default data in HAZ-Taiwan to provide these inputs. The second type of data uses aggregated census tracts to estimate direct physical damage. This includes building types and aggregated data on the general building stock, which were also provided by the default data. The third type of data is demographic data from the census and data on the replacement costs of structures taken from a survey of building contractors. These inputs are required to calculate direct casualties and economic losses.

The format of the database in HAZ-Taiwan is based on census tracts for each Li, which is the basic unit of city administration in Taipei City. The assumptions in each database unit, which contains a specified mix of model building-structure types, are based on the occupancy class of each building. HAZ-Taiwan estimates damage for each building type by assigning a fragility curve, which is a calculation of the cumulative probability of being in or exceeding each damage state for a given level of ground shaking. The database on dollar exposure can also be tabulated using an occupancy level and building type for each census tract.

Assumptions about earthquake source

In order to estimate earthquake hazards and risk, three seismic scenarios were selected—each with a characteristic earthquake magnitude, location and frequency (see table 1). Two of the seismic sources (the sea off Yilan and the Shincheng fault) were considered in the Taipei City Local Disaster Prevention Plan. The third source, which is one of the most active faults in the northern region of Taiwan, was suggested by the NCREE.

It should be noted that these are not the only possible sources of an earthquake that might strike Taipei. However, they are the *most probable* sources for an earthquake and their use simplifies the model in several ways. First, our model selects a single characteristic earthquake magnitude for each source zone and our simplification assumes, for each source zone, that all the seismic activity will be released over time only by an earth-

Table 1 Three possible earthquake scenarios

Earthquake source	Magnitude	Fault type	Location	Depth	Projected frequency[a]
Sea off Yilan	7.61	–	332899, 2694039	10 km	1.14
Shincheng fault	7.13	Reverse	269000, 2742000	10 km	0.42
Shitan fault	7.13	Reverse	245917, 2721782	10 km	0.42

Note

[a] The probability of an earthquake occurring in a period of 1000 years.

quake of the characteristic size. The probability of such an earthquake occurring in 1,000 years, the measure proposed by the NCREE, is shown in table 1.

Second, we assume a fixed location for each selected earthquake source. In fact, an earthquake could occur anywhere along each fault zone or source zone. We have chosen the midpoint of each fault or source zone segment because HAZ-Taiwan uses a deterministic calculation to model earthquake hazard, which limits our choice to a discrete earthquake and requires us to fix a location for each earthquake source.

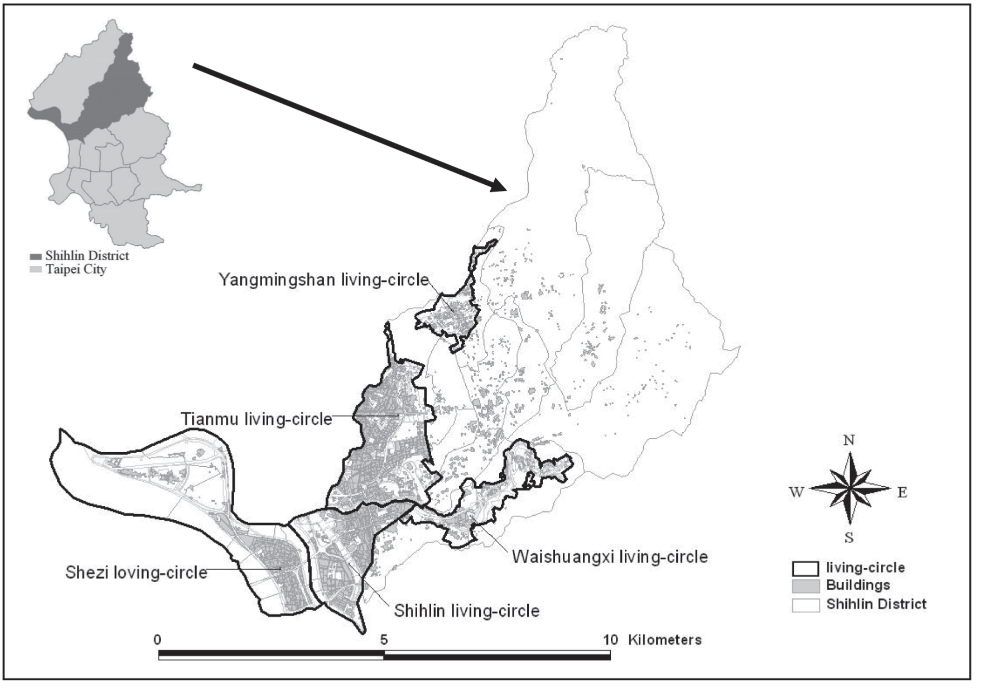
Third, the HAZ-Taiwan model is based on census areas and assumes homogeneous soil, demography and building-type conditions throughout each Li. This introduces significant limitations to our analysis and to the maps presented below.

Estimates of casualties and annualised direct economic losses

Shihlin District is located in north and north-east Taipei. It has a population of 291,493 and an area of 62.4 km^2. It is an area with a great diversity of land use types including urban land (23%), non-urban land (54%) and part of the Yangmingshan National Park (23%). In the General City Plan of Taipei, the mainly developed areas contain five 'living-circle plans'—Shihlin, Tianmu, Shezi, Yangmingshan and Waishuangxi.

Figure 1 indicates the boundary of each living-circle superimposed on the distribution of development in the study area. Figure 1 also shows that the core developed areas are located at the southern and central parts of Shihlin District, which are mainly composed of long-established developed communities with a dense mix of land uses,

Figure 1 Distribution of buildings and living-circles over Shihlin District



including residential (14%) and commercial (1.4%). Figure 1 shows the location of key developments and properties and the most vulnerable areas.

Estimating seismic hazard

By running HAZ-Taiwan for each of the three hypothetical earthquake sources, the estimated peak ground acceleration (PGA) shows that an earthquake on the Shincheng fault would be the most hazardous (within 0.1g and 0.3g). The areas estimated to have the highest PGA are concentrated in the southern and south-western parts of Shilin District. Moreover, both the earthquake scenario on the Shincheng fault and the earthquake scenario on the seabed off Yilan would cause tremendous damage—possibly exceeding that caused by the Chi-Chi earthquake in 1999.

Estimates of damage to buildings

Predictions of damage to buildings resulting from each hypothetical earthquake event vary significantly according to the seismic magnitude and location. Figure 2 shows the variations in predicted building damage superimposed on Li boundaries across the Shihlin District, measured as the probability of at least extensive damage as a result of the proposed Shincheng fault event.[8] The results illustrate that the distribution of the areas with a higher probability of at least extensive building damage is concentrated in the Shihlin, Tianmu and Shezi living-circles. These areas are also the major portions of the earliest urbanisation and assemblage of mixed-use residential and commercial areas in Shihlin District.

Figure 2 clearly demonstrates that reducing the vulnerability of these areas by implementing land use planning tools would be a big challenge for planners. Although the benefits of a policy to control land use and reduce the vulnerability of the most hazardous

Figure 2 The distribution of at least extensive damage to buildings resulting from an earthquake on the Shincheng fault

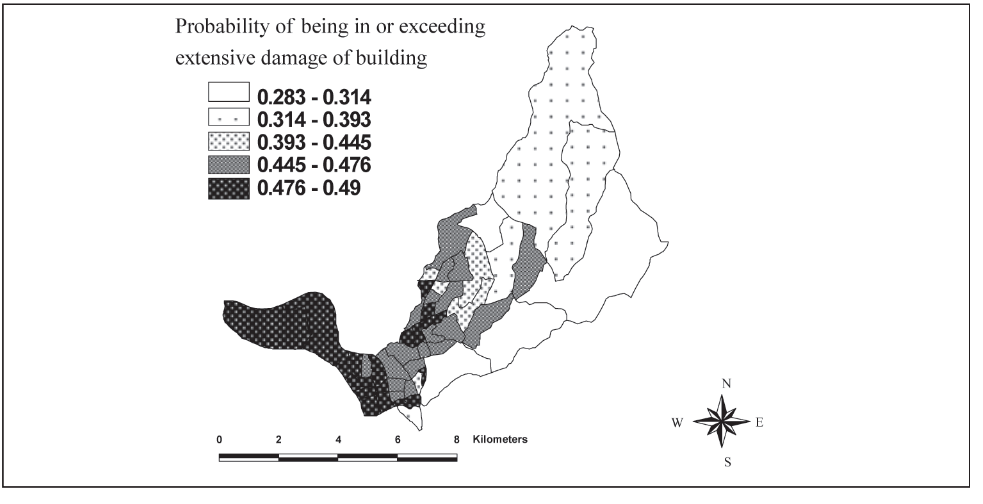


Table 2 Estimated earthquake losses for Shihlin District for current land uses

Earthquake source	Expected loss from each earthquake (NT$ billions)	Probability of earthquake per 1000 years	Expected annualised loss (NT$ millions)	Damage-to-cost ratio
Sea off the Yilan	122.7	1.14	139.9	0.029%
Shincheng fault	128.1	0.42	53.8	0.011%
Shitan fault	90.2	0.42	37.9	0.001%
Mean	113.7	–	77.2	0.014%

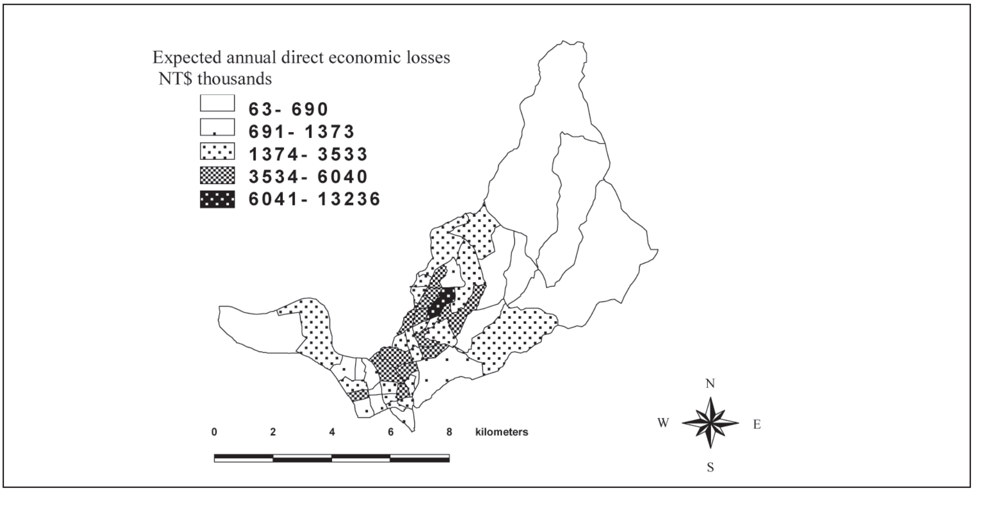
areas are obvious, it is difficult to change the status quo in developed areas because of the development-friendly land use policy in Taipei.

Calculating expected annualised direct economic losses

Table 2 summarises expected annualised direct economic losses, estimated using HAZ-Taiwan, resulting from the three hypothetical earthquake scenarios. The losses attributed to each earthquake event differ considerably as a result of the estimates of damage to buildings. The two most damaging events would be the earthquakes on the Shincheng fault and on the seabed off Yilan—with expected losses of over NT$128 billion and NT$122 billion, respectively.[9] The annualised expected losses resulting from these two earthquakes are just under NT$54 million and NT$140 million, respectively.[10] The predicted average annualised direct cost of the three earthquakes is around NT$77 million.

Figure 3 shows that the expected annualised cost of damage varies across the Shihlin District. It indicates that the areas facing the greatest losses are the Shihlin and Tianmu living-circles. Combining the data summarised in figure 2 with that in figure 3 demon-

Figure 3 Expected annualised direct economic losses resulting from an earthquake on the seabed off Yilan



strates that the areas facing the heaviest expected losses and the highest expected levels of damage to buildings are located in the centre of Shihlin District.

Olshansky and Wu (2001) suggests a damage-to-cost ratio as a convenient way of expressing the relative hazard to each Li. This is calculated as a ratio of the expected annualised direct economic losses to total replacement cost. It expresses annualised expected damage as a proportion of the Li's economic value. The results of the damage-to-cost estimates are given in table 2. The average value of the ratio is about 0.014%, meaning that the earthquake risk in Shihlin District is 0.014% of the total exposed building value. If earthquakes are not regarded as an important priority in Taipei, this number may not be large enough to persuade decision-makers to invest immediately in disaster-reduction measures.

An estimate of casualties

HAZ-Taiwan provides an output of estimated casualties consisting of a casualty breakdown by severity of injury as defined by a four-level injury-severity scale that runs from 'severity 1 (not requiring hospitalisation)' to 'severity 4 (killed instantly or fatally injured)'. Casualties are computed at Li level and aggregated to the whole study region. Table 3 indicates that the estimated casualty levels resulting from a Shitan fault event at 2 am are significantly lower than those for either of the other two hypothetical earthquake events striking at the same time of day. The average number of expected casualties of all levels of severity is 15,810, accounting for 5.4% of the total residents in Shihlin District. If such an earthquake were to strike, the number of casualties would be higher than in the Chi-Chi earthquake because the Shihlin District is located in the metropolitan area. The casualty estimates form the basis for emergency management and planning. Local planning for the post-disaster emergency health and medical services network, in particular, should be based on the information provided about the number of predicted casualties and their predicted severity.

Identifying vulnerable jurisdictions

Any evaluation of land use policies in developed areas should ensure that priority has been given to areas where it is most necessary for measures be adopted to reduce the levels of risk of damage and casualties caused by earthquakes. Identifying variations

Table 3 Estimates of casualties (persons)

Injury level	Sea off the Yilan	Shincheng fault	Shitan fault	Mean
Severity 1	13,437	14,145	10,136	12,573
Severity 2	2,663	2,808	1,985	2,485
Severity 3	404	426	299	376
Severity 4	404	426	299	376
Total	**16,909**	**17,805**	**12,719**	**15,810**

Table 4 Differences in characteristics among clusters

Variables	Comprehensive vulnerability	Focused vulnerability	Slight vulnerability	p value[c]
Population	6,070[a]	6,864 (1,663)[b]	5,316 (2,184)	0.04
Expected annualised earthquake losses	7.13 (NT$ millions)	2.29 (0.59) (NT$ millions)	0.93 (0.59) (NT$ millions)	0.00
Value of building stock	180 (NT$ millions)	6.45 (1.25) (NT$ millions)	2.50 (1.50) (NT$ millions)	0.00
Number of observations	1	18	31	

Notes
[a] Mean values
[b] Standard deviations in parentheses
[c] *p* values are for *F*-test among clusters

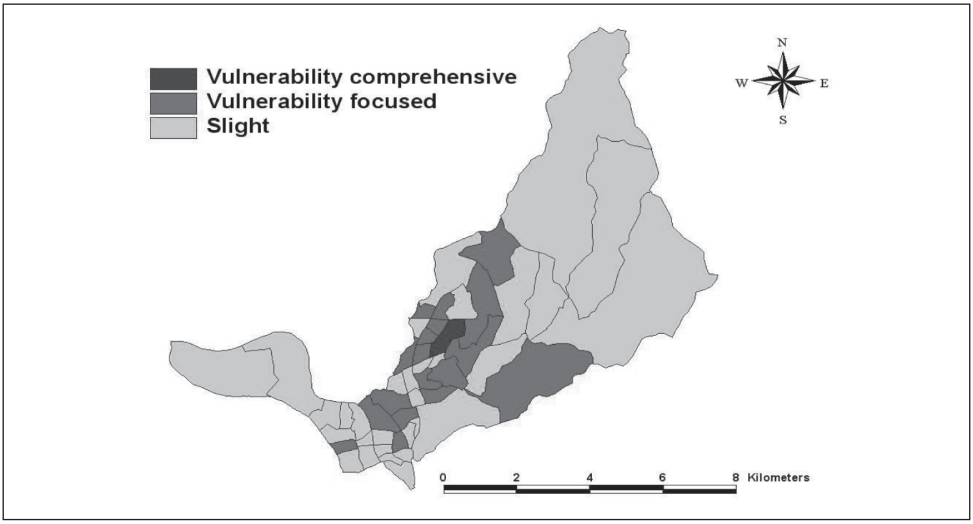
in vulnerability across jurisdictions is an important input to such evaluations. We employed cluster analysis to identify groupings of Lis with similar populations, expected annualised earthquake losses and values of exposure of the building stock to damage over the study areas. Lis in each cluster are broadly similar in terms of their vulnerability, while the clusters are diverse in terms of their overall earthquake vulnerability profile.

We used cluster analysis to identify three distinct clusters that we labelled 'comprehensive vulnerability', 'focused vulnerability' and 'slight vulnerability'. These labels are based on our interpretation of the data that describes each cluster. The group labelled comprehensive vulnerability is composed of the Lis that are relatively compact and densely developed. The focused vulnerability group has a somewhat lower value of exposed property and a lower level of expected economic losses. The Lis identified as slightly vulnerable are relatively slower growing areas of lower density development that might be less vulnerable than the comprehensive and focused clusters.

Table 4 shows the similarities and differences between the Lis that come under the three groups. While the Lis with focused vulnerability are less vulnerable than the comprehensively vulnerable Li, the average population of the 'focused' Lis is higher than that of the 'comprehensive' Lis. In order to gain a better understanding of the distribution of the groups, figure 4 illustrates the geographical location of the three clusters. The map demonstrates that the 'comprehensive' Li and most of the 'focused' Lis are located in the central part of the district. It also shows the areas that most require land use planning policies or relevant measures that reduce, or at least do not increase vulnerability.

As is indicated by the Shihlin District's current development, the most hazardous areas would be the central and south-western parts. These areas have a long history of development, were some of the earliest to be urbanised and are now highly urbanised. It is therefore likely to be a big challenge for city planners to redirect future development to less hazardous areas or to conduct a review of the master plan in order to

Figure 4 The distribution of clusters



reduce risk. Can city planners use an engineering-based risk analysis tool such as HAZ-Taiwan to assess the effects of earthquake risk mitigation measures such as undertaking a review of the master-plan and related policies? Like HAZUS, HAZ-Taiwan is not designed to evaluate land use policies. It therefore needs a methodology that can convert land use maps into a detailed building inventory that can then be used for the application of HAZ-Taiwan.

A comparative risk-benefit analysis of land use plans

Land use in the study area

The case study consists of three land use categories derived from maps of *existing*, *agreed* and *planned in outline* land uses. The maps of agreed and planned in outline land uses were obtained from the Department of Urban Development at the Taipei City Government (DUDTCG). The 2002 map of agreed land uses shows land uses projected to the year 2004. The planned in outline map shows projected developments to the year 2030. The DUDTCG also provided a detailed map of existing land uses, which provides a basis for comparative analysis in the study.

The three land use maps were first converted into detailed building inventories so they could be directly input into HAZ-Taiwan. We assumed that all land uses in the agreed and planned in outline land use maps were developed fully to the floor area ratios regulations contained in the Land Use Control Regulations of Taipei City. The land uses were then converted into a building inventory for each Li, which was designed to be compatible with the building occupancy categories of HAZ-Taiwan. For this purpose, the land uses on each map were generalised into six categories: a) agricultural use (*Ag*); b) residential use (*Re*); c) commercial use (*Co*); d) educational use (*Ed*);

Table 5 Comparison of the existing, agreed and outline planned building inventory (1000m^2) as well as population conditions

	Ag	Re	Co	Ed	In	Pu	Population
Existing	323	5,992	513	575	436	500	291,493
Agreed	323	12,021	2,824	575	835	2,840	406,816[d]
Planned [a]	323	11,648	3,090	778	662	2,689	394,087
Change 1[b]	0	-373	266	203	-173	-151	-12,729
Change 2[c]	0	5,656	2,577	203	226	2,189	102,594

Notes
Ag: agricultural; *Re*: residential; *Co*: commercial; *Ed*: educational; *In*: industrial; *Pu*: governmental and public
[a] Planned = Planned in outline (2030)
[b] Change 1 = Planned minus Agreed
[c] Change 2 = Planned minus Existing
[d] The population used for the Agreed and Planned in outline land use conditions is the planned population in the General City Plan of Taipei.

e) industrial use (*In*); and f) governmental and public uses (*Pu*). In order to obtain a more comprehensive evaluation of the risk-benefit impacts for each Li, and in contrast to standard analysis procedures, the population in the study was also considered when undertaking the risk-benefit analysis.

Table 5 compares the building inventory and population conditions in the maps of existing, agreed and planned in outline land uses. The study indicates that the changes in the study area between agreed and planned in outline land uses represent a 469,000 m^2 increase in the total building floor area for commercial and educational uses, and a 697,000 m^2 decrease in floor areas for residential, industrial, governmental and public uses. In total, there would be a 228,000 m^2 reduction in the total building floor area. If Shihlin District were to be fully built out based on the planning conditions in the planned in outline (2030) land use map, the total building floor area would increase by 10,851,000 m^2 compared to the map of existing land use. Table 5 also shows that the projected population in the outline plan is approximately 394,100 in contrast to the total in the plan of agreed land uses of 406,800—a difference of around 12,700.

Estimating the risk-benefit multiplier

The land development risk-benefit ratio can be applied to evaluate any change of land use in any Li. In order to estimate seismic risk, the ratio can be multiplied by the total change to the value of the building inventory for any proposed land use change. The importance of this is that it makes it possible to determine the risk-benefit multiplier for each Li for each type of building use. The risk-benefit multiplier is a quantitative description of each change in building-use category represented by the various land use maps.

Earthquake damage in each Li can be shown as:

$$Exloss = a_0 + a_1 Ag + a_2 Re + a_3 Co + a_4 Ed + a_5 In + a_6 Pu + a_7 Pop + e_1 \quad (3)$$

Table 6 OLS regression results for the risk-benefit models

Variables/models	Sea off Yilan	Shincheng fault	Shitan fault	Benefit
Constant	588033358 (1.50)[a]	581716152 (1.45)	246658707 (1.38)	-805194105 (-1.04)
RE	6742.15** (7.92)	6994.96** (8.02)	5189.74** (13.41)	25309.55** (15.12)
Co	7172.23** (4.92)	7617.60** (5.10)	5555.47** (8.38)	28129.27** (9.82)
In	9835.60** (3.39)	10182.43** (3.43)	6197.95** (4.70)	11949.92** (2.10)
Ag	-38612.23** (-3.28)	-40582.45** (-3.37)	-15919.47** (-2.98)	43248.68* (1.87)
Go	5225.54** (3.64)	5300.88** (3.60)	3425.18** (5.24)	27232.14** (9.65)
Ed	9596.37* (1.69)	10748.67* (1.79)	5346.22** (2.00)	29940.19** (2.59)
Pop	33306.36 (0.55)	51212.61 (0.82)	18638.49 (0.67)	93540.67 (0.78)
R^2	0.78	0.78	0.91	0.95
F values	22.21	21.19	58.53	135.76
Observations	50	50	50	50

Notes
[a] *t*-values in parentheses
* Significant at the 0.1 level
** Significant at the 0.05 level

where *Exloss* (in NT$), the dependent variable, denotes the total expected earthquake loss calculated by HAZ-Taiwan. *Ag*, *Re*, *Co*, *Ed*, *In* and *Pu* are building-use categories shown on the most recent (2002) land use map; *Pop* is population; $a_0, a_1, \ldots, a_6$ are coefficients; and e_1 is the error term.

Similarly, the urbanisation benefit to each Li can be presented as:

$$Bene = b_0 + b_1 Ag + b_2 Re + b_3 Co + b_4 Ed + b_5 In + b_6 Pu + b_7 Pop + e_2 \quad (4)$$

where dependent variable *Bene* (in NT$) is the total building replacement cost derived by HAZ-Taiwan, $b_0, b_1, \ldots, b_6$ are coefficients; and e_2 is the error term.

The results of the OLS (ordinary least squares) regression analysis are presented in table 6. All estimated coefficients of the models are significant at the 0.05 or 0.1 levels, apart from population. The results conform to expectations in that the categories *In*, *Ed* and *Co* present higher risks than the other categories. Only one variable—*Ag*, the most undeveloped building category—has a negative relationship with the expected earthquake losses. This implies that an increase in land use for agriculture will decrease the expected earthquake losses. As is shown by the estimates in the benefit model (equation 4), the categories *Ag*, *Ed* and *Co* are reflected by higher multipliers. In all four models, the coefficients of variable *Pop* are positive. This indicates that a higher number of residents is more likely to increase economic benefits but would also be associated with a higher level of seismic risk.

Annualised estimated earthquake risk-benefit analysis

A comparison of the earthquake losses between existing, agreed and planned in outline land use patterns, using the multipliers estimated by equation (3), is presented in table 7. Table 7 shows that the outline plan would lead to an average reduction in total damage of approximately NT$438 billion compared to the maps of agreed land uses. If the effect of changes to building use alone is considered, this reduces estimated total losses by about NT$1.02 billion. The total sum of the difference between the planned in outline land use map and the map of existing land uses is approximately NT$3,594 billion. If the effect of population change is ignored, the amount of expected losses associated with the outline plan would increase by NT$67 billion.

There is another way to consider the multipliers estimated for each Li using the damage and benefit models. In a similar way to the damage-to-cost ratio, we calculated a risk-benefit ratio of predicted annualised economic losses to estimated replacement costs (or urbanisation benefit). This ratio can be considered to be a measure of long-term probabilistic earthquake hazard in Shihlin District expressed as a monetary multiplier. For each of the land use categories, if land development value represents a key vulnerability when the land use plan is built out, the earthquake risk equals that hazard multiplied by vulnerability.

Table 8 summarises the estimates of expected earthquake losses and the risk-benefit ratio for the two land use plans (2004 and 2030). The table shows the average predicted annualised earthquake losses for the agreed plan and the outline plan to be approximately NT$91.4 million and NT$90.8 million, respectively—in contrast to the average under existing land uses of NT$77 million.

Comparing the outline plan with the agreed land use map shows a reduction in expected annualised earthquake losses of about 0.7 per cent. This is slightly larger than the reduction of 0.4 per cent in the total value of buildings in the outline plan. Moreover, about 0.04 per cent per year of the building value of NT$1.85 billon may be offset by reductions in future land use. Although the difference in the risk-benefit ratio between the planned in outline and the agreed land use plans is slight, the planned new development would be about 86 per cent more likely to be damaged than the agreed land use pattern.

Table 8 Comparison of expected earthquake damage between agreed (to 2004) and planned in outline (to 2030) land uses

	Expected earthquake loss (NT$ billions)	Mean of each Li	SD	Expected annualised earthquake loss (NT$ millions)	Expected benefit (NT$ billions)	Risk-benefit ratio
Agreed	133.80	2.68	1.29	91.43	461.92	0.0198%
Outline	132.81	2.66	1.23	90.75	460.07	0.0197%
Decrease	0.99	–	–	0.68	1.85	0.0368%

Table 9 Comparison of the expected changes to the earthquake damage and risk-benefit ratios between the planned in outline (2030) and agreed (2004) land use plans for 18 Lis

Li	Re (m^2)	Co (m^2)	In (m^2)	Ag (m^2)	Pu (m^2)	Ed (m^2)	Expected change of annualised earthquake damage (NT$ millions)	Expected change of annualised earthquake risk (NT$ millions)	Expected change to the risk-benefit ratio (%)
Sishan	1007	0	-3358	0	0	0	-22.99	-0.01	0.08
Tianshou	-64566	0	0	0	0	64566	146.58	0.1	0.02
Tianfu	-135362	0	0	0	0	135362	305.21	0.2	0.02
Lansing	0	-7979	0	0	10233	0	-6.52	-0.004	-0.01
Cueishan	-35827	-54292	-7781	0	-148052	0	-1,350.74.	-0.9	0.01
Desing	-9142	70549	-81810	0	0	0	-294.14	-0.2	-0.02
Fulin	0	1602	0	0	26600	0	134.57	0.1	0.01
Jioujia	-19422	19422	0	0	0	0	9.18	0.01	0.01
Yonglun	0	0	630	0	0	0	5.51	0.003	0.05
Shezi	0	-3996	0	0	-25420	0	-145.32	-0.1	0.01
Fude	-4544	72089	-80651	0	0	3314	-216.18	-0.1	-0.01
Renyong	-10151	16824	0	0	0	0	50.05	0.03	0.01
Yisin	-10515	20824	0	0	0	0	74.88	0.05	0.01
Shechin	-46168	46168	0	0	0	0	21.83	0.01	0.01
Hulu	-25677	25677	0	0	0	0	12.14	0.01	0.01
Chengde	-43560	97928	0	0	0	0	389.31	0.2	0.01
Fugung	0	0	0	0	-14381	0	-66.88	-0.04	0.01
Mingsheng	33649	-33649	0	0	0	0	-15.91	-0.01	0.01

Table 9 indicates the changes in the pattern of expected annualised earthquake damage under agreed and planned future land use patterns for 18 Lis (the other Lis are unchanged). Although it was expected that the level of annualised earthquake damage for several Lis would decline, a substantial amount of planned in outline development is located in Chengde, Yisin, Renyong, Jioujia, Shechin Li, and so on, where low-density residential land uses will be converted to high-density developments and commercial uses. Most of these areas are located in seismically highly hazardous regions. Thus the potential earthquake risk posed by the proposals in the outline land use map will have to be considered during the detailed development control process. The expected change to the risk-benefit ratio, shown in the table 9, shows the relationship between expected changes in the annualised value of earthquake damage to expected changes to development values. Where the risk-benefit ratio and the change to annualised earthquake damage risk are both negative—for example, in Lansing Li—this indicates that earthquake damage decreases while development value increases, which represents a decision to convert from higher seismically hazardous land use patterns to less hazardous land use patterns.

Conclusions

In developing nations the processes of local and community land use planning rarely use risk-based approaches to inform their decision-making. This study presents a method of risk-benefit analysis for evaluating land use policies that uses available land use maps and surveys and the HAZ-Taiwan earthquake loss estimation system. The analysis shows the earthquake damage, casualties and long-term annualised earthquake risk for the Shihlin District of Taipei. The estimated cost of earthquake damage is about NT$77 million per year. Cluster analysis identified vulnerable areas and indicates that the areas under the greatest threat and requiring vulnerability reduction measures are located in the central part of Shihlin. The average number of predicted casualties of all levels of severity is over 15,800, accounting for 5.4 per cent of the population of the study area.

We also compared expected earthquake damage between existing, agreed and future land uses, using a combination of the general city plan land use maps of whole Lis and maps of the living-circles in the case study area. We calculated a risk-benefit ratio using multipliers derived from earthquake damage and development benefit models to express the relationship between average expected earthquake damage and the value of urbanisation. Ignoring the effect from population, the predicted annualised earthquake losses under the planned in outline future land use pattern is about NT$90 million, against the average for the agreed land use plan of NT$91 million. The expected average annualised earthquake losses are thus calculated to decrease by approximately NT$1 million per year by adopting the 2030 outline plan.

Ever increasing disaster risks make sustainable urban growth or invulnerable development the key issue in Asian metropolitan development processes (Bankoff, 2003).[11] This demands the urgent incorporation of risk-based planning mechanisms into land use decision-making processes (Anderson and Woodrow, 1991). Based on the concept of risk, this mechanism implies that the impacts of each land use decision cannot be fully determined *ex ante*. However, exploring an available risk-benefit approach forms a basis for providing information about the specific risks attached to various land uses in different areas. It is crucial that planners apply such tools to steer urban growth away from particularly hazardous or risky areas. The findings of risk-benefit analysis can also provide supporting information to evaluate identified risk management strategies.

This paper demonstrates that earthquake risk analysis is not limited to current monetary or even current values. It refers to casualties and residents' perceptions of hazards and of risk as well as other possible effects that would stem from seismic hazard (Mileti, 1999). While a monetary risk analysis is easy to apply and to understand, risk analysis should be conducted using a more comprehensive approach that takes account of many criteria. More research and technology development are needed in this area. Taking account of public participation, as well as public opinion, preferences and perceptions, in the risk analysis and risk management processes is particularly important and should form a central part of future studies (Pavlikakis and Tsihrintzis, 2003).

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Endnotes

1 See Deyle et al. (1998) and Olshansky and Wu (2001) for a detailed definition of the terms risk, hazard and vulnerability.

2 Deyle et al. (1998) suggests that hazard assessment could be conducted at three different levels of sophistication: hazard identification, vulnerability assessment and risk analysis.

3 The Chi-Chi earthquake occurred on 21 September 1999. It was one of the largest on-land earthquakes to occur in Taiwan in the 20th century, killed 2,417 people and caused 11,305 injures. The earthquake resulted in the collapse of 10,366 homes and extensively damaged another 14,720 (Wu and Lindell, 2004).

4 Concepts such as 'sustainable hazards mitigation' and 'invulnerable development' are incomplete because they may fail to recognise the importance of vulnerability or the multiple disciplines related to disaster management. In order to overcome these drawbacks, McEntire et al. (2002) proposes a new

concept of 'comprehensive vulnerability management' that is defined as holistic activities directed to the mitigation of disasters by decreasing risk and susceptibility and building resistance and resilience. This concept provides a more holistic approach that could help to reduce vulnerability and risk to earthquake as land development proceeds.

[5] HAZUS is a model developed by the US Federal Emergency Management Agency to predict the effects of hypothetical earthquakes.

[6] HAZ-Taiwan follows basically the same approach employed in HAZUS. However, minor modifications to the analysis model and parameters have been made to accommodate the local environment and engineering practices in Taiwan (Yeh et al., 2003).

[7] Replacement costs are widely used as an estimate of loss or dollar exposure for a given occupancy and building type in each census area (Olshansky and Wu, 2001). The replacement costs in HAZ-Taiwan are estimated as the product of the floor area of each building type in a given occupancy.

[8] In HAZ-Taiwan estimates of building damage due to ground shaking are presented as the probability of being in or exceeding a particular damaged state. This damaged state varies from 'none' to 'complete' as a continuous function of building deformation.

[9] The New Taiwan Dollar (NT$) is convertible with US Dollars at an exchange rate in 2006 of NT$1 = US$0.03.

[10] Expected annualised losses are calculated by multiplying the total expected loss by the probability of earthquake occurrence.

[11] McEntire (2000) defines invulnerable development as 'development pursued in such a manner as to address vulnerability'. Thus, a more holistic and different view provided by McEntire is that invulnerable development is a process that attempts to reduce risk through liability reduction and capacity building. In pursuit of invulnerable development, tasks should include: a) adjusting cultural attitudes to disasters; b) connecting development practices with vulnerability mitigation; and c) establishing emergency management institutions (McEntire et al., 2002).

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