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Urban Disaster Prevention Shelter Vulnerability Evaluation Considering Road Network Characteristics

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Abstract: Large-scale national disasters have recently occurred worldwide, causing tremendous damage to life and property. Therefore, urban safety has become a critical issue, and disaster prevention and mitigation are also considered in urban development and infrastructure construction. When earthquake disasters occur, road networks play major roles in rescue activity for responding to urban damage. The urban-disaster prevention spatial system attempts to mitigate hazards by considering shelters, routes for evacuation and rescue and necessary logistics. A literature review shows numerous studies related to a disaster-prevention shelter survey before or after hazards, however, they are less concerned with the reliability of shelter evaluation. This study assesses shelter evaluation by considering road networks. The authors construct 10 selected indices individually related to road networks. Three integrated composite indices are established to explain planned-shelter risks using the Arc GIS diagram of a spatial concept of an urban-planning review process. The relationship between shelters and evacuation/rescue routes is important for disaster-prevention planning. This survey investigates the factors of road networks, fire engine rescue routes, fire station location and road/population density for vulnerability evaluations.

Key words: Geographic information system, urban safety, road networks, shelter.

Nomenclature

Shelter	Names
S-1	National Sun Yat-sen University
S-2	Chung-HWA School of Arts
S-3	Gushan Senior High School
S-4	Dah Yung Senior High School
S-5	St. Paul's High School
S-6	Shou Shan Junior High School
S-7	Jiourn Primary School
S-8	Ku Yen Elementary School
S-9	Nei Wei Primary School
S-10	Chung Shan Elementary School
S-11	Gushan Elementary School
S-12	Shou Shan Primary School
S-13	Lung Hua Primary School

1. Introduction

Great earthquakes cause huge damage to human life and property. In 1999, the 921 great earthquake fiercely damaged the central part of Taiwan, which exhibited insufficient preparation in urban disaster prevention. In the quake aftermath, numerous rescue works were conducted. However, the damaged road network made rescue operations difficult and hazardous for the first 72 hours. Urban safety has been an important subject in urban planning and development. Preparing a disaster prevention plan necessitates additional land development projects. Because most planning issues focus on the rural system and immediate rescue, official urban planning requests current disaster prevention plans. However, a static plan is necessary for periodic review, and monitoring indexes should also verify disaster-prevention ability. In this study, the authors establish an easy review process on urban-shelter planning of the fire station-rescue optimum location. Ten independent indexes are selected as three composite indexes. The surveyed area is located in Gushan District, Kaohsiung City. The urban emergent shelters for temporary evacuation are filed and

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retrieved in Arc GIS. The evaluation results in CI-1-CI-3 are shown in a visual map and can be reviewed in urban-disaster planning.

2. Literature Review

Urban-road network efficiency changes following an earthquake because of road damage caused by collapsed buildings and blockage. Therefore, disaster-resilient urban planning is critical. Tsukaguchi et al. [1] conducted a survey after the Great Hanshin-Awaji Earthquake and applied a discriminate model to verify the causes of road closure. They also developed a simulation model to improve different network structures of road network design. Odani et al. [2] analyzed traffic conditions immediately after the Great Hanshin-Awaji Earthquake, considering not only the main roads, but other minor roads that suffered serious damage. Lee et al. [3] surveyed after the 921 Great Earthquake and found that a street width less than 4 m was the main cause for road closure after earthquakes in Taiwan. Chen et al. [4] combined reliability and uncertainty analysis, network equilibrium models and sensibility analysis of an equilibrium network flow to assess the performance of a degradable road network. Hongo et al. [5] considered the local characteristics of rich cultural heritage sites in Kyoto, using the road network viewpoint on 10 independent indexes and three composite indexes, as a useful tool for road network improvement.

GIS technology is appropriate for various usages including resource management, land surveying and business planning. GIS is a computer system capable of assembling, storing, manipulating, analyzing and displaying geographically referenced information (i.e., data identified according to locations, U.S. Geological Survey [6]) and can use digital mapping technology to provide options for decisions. Practitioners increasingly rely on the total GIS solution. GIS is used more often than other information systems by enabling both spatial and non-spatial data, leading to its specific roles in data management and integration, data query and analysis and data visualization [7]. The GIS system combines spatial and non-spatial data to construct thematic maps for communicating complex geographic information that can not be worked in tables or list forms.

The study of Kates [8] on evacuation behavior found that earthquake damage to buildings, bridges, and roads destroyed after quakes hampered evacuation to shelters in varying degrees. Lindell et al. [9] examined the relationships of the self-reported adoption of 12 seismic hazard adjustments (pre-impact actions to reduce danger to persons and property) with respondents' demographic characteristics, perceived risk, perceived hazard knowledge, perceived protection responsibility and perceived attributes of the hazard adjustments. Kimura et al. [10] considered evacuation behavior and found that following shocks over 6.7 on the Richter scale, 30% of people decided to evacuate to designated shelters. Ayis et al. [11] selected 999 people over 65 years of age to study the mobility of the aged and found lower mobility and poor perceived health. Mobility significantly (and negatively) related to over 70 years of age. Tai et al. [12] explained four possible actions related to the spatial decision concerning disaster prevention Ⅰ. Shelters help reduce risks and meet evacuation needs Ⅱ and Ⅲ. Disaster prevention provides an efficient way to meet both requirements Ⅳ. Providing disaster prevention information raises disaster preparedness in people.

3. Model

In this study, the authors evaluate shelter accessibility by considering road network systems. For evacuation, quake shelters are located as near as possible to residents. However, shelters should consider safety without road blockage and fire station rescue efficiency. Hongo et al. [5] considered local characteristics of the rich culture heritage in Kyoto and used the road network viewpoint in 10 independent indexes and three composite evaluation indexes. Therefore, in this study, the authors modify certain index contents for applying to the evaluation of the urban-area evacuation shelter. Each index is explained as the following:

X_1: Road width > 8 m, fire station to shelter shortest route;

X_2: Road width > 15 m, fire station to shelter shortest route;

X_3: Road width > 20 m, fire station to shelter shortest route;

X_4: Shelter field area to road width > 8 m shortest route;

X_5: Shelter field area to road width > 15 m shortest route;

X_6: Shelter field area to Road width >20 m shortest route;

X_7: Network distances/linear distance (fire station to shelter) = X_7/shortest distance between fire station to shelter;

X_8: Urban planning road ratio (urban planning road area/urban area);

X_9: Neighborhood urban planning road ratio (neighborhood urban planning road area/shelter located in neighborhood area);

X_{10}: Shelter located in neighborhood population density.

For comprehensive analysis, the authors further integrated the 10 indexes as three CIs (composite indexes) for comparison.

CI-1:

$$Y = \frac{X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9 + X_{10}}{10}$$

applied the additive rule considering the substitution relationship of indexes.

CI-2:

$$Y = X_1 \times X_2 \times X_3 \times X_4 \times X_5 \times X_6 \times X_7 \times X_8 \times X_9 \times X_{10}$$

applied the multiply rule considering the independent relationship of indexes.

CI-3:

$$Y = \frac{X_1 + X_8}{2} \times X_2 \times X_3 \times \frac{X_4 + X_9}{2} \times X_5 \times X_6 \times X_7 \times X_{10}$$

considering substitution of X_1 and X_8, X_4 and X_9 using the additive rule and integration using the multiply rule.

4. Results and Discussions

4.1 Data Collection

In this study, the authors selected elementary schools, junior high schools, senior high schools and universities as shelter candidates in Gushan District, Kaohsiung City. The authors then considered using a field facility for temporary evacuation and camping. Classrooms, offices and kitchens can be used for daily necessities and logistic managements. All shelter locations in the surveyed area are represented in Fig. 1.

The collected independent index data are shown in Table 1. The authors further define the index evaluation criteria as follows:

(1) Index X_1-X_3: The shortest distance between the fire station and shelters in Gushan District is 5,940 m. The criterion is assumed as 6,000 m;

(2) Index X_4-X_6: Considering the reasonable distance of shelters to the nearest link greater than 8 m width is as near as possible. The criterion is assumed as 1,000 m;

(3) Index X_7: Ratio of actual distance to the nearest linear distance;

(4) Index X_8-X_9: Ratio of ward road area to urban planning area in Kaohsiung City;

(5) Index X_{10}: Ratio of shelters located in neighborhood population areas.

4.2 Safety Evaluation of Shelters

Deriving from Table 2, Table 3 is using the composite index definition. The composite index scale range is from 0 to 1. The smaller figures mean the evaluation result is safer, and vice-versa. Finally, the authors apply the Arc GIS for visualization of CI-1-CI-3. Relative safety can be judged and the candidate sites easily estimated. The evaluation results are illustrated in Figs. 2-4 and discussed as follows.

Fig. 2 shows that S-1 (National Sun-Yat-Sen University) is far from the fire station in Gusun District and in potential danger after the quake. However, S-1 is also near to a mountain (Shou Shan)

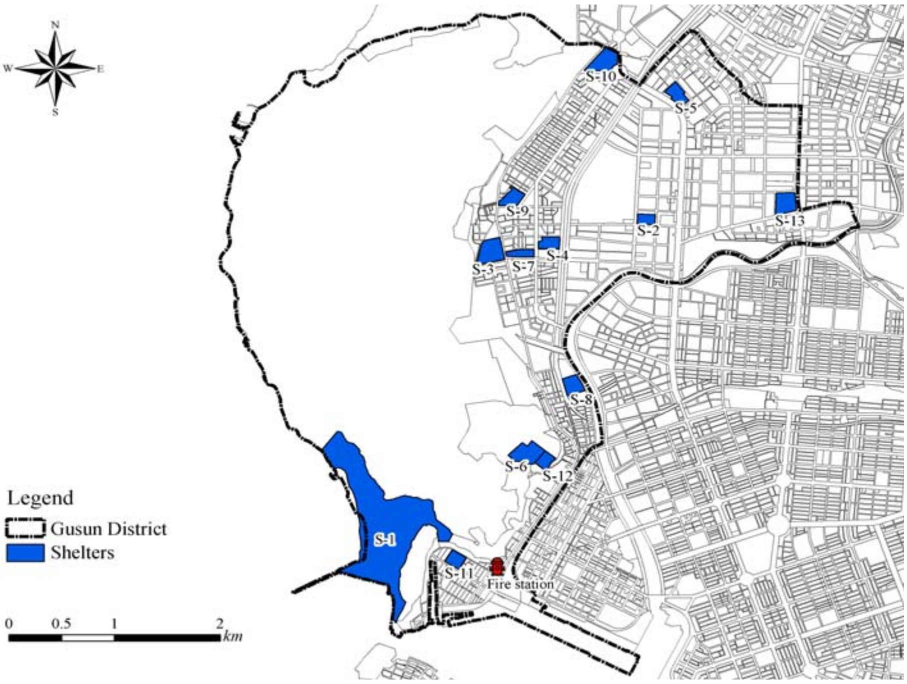

Fig. 1 Shelters (school facility).

Table 1 Evaluation data of each shelter.

Index	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13
X_1	2,606.83	4,707.31	3,421.28	3,892.50	5,956.79	1,509.87	3,855.87	2,345.60	4,186.00	5,968.00	634.11	1,272.24	5,700.95
X_2	2,735.48	4,738.44	3,893.10	4,023.47	5,956.79	1,632.49	3,855.87	2,434.95	4,315.90	5,968.00	706.98	1,314.60	5,700.95
X_3	3,623.03	5,579.25	3,893.10	4,023.47	6,644.24	1,861.24	3,855.87	2,637.98	4,395.07	5,968.00	1,067.66	1,314.60	6,756.89
X_4	128.65	31.13	118.62	125.74	111.61	122.62	52.66	70.11	81.84	111.35	68.13	65.86	50.08
X_5	156.98	31.13	150.82	130.97	111.61	235.32	52.66	89.35	129.90	111.35	72.87	223.05	50.08
X_6	1,089.23	400.53	150.82	130.97	111.61	381.37	52.66	292.38	209.92	111.35	433.54	223.05	1,056.89
X_7	2,606.83 1,016.20	4,707.31 3,777.69	3,712.28 3,048.12	3,892.50 3,312.35	5,956.79 5,003.48	1,509.87 1,077.40	3,855.87 3,209.15	2,345.60 2,010.60	4,186.00 3,624.47	5,968.00 5,084.93	634.11 435.37	1,272.24 1,087.70	5,700.95 4,591.03
X_8	Road area:1,420,123.59 m^2	Ward area: 20,638,246.06 m^2			Urban planning area:19,218,122.47 m^2								
X_9	1,092,450.58 3,686,921.06	1,437,957.55 1,884,344.38	268,412.32 2,748,493.10	129,410.51 200,413.94	237,229.17 238,871.38	719,213.74 1,271,358.90	134,066.76 179,721.93	140,386.62 254,175.23	123,716.06 163,170.36	205,733.78 223,999.76	97,462.31 222,196.51	719,213.74 1,271,358.90	1,122,917.96 1,373,234.97
X_{10}	6,325.35	4,354.26	894.91	17,310.00	27,630.77	2,724.73	23,372.22	15,590.27	18,037.50	12,190.91	8,872.73	2,724.73	7,837.23

Remark: ① X_1-X_7: m, ② X_8-X_9: m^2, ③ X_{10}: person.

Table 2 Independent index results of each shelter.

Facility CI	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13
X_1	0.43	0.78	0.57	0.65	0.99	0.25	0.64	0.39	0.70	0.99	0.12	0.21	0.95
X_2	0.46	0.79	0.65	0.67	0.99	0.27	0.64	0.41	0.72	0.99	0.12	0.22	0.95
X_3	0.60	0.93	0.65	0.67	1.11	0.31	0.64	0.44	0.73	0.99	0.18	0.22	1.13
X_4	0.13	0.03	0.12	0.13	0.11	0.12	0.05	0.07	0.08	0.11	0.07	0.07	0.05
X_5	0.16	0.03	0.15	0.13	0.11	0.24	0.05	0.09	0.13	0.11	0.07	0.22	0.05
X_6	1.09	0.40	0.15	0.13	0.11	0.38	0.05	0.29	0.21	0.11	0.43	0.22	1.00
X_7	2.57	1.25	1.22	1.16	1.19	1.40	1.20	1.17	1.15	1.17	1.46	1.17	1.24
X_8	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
X_9	0.57	0.76	0.10	0.65	0.99	0.57	0.75	0.55	0.76	0.92	0.64	0.57	0.82
X_{10}	0.64	0.44	0.09	1.75	2.8	0.28	2.37	1.58	1.83	1.24	0.90	0.28	0.79

Table 3 Composite index results of each shelter.

Facility CI	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13
CI-1	0.758	0.634	0.463	0.687	0.933	0.475	0.732	0.592	0.724	0.756	0.492	0.411	0.791
CI-2	0.00235	8E-05	6.6E-06	0.00079	0.00444	4.8E-05	6.5E-05	0.00012	0.0012	0.0016	4.3E-06	6E-06	0.0019
CI-3	0.01884	0.00164	8.6E-05	0.00474	0.02339	0.00061	0.00091	0.00178	0.01034	0.00851	0.00016	0.00014	0.0215

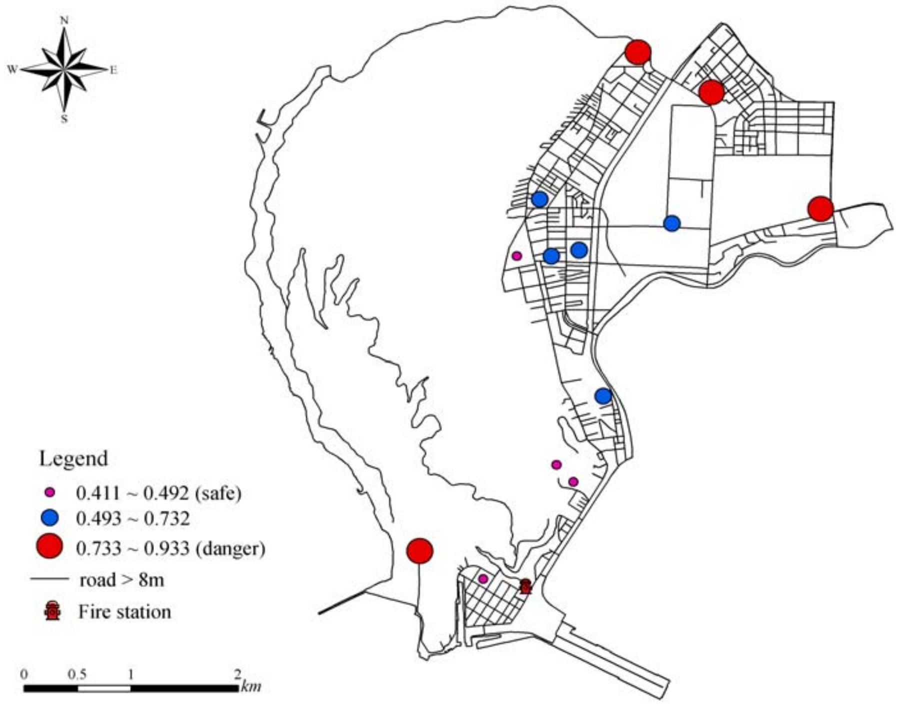

Fig. 2 CI-1 results.

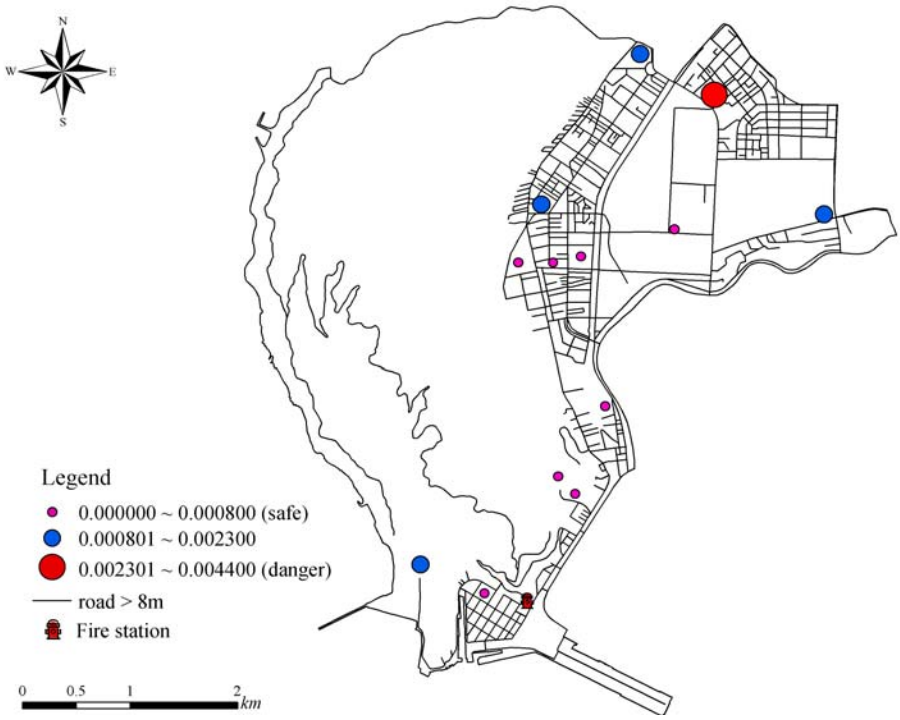

Fig. 3 CI-2 results.

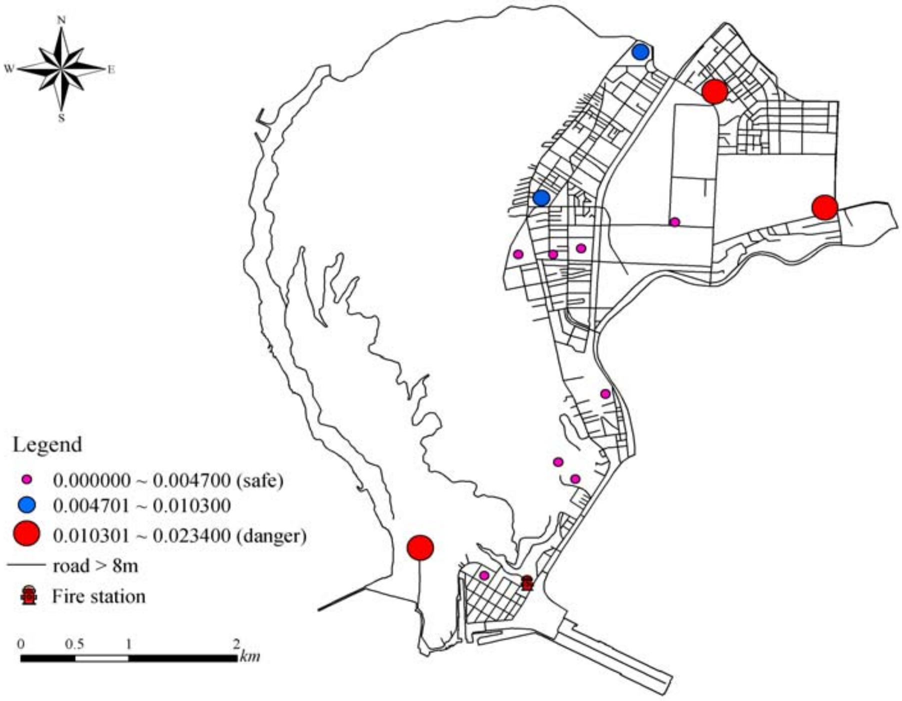

Fig. 4 CI-3 results.

and connectivity is limited in only one path (8 m— width). Therefore, the risk of links makes the rescue more difficult.

Fig. 3 shows that S-5 is more dangerous because: (1) The local road area is relatively lower than the others; (2) The population density is higher than the others. Therefore, it is necessary to further consider.

Finally, CI-3 shows that S-1, S-5 and S-13 are more dangerous because the urban planning road ratio is lower than in other districts. Blockage of the road network and connectivity require review.

5. Conclusions

Residents are required to evacuate after an earthquake and planned shelters should be reviewed in advance for safety. Several types of evaluation methods can be used for quake resistance. However, the planning basics are the efficient performance of road networks following an earthquake. This study mainly focuses on road network connectivity to the rescue location and the results are as follows:

(1) CI-1 shows the more dangerous shelters to be S-1, S-5, S-10 and S-13. The long distance of S-5, S-10 and S-13 from the fire station could be improved by relocating or re-establishing the fire station. However, S-1 is more difficult to improve because the landscape is not a recommended location for a shelter;

(2) CI-2 shows that S-5 needs more consideration because of the long distance to the fire station and high density. The community disaster-prevention plan will consider improving this situation;

(3) CI-3 shows that S-5, S13 and S-1 are more dangerous because of a lacking road area in this district. Road network blockage should be reviewed using other methods to reduce the probability of road closures after earthquakes.

Finally, this study considers the road network and applies a simple composite index to explain the complex situation in an earthquake occurrence. However, the results ignore certain factors that further studies could add and improve.

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