SEISMIC VULNERABILITY ANALYSIS OF EXPOSURES BY MESH-BASED SCENARIO SIMULATION AND APPLICATION ON POLICY SUPPORT

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Abstract

The disaster vulnerability has increased in the past two decades because of population concentration and complicate infrastructures constructed in urban areas. If a catastrophic earthquake occurred near metropolitan cities, the induced casualty and loss would be more extensive than those in the 1999 Chi-Chi earthquake. Therefore, the seismic vulnerability of exposures subjected to large-scale earthquakes under current environment conditions in metropolitan cities should be evaluated for disaster management. Based on variety of inventory database collected from government agencies, we developed a mesh-based scenario simulation tool: Taiwan Earthquake Impact Research and Information Application Platform (TERIA). TERIA is capable of disclosing vulnerable exposures (casualty, buildings and infrastructures) and their spatial distribution of damages interpreting in 500 m x 500 m meshes on interactive interfaces. We integrate analytical results in terms of major theme maps to explore the correlation of impact issues, including emergency rescue and medical care, evacuation and shelter, and governmental operation affected by damages of buildings, transportation and lifeline systems. Our research accomplishment has been submitted to the Disaster Prevention and Protection Expert Consultation Committee, the Executive Yuan to formulate policy suggestions for making cities resilient. The quantitative impact analysis by scenario simulation in details could be helpful to elaborate a more thorough mitigation planning for enhancing the disaster resilience against future major earthquakes.

Keywords: earthquake, vulnerability analysis, scenario simulation, policy support

1. Introduction

As located on the subduction zone between the Philippine Sea Plate and the Eurasia Plate, more than a dozen of disastrous earthquakes struck Taiwan in the past century. Figure 1 displays locations of 14 disastrous earthquakes and the population distribution in 500 m x 500 m mesh. Approximately 70% of the population (23 million in total) clusters in 6 metropolitan cities in the western plain areas. In case of an earthquake with magnitude greater than 7.0 occurred in the western plain areas, it would cause sever casualty and damages, such as the Meishan earthquake in 1906 (M_L=7.3, 1,258 death), the Hsinchu-Taichung earthquake in 1935 (M_L=7.1, 3,276 death), and the Chi-Chi earthquake in 1999 (M_L=7.3, 2,415 death). In recent decades, the disaster vulnerability in urban areas has risen because of population concentration and complex infrastructures constructed in Taiwan. Two major earthquakes, 2016 Meinong earthquake (M_L=6.6, 117 death) and 2018 Hualien earthquake (M_L=6.2, 17 death) reminded us the potential seismic threat to Taiwan. Therefore, the seismic resistant capacity subjected to large-scale earthquakes under current environment conditions should be evaluated for disaster mitigation planning.

To reduce the disaster impact, central ministries formulated the Operation Plans of Disaster Prevention and Response for each type of disaster following the Disaster Prevention and Response Act issued in 2000. Local governments drew up the Local Plan of Disaster Prevention and Response covering each specified disaster. City/county governments carried out scenario simulations to analyze possible damages subjected to specific earthquake sources in the Local Plan of Disaster Prevention and Response. However, the analytical results were interpreted based on individual exposure without considering the interaction effect among damages of multiple exposures. Therefore, we propose three kinds of major theme maps, i.e., emergency rescue and medical care, evacuation and shelter, and government operation, to reveal the impact on the these issues resulting from damages of buildings, roads and bridges, and lifeline systems which are informative for effective mitigation planning under limited resources.

No.	Earthquake	Date	Magnitude (M_L)	Depth (km)	Casulties	
					Ceased	Injured
1	Douliou	1904/11/06	6.1	7.0	145	158
2	Meishan	1906/03/17	7.1	6.0	1,258	2,385
3	Nantou Series	1916/08/28	6.8	45.0	71	285
		1916/11/15	6.2	3.0		
		1917/01/05	6.2	0.0		
		1917/01/07	5.5	0.0		
4	Hsinchu-TaiChung	1935/04/21	7.1	5.0	3,276	12,053
5	Chungpu	1941/12/17	7.1	12.0	358	766
6	Hsinhua	1946/12/05	6.1	5.0	74	182
7	Longitudinal Valley Series	1951/10/22	7.3	4.0	>85	>1,000
		1951/10/22	7.1	1.0		
		1951/10/22	7.1	18.0		
		1951/11/25	6.1	16.0		
		1951/11/25	7.3	36.0		
8	Hengchun	1959/08/15	7.1	20.0	17	85
9	Paiho	1964/01/18	6.3	18.0	106	653
10	Hualien	1986/11/15	6.5	15.0	13	45
11	Chi-Chi	1999/09/21	7.3	8.0	2,415	11,305
12	Tauyuan	2010/03/04	6.4	5.0	0	96
13	Meinong	2016/02/06	6.6	14.6	117	551
14	Hualien	2018/02/26	6.2	6.3	17	291

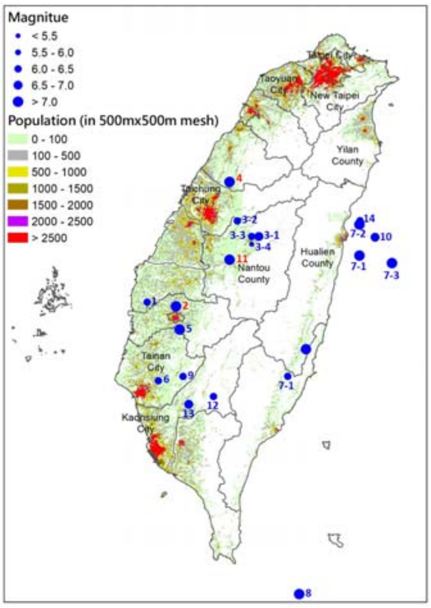


Fig. 1 – Major earthquakes and population distribution in Taiwan

2. Earthquake scenario simulation tool

With the adoption of the Sendai Framework for Disaster Risk Reduction 2015-2030, the United Nations Office for Disaster Risk Reduction (UNDRR, formerly known as UNISDR) published "The Ten Essentials for Making Cities Resilient" guiding local governments to strengthen their capacities and build resilience against disasters [1]. In Essential 2: Identify, Understand and Use Current and Future Risk Scenarios, local government should identify probable and worst case risk scenarios, carry out risk assessment, and use them for response and recovery plans. To evaluate the seismic capacity of exposures, we proposed the risk assessment methodology consisting of scenarios in two levels: (1) Extreme scenario: quantitative analysis in an extreme scenario to examine the disaster resilience of organizations; (2) Operative scenario: scenario simulation in various levels of excitations to identify weak items and their damage distribution which can be applied to local mitigation plans to enhance the capability against disasters, as shown in Figure 2.

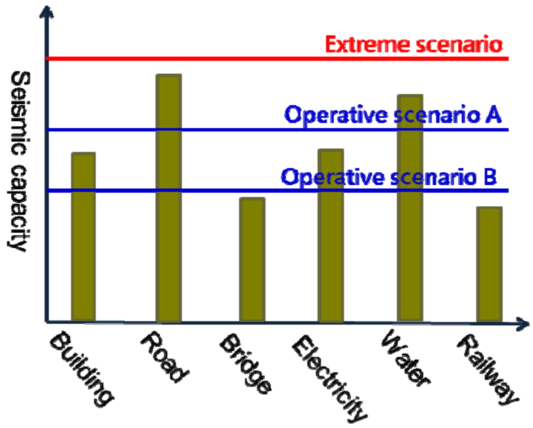


Fig. 2 – Evaluation for seismic capacity of exposures using scenario simulation tools

We build the Taiwan Earthquake Impact Information Platform (TERIA) using the state-of-the-art analysis techniques based on the inventory database by mutual cooperation among the academic institutions and governmental agencies (Figure 3). Considerable efforts were devoted to construct the inventory database, including building, population, infrastructure, and lifeline system. The TERIA can analyze the ground motion response, potential of liquefaction and landslide, casualty, damages of buildings, roads, bridges, electricity, and portable water facilities. We used fragility curves to estimate possible damages of buildings and facilities [2], [3]. The analytical results in a 500 m × 500 m mesh at different layers can be integrated to interpret the disaster scenario in details.

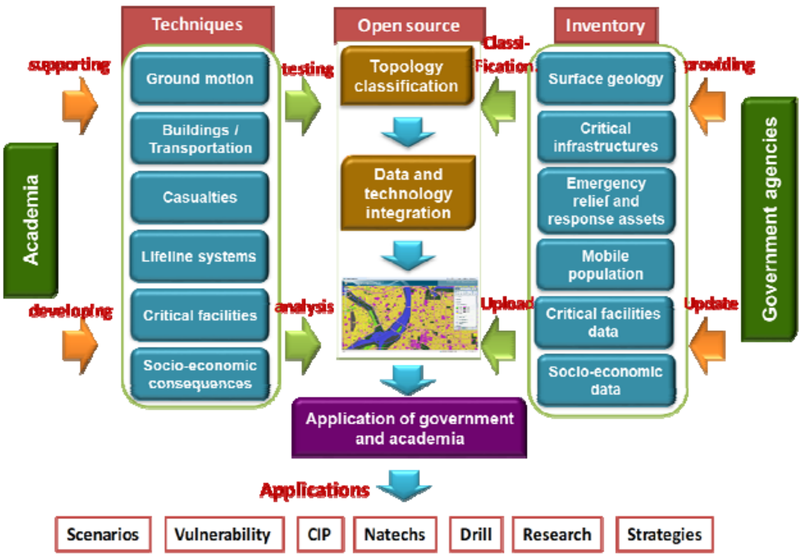


Fig. 3 – TERIA platform framework

3. Major theme maps for disaster mitigation planning

After an earthquake occurred, emergency rescue and medical care, evacuation and shelter, government operation are three priority tasks during emergency operation. However, to deploy these tasks may be affected by transportation interruption, building damage, and malfunction of lifeline systems, as the correlation shown in Figure 4. We adopted the large-scale earthquake scenario simulation results for northern Taiwan and propose three major theme maps for disaster mitigation planning as following.

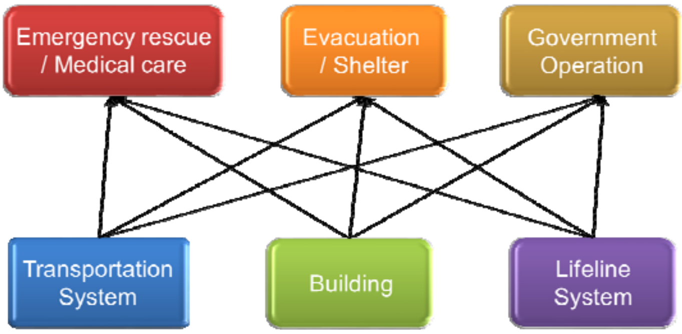


Fig. 4 – Major theme maps to interprete the correlation of impact issues

3.1 Large-scale Earthquake Scenario Simulation for Northern Taiwan

Based on the minutes of the 36th meeting of the Central Disaster Prevention and Response Council in 2017, a task force "Scenario Simulation for Large-scale earthquakes" was launched to explore possible seismic impact to urban areas. The Ministry of Science and Technology is in charge of the Earthquake Source Team and Loss Estimation Team, and the Ministry of the Interior organizes the Countermeasure Team including representatives from central ministries, Taipei city, New Taipei City, Keelung city, and Taoyuan city governments. The Earthquake Source Team chose the Shanchiao fault as the earthquake source and determines the magnitude (M_w=6.6), and fault parameter (strike=24°, dip =65°, slip= -90°). With the digital topography data and three dimensional underground velocity model, wave propagation by means of finite difference method was performed to obtain the seismic response at the engineering bedrock (V_s=760 m/sec). Consequently, the Loss Estimation Team calculated the ground response in consideration of site effect. Figure 5 shows the distribution of peak ground acceleration (PGA). The maximum PGA exceeds 800 gal and the ground response on the Intensity Level 7 (PGA>400 gal) covers 19 districts in four cities/counties.

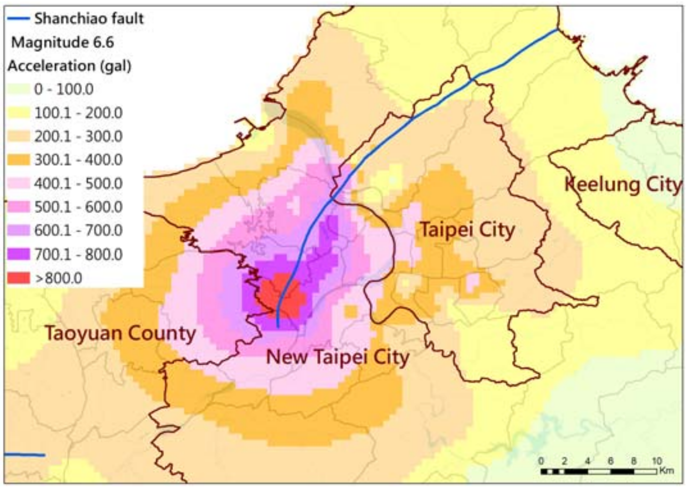


Fig. 5 – Distribution of peak ground acceleration for the Shanchiao fault simulation

3.2 Major theme maps for emergency rescue and medical care

We analyzed the casualty, shelter demand, and damages of buildings, roads, bridges, potable water and power systems resulted from the ground shaking. Integration of various analytical items could elaborate the interdependent relationship among impact issues. Figure 6 illustrates the distribution of building damage in the mesh of 500 m × 500 m. Serious building damage were found in the red area because majority of them were built more than 30 years. From the photos taken in the field, narrow laneways could be obstacles to emergency rescue in these areas.

Fig. 6 – Building damage and the impact to emergency rescue

Table 1 lists the estimated casualty in various degrees of injury for 4 cities. We defined the sum of moderate injury (a) plus serious injury (b) is the hospitalization demand, denoted as (a+b). Because hospitals have their regular bed demand for patients, only approximate 10%[1] of beds in hospitals may be available for emergency operation, which can be regarded as the supply for hospitalization. Therefore, the difference between supply and demand for hospitalization were calculated in Table 1, denoted as (c-a-b). The shortage of hospitalization for New Taipei City and Taipei City are -2,307 and -297, respectively. Even though there are some surplus of hospitalization for Taoyuan city and Keelung city, the total amount of available beds is insufficient to balance the hospitalization demand (shortage as -1,495). Outbound transportation to other cities are required for injury patients. Some impact issues are described as following:

1. Emergency rescue affected by transportation interruption: To dispatch rescue teams to the most serious areas or transport injury people to other districts may be interrupted because some outreach bridges are in high or medium risks of closure for transportation (Figure 6).
2. Medical care influenced by power failure: Some substations are seriously damaged and majority of distribution circuit is under moderate to serious damages in Sinjhang district, as shown in Figure 7(a). Power failure may last for several days which would affect the medical operation in this region.
3. Medical care influenced by malfunction of portable water system: Most of the treatment plants, pumping stations, and distribution pipes are subjected to moderate damage. Shortage of portable water for a couple of days may influence the medical operation in this region.

[1] Suggestion from the Disaster Prevention and Protection Expert Consultation Committee, the Executive Yuan (2016).

Table 1 – Hospitalization demand and supply

City	Minor injury	Moderate injury (a)	Serious injury (b)	Death	Hospitalization demand (a+b)	Available beds (c)	Supply-Demand (c-a-b)
New Taipei city	5,039	2,185	1,389	971	3,574	1,267	-2,307
Taipei city	3,510	1,460	900	660	2,360	2,063	-297
Taoyuan city	515	181	107	73	288	1,185	897
Keelung city	10	5	1	1	6	218	212
Summary	9,074	3,831	2,397	1,705	6,228	4,733	-1,495

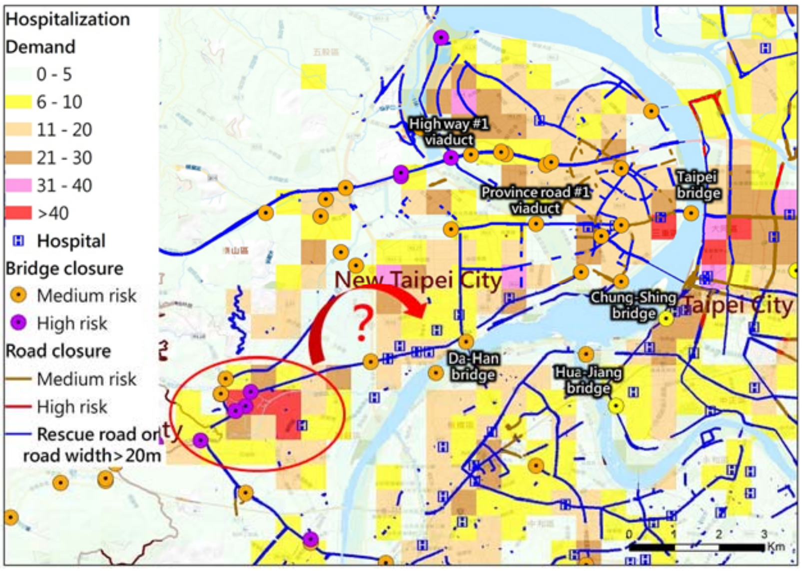
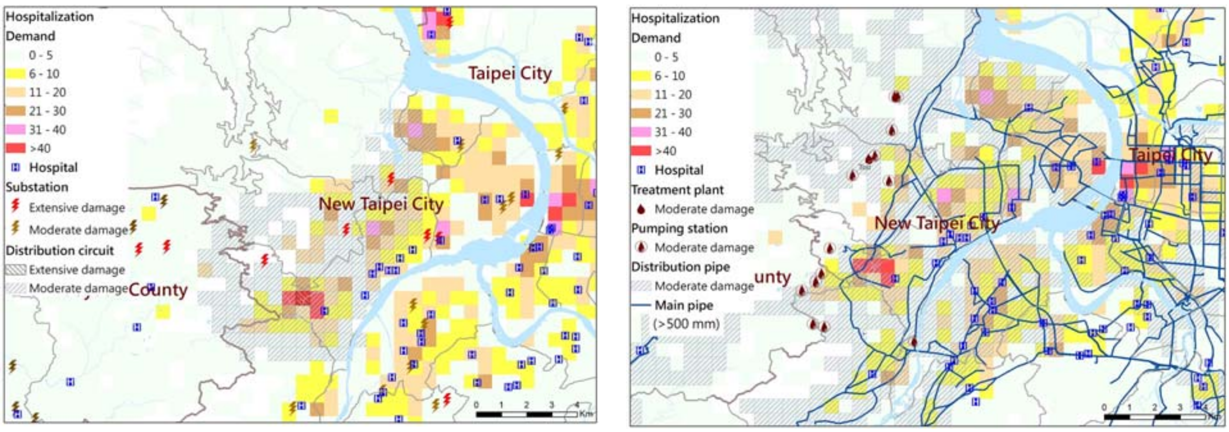


Fig. 6 – Major theme map for emergency rescue



(a)Medical care influenced by power failure (b) Medical care influenced by malfunction of portable water system

Fig. 7 – Major theme map for medical care

Based on the major theme maps for emergency rescue and medical care, we propose some suggestions for disaster mitigation planning as following:

1. Plans of emergency rescue and medical care for mass injury patients: According to the estimated casualty amount and distribution, city governments should designate the assembly point for rescue teams and resources and supporting resources from other cities. City governments should configure the dispatch mechanism for massive injury patients to surrounding cities based on the number of available beds in emergency responsible hospitals.
2. Ensure the transportation without obstruction for emergency rescue: City governments should designate the emergency rescue road in consideration of road width, locations of important government agencies and assembly points for rescue teams and resources. In case of possible closure of roads and bridges, city governments should configure the alternative roads for emergency rescue and transporting injury patients.
3. Countermeasures to malfunction of portable water and power systems for hospital operation: For the hospitals affected by power outage, the emergency power generator and its fuels should be well prepared. For the areas under water shortage, temporary water supply cars should be sent to the hospitals to maintain their medical operation.

3.3 Major theme maps for evacuation and shelter

As a result of building damage, residents cannot return to their houses and need evacuation to shelters. The shelter demands for three cities are estimated as Table 2. The shelter capacity is calculated by the summation of the allowable amount of each shelter. Although the shelter capacities for three cities are all greater than their estimated shelter demand, the shelter capacity may be reduced resulting from damage of shelters. Some impact issues can be revealed from the major theme maps for evacuation and shelter as following:

1. Evacuation interfered by transportation interruption: As shown in Figure 8, many bridges are under medium to high risk of closure which would impede the evacuation movement to shelters and the transportation from resource assembly points to shelters.
2. Power failure reduces the functionality of shelters: Because some substations are seriously damaged and majority of distribution circuit is under moderate to serious damages in Sinjhang district, the shelters in this region may lost power for several days which would affect the functionality of shelters, as illustrated in Figure 9(a).
3. Water shortage reduces the functionality of shelters: As the treatment plants, pumping stations, and distribution pipes were moderately damaged from analytical results, people staying in the shelters may be subjected to shortage of portable water for a couple of days, as shown in Figure 9(b).

From the major theme maps for evacuation and shelter, we propose some suggestions for disaster mitigation planning as following:

1. Configuration of shelters and assembly points of resources: Based on the estimated the amount and distribution of shelter demand, city governments should designate the appropriate shelters and ensure their seismic resistant capacity. Besides, city governments should configure the assembly points of resources and allocate resources properly.
2. Ensure the transportation for evacuation and shelter: For the shelters possibly affected by the interruption of transportation, city governments should configure alternative roads for evacuation and rapid recovery plan of emergency rescue road to ensure the transportation of resources to shelters.
3. Countermeasures to malfunction of portable water and power systems for shelters: For the shelters in the area subjected to power outage, the emergency power generator and its fuels should be well prepared. Temporary water supply cars should be allocated to the areas with water shortage to maintain the operation of shelters.

Table 2 – Shelter demand and capacity

City	Shelter capacity	Shelter demand	Capacity - Demand
New Taipei City	389,505	39,836	349,669
Taipei City	174,370	18,093	156,277
Taoyuan city	156,852	2,471	154,381

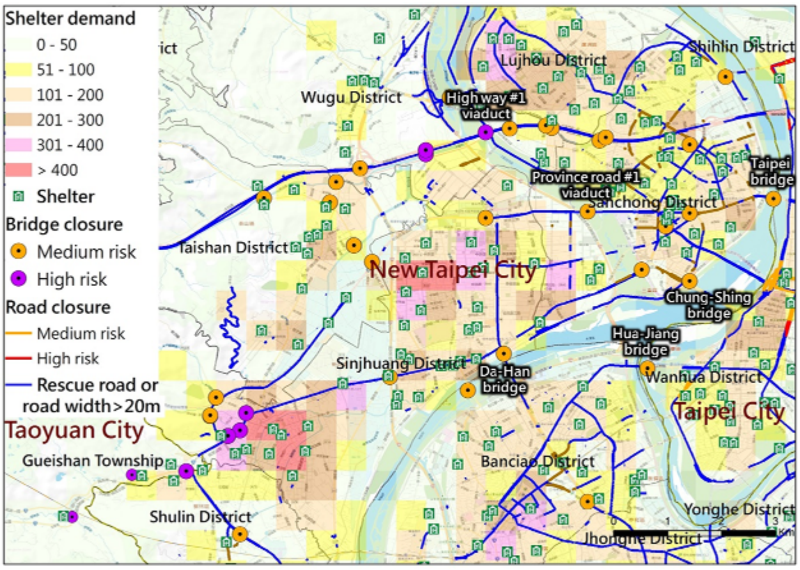
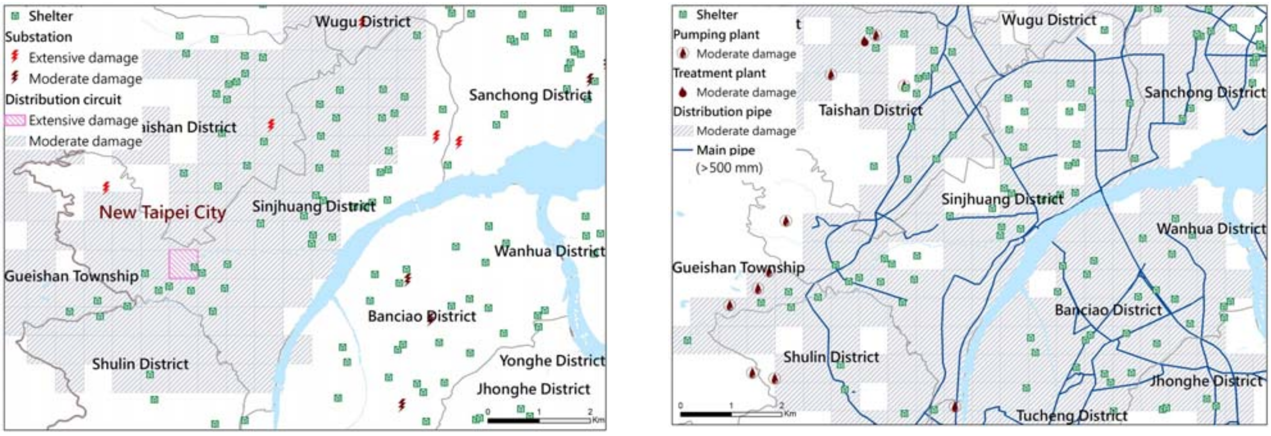


Fig. 8 – Major theme map for evacuation



(a)Shelter influenced by power failure

(b) Shelter influenced by malfunction of portable water system

Fig. 9 – Major theme map for shelter

3.4 Major theme maps for government operation

Once a major earthquake occurred, the government would launch the emergency operation. Whereas, the government agencies themselves may be under disaster risks or the operation functionality may be reduced resulted from damages of infrastructures. Some impact issues were raised from the major theme maps for government operation as following:

1. Damage risk of public buildings: Figure 10 encloses the evaluated damage risks of public buildings and locations of emergency operation centers (EOC) of cities and districts. There are some public buildings, under high to medium risks of damages in New Taipei City. Fortunately, all the central ministries in Taipei City are in low risks of damages. However, many bridges connecting these two cities are in medium to high risk of closure which may interfere the transportation of rescue teams and resources from Taipei City to New Taipei City.
2. Government operation affected by power outage: Because many substations are extensively damaged as indicated in Figure 11, power outage may last for several days to weeks. It may influence the telecommunication and emergency operation at EOCs.

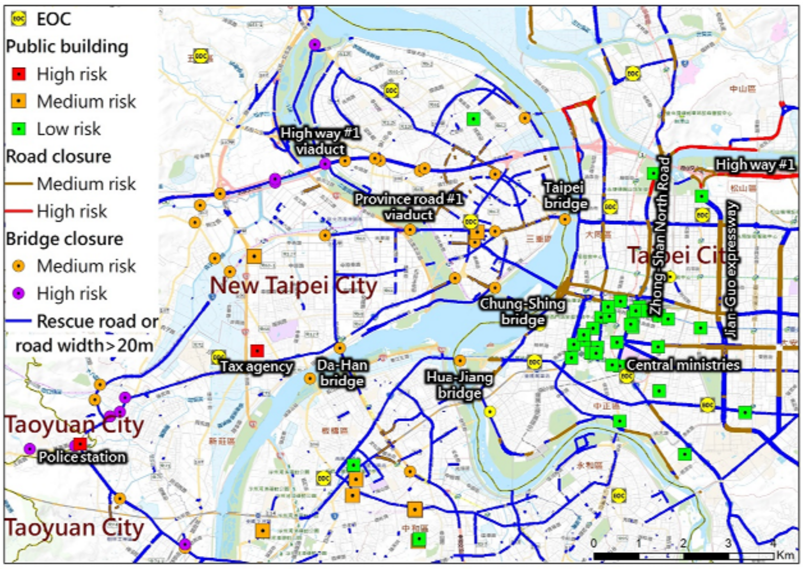


Fig. 10 – Major theme map for government operation affected by transportation

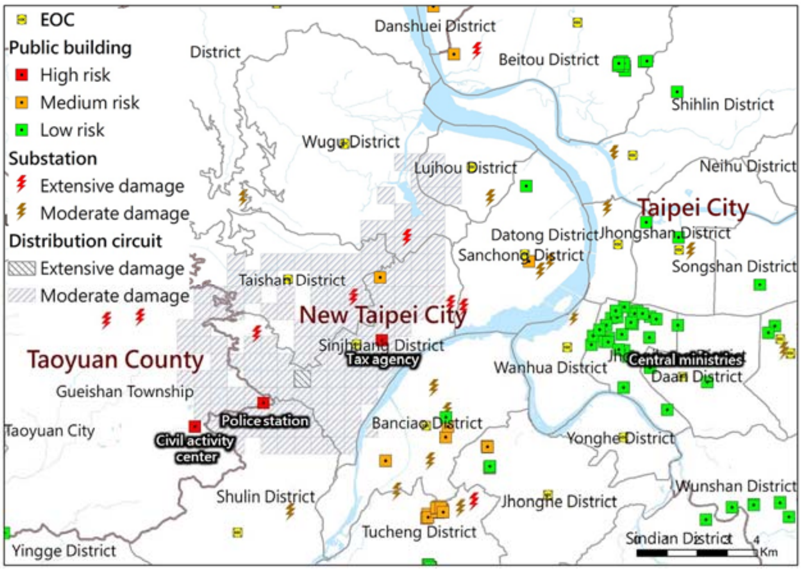


Fig. 11 – Major theme map for government operation affected by power outage

With respect to the major theme maps for government operation, we propose some suggestions for disaster mitigation planning as following:

1. Improve the seismic resistant capacity of important government agencies: The seismic resistant capacity of important government agencies (central ministries, city governments, EOCs, township governments, police and fire stations) should be evaluated and retrofitted to meet the specified requirement of building codes.
2. Evaluation and retrofit of viaducts and bridges: The old viaducts and bridges, especially for those designated as emergency rescue roads, should be evaluated and retrofitted to ensure their transportation function.
3. Countermeasures to power outage: Power generators and their fuels should be prepared in the important government agencies to reduce the impact of power outage to emergency operation and telecommunication.

4. Application of Major Theme Maps on Policy Suggestions

The 9th Disaster Prevention and Protection Expert Consultation Committee, the Executive Yuan chose "Construction of a Resilient City under Extreme Scenarios" as the main topic to propose policy suggestions to governments [4]. With reference to 10 essentials from [1], this committee presents 8 policy suggestions in consideration of the social environment and infrastructure in Taiwan, including (1) Refine the operation mechanism and system for disaster mitigation; (2) Clarify the disaster risk and scenario; (3) Enhance the resilience of financial affairs; (4) Consider the disaster risk for urban development and design; (5) Engage more efforts to empower the social resilience; (6) Improve the capability in response to disasters for infrastructures; (7) Refine the disaster response ability; (8) Pay attention to cultivate the ability of recovery and reconstruction regularly.

Figure 12 elaborates the flow chart regarding how to construct a resilient city in consideration of disaster vulnerability of social environment and infrastructure. Our research accomplishment in terms of major theme maps were adopted in the Step 2 (Impact analysis by integration of analytical results) and to identify the disaster vulnerability (weak items and their distribution) in the Step 3. Consequently, corresponding strategies were proposed to enhance the disaster resilience under the extreme scenario interpreted from our analytical results.

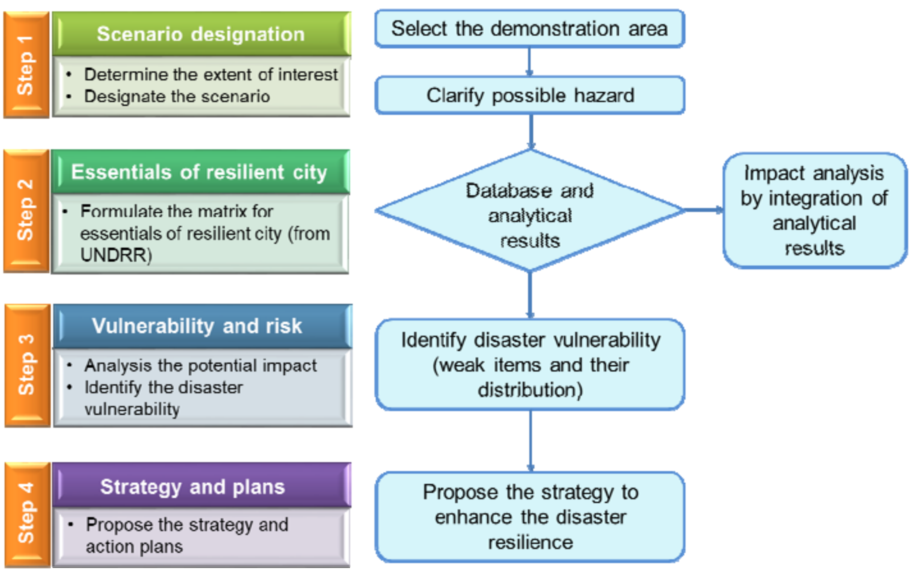


Fig. 12 – Construction of a resilient city (refined from [4])

For the second policy suggestion "Clarify the disaster risk and scenario", some strategies were presented as following:

1. Central government should collaborate with academic institutions on seismic scenario simulation for metropolitan cities, then provide the simulation results to local governments for disaster mitigation planning.
2. Identify the infrastructure and public buildings prone to high disaster risk and promote the seismic evaluation and retrofit plans for them in priority.
3. Central governments should establish the analytical model of landslide susceptibility. Local governments should assess the vulnerability for the tribes prone to landslide and organize corresponding measures integrated in urban planning.
4. Proceed detail investigation for old buildings, infrastructure, and distribution of underground lifeline. Establish the basic attribute database and GIS system for them.

5. Conclusions

1. The major theme maps disclose the disaster scenario and correlation of impact issues in details

We propose the major theme maps in terms of emergency rescue and medical care, evacuation and shelter, and government operation in this study. Integration of multiple analytical results clearly indicates the damage distribution of exposures and interprets the relationship of impact issues. It is helpful to more comprehensive planning for hazard mitigation.

2. The scenario simulation results have been applied to policy suggestions

We submit the scenario simulation results to the Disaster Prevention and Protection Expert Consultation Committee to identify the disaster vulnerability under an extreme scenario. Policy suggestions and corresponding strategies on construction of a resilient city were proposed by the committee for local governments.

6. References

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