RED-ACT Report

Real-time Earthquake Damage Assessment using City-scale Time-history analysis

Mar. 02, M6.2 Japan Nemuro-hanto Earthquake

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Acknowledgments and Disclaimer

The authors are grateful for the data provided by K-NET and KiK-net. This analysis is for research only. The actual damage resulting from the earthquake should be determined according to the site investigation.

1. Introduction to the earthquake event

At 12: 23, Mar. 02, 2019 (Local Time, UTC +9), an M 6.2 (JMA) earthquake occurred in Japan Nemuro-hanto. The epicenter was located at 146.8 42.1, with a depth of 10.0 km.

2. Recorded ground motions

30 ground motions near to epicenter of this earthquake were analyzed. The names and locations of the stations can be found Table 1. The maximal recorded peak ground acceleration (PGA) is 62 cm/s/s. The corresponding response spectra in comparison with the design spectra specified in the Chinese Code for Seismic Design of Buildings are shown in Figure 1.

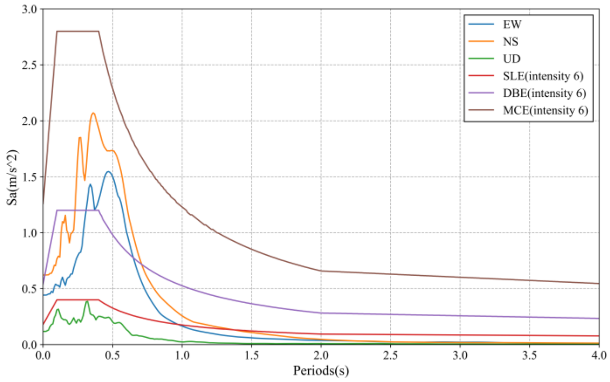

Figure 1 Response spectra of the recorded ground motions with maximal PGA

3. Damage analysis of the target region subjected to the recorded ground motions

Using the real-time ground motions obtained from the strong motion networks and the **city-scale nonlinear time-history analysis (see the Appendix of this report),** the damage ratios of buildings located in different places can be obtained. The building damage distribution and the human uncomfortableness distribution near to different stations is shown in Figure 2 and Figure 3, respectively. These outcomes can provide a reference for post-earthquake rescue work.

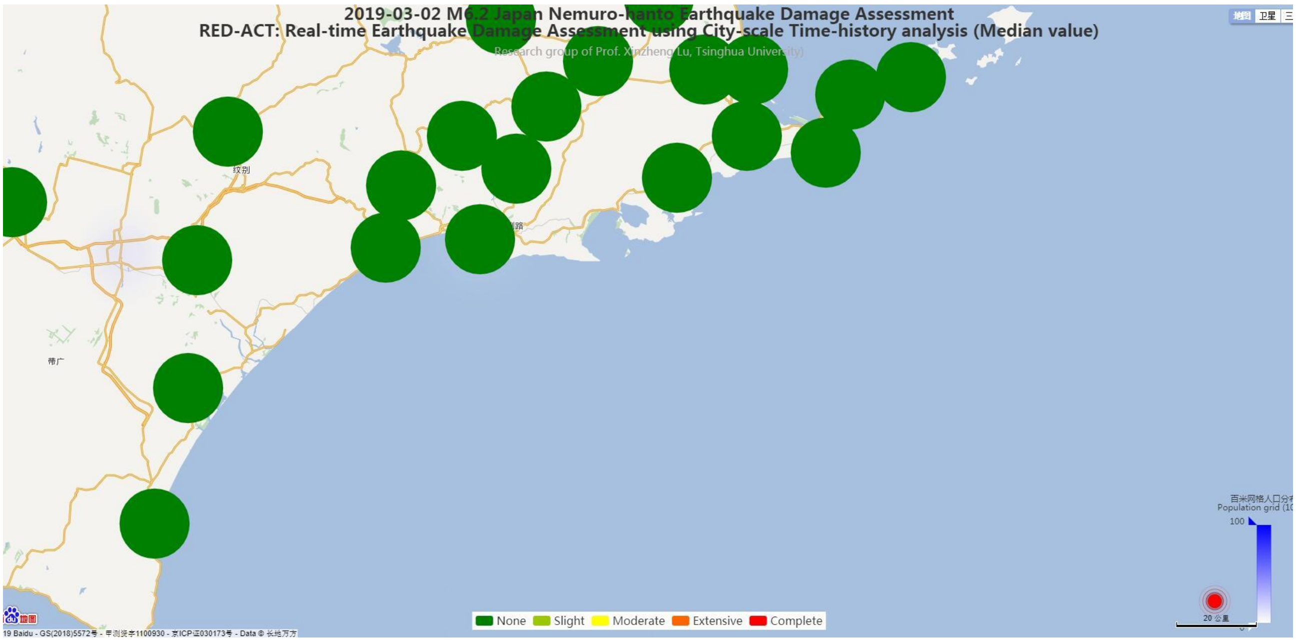

Figure 2 Damage ratio distribution of the buildings near to different stations

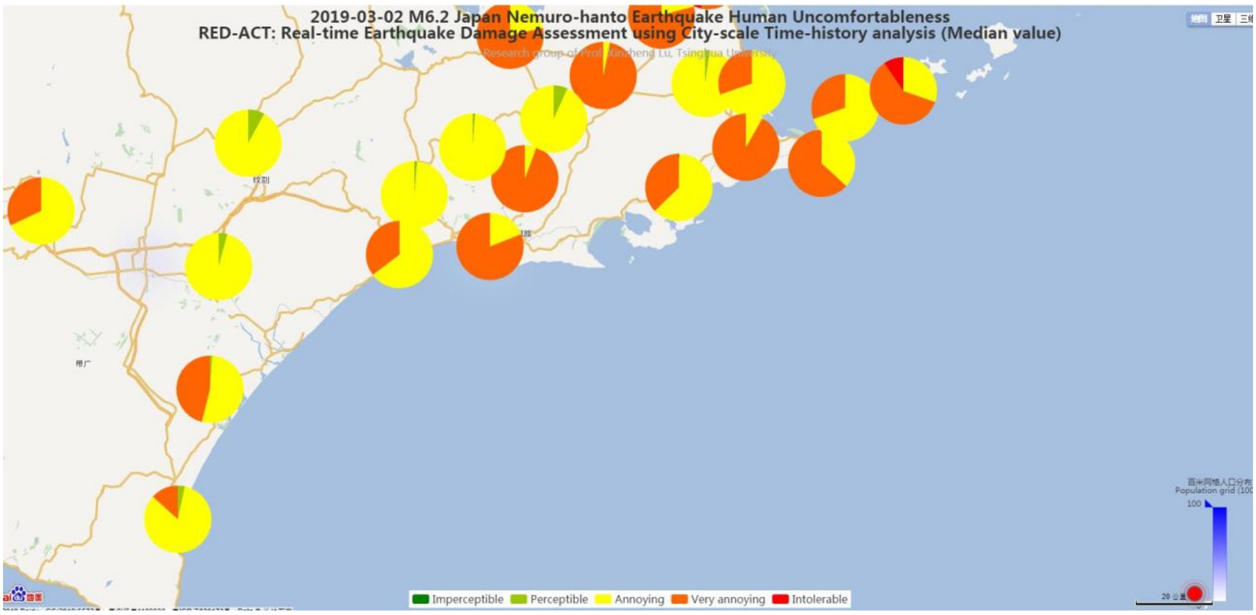

Figure 3 Human uncomfortableness distribution near to different stations

The details can be accessed at

http://www.luxinzheng.net/software/2019-03-02-Japan-6.2.html

http://www.luxinzheng.net/software/2019-03-02-Japan-6.2-Acc.html

Table 1 Names and locations of the strong motion stations

No.	Station Name	Longitude	Latitude
1	AOM010	141.142	40.8721

2	AOM012	141.481	40.5138
3	HKD063	145.248	44.106
4	HKD065	145.056	43.7938
5	HKD066	145.131	43.6619
6	HKD067	144.973	43.555
7	HKD068	144.77	43.4108
8	HKD069	145.117	43.3941
9	HKD070	145.284	43.3852
10	HKD071	145.26	43.2326
11	HKD072	145.521	43.1948
12	HKD073	145.6	43.3327
13	HKD074	145.803	43.368
14	HKD075	145.029	43.1309
15	HKD077	144.382	42.9845
16	HKD078	144.498	43.1486
17	HKD079	144.6	43.3033
18	HKD080	144.448	43.5077
19	HKD083	144.325	43.233
20	HKD084	144.123	43.1141
21	HKD085	144.07	42.9581
22	HKD089	143.554	43.2436
23	HKD092	143.448	42.9283
24	HKD097	143.421	42.6181
25	HKD099	142.839	43.0736
26	HKD100	143.312	42.2864
27	IWT012	141.138	39.3209
28	IWT020	141.329	39.7841
29	IWT021	141.082	39.9203
30	KGS011	130.349	31.5896

Appendix

Real-Time Regional Time-history Analysis and Its Application in Resilience-Oriented Earthquake Emergency Response

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Abstract: The resilience of cities has received worldwide attention. An accurate and rapid assessment of seismic damage, economic loss, and post-event repair time can provide an important reference for emergency rescue and post-earthquake recovery. Based on the city-scale nonlinear time-history analysis and the regional seismic loss prediction, a real-time regional time-history analysis method is proposed in this work. In this method, the actual ground motion records obtained from seismic stations are input into the typical regional building models of the earthquake-stricken area, and the nonlinear time-history analysis of these models is subsequently performed. The seismic damage of target regional buildings subjected to this earthquake is evaluated according to the analysis result. The economic loss and repair time of the earthquake-stricken areas are calculated using the regional seismic loss prediction. The method proposed in this work has been applied in many earthquake events. The main conclusions are as follows: (1) The uncertainty problem of ground motion input is solved properly with the proposed method based on the real-time ground motion obtained from the seismic stations; (2) The amplitude, spectrum, and duration characteristics of ground motions as well as the stiffness, strength, and deformation characteristics of different buildings are fully considered in this method based on the nonlinear time-history analysis and multiple-degree-of-freedom (MDOF) models; (3) Using the real-time city-scale time-history analysis and the corresponding report system, the assessment of the earthquake destructive power, repair time, and economic loss can be obtained shortly after the earthquake event, which provides a useful reference for scientific decision making for earthquake disaster relief. This work is of great significance to enhancing the resilience of earthquake-stricken areas.

Keywords: city-scale nonlinear time-history analysis, real-time regional time-history analysis, resilience-oriented earthquake emergency response

1 Introduction

Earthquakes cause severe damage and economic loss to urban areas, and the resilience of cities has received worldwide attention. An accurate and rapid assessment of seismic damage, economic loss, and post-event repair time can provide an important reference for emergency rescue and post-earthquake recovery. Therefore, it is of great importance to enhancing community resilience. The relationship between the resilience and rapid loss assessment can be expressed as the resilience-oriented earthquake emergency response, as shown in Figure 1.

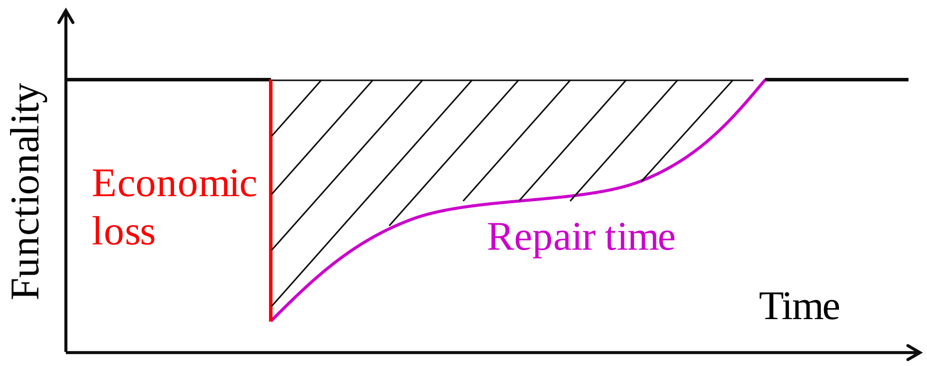


Figure 1. Resilience-oriented earthquake emergency response

The experience of several major earthquakes in recent years indicates that the assessment of the building damage in the earthquake-stricken area needs to be improved further. After an earthquake, the communication in the disaster area is delayed, the disaster site is usually chaotic, and there are not enough professionals to evaluate building safety in a short time. Furthermore, the rumors and fake information on the internet may interfere with an accurate seismic damage assessment. Therefore, it is necessary to propose a scientific, objective, and timely method for earthquake loss assessment.

To date, the near-real-time earthquake loss estimation tools mainly include: Prompt Assessment of Global Earthquakes for Response (PAGER), Global Disaster Alert and Coordination System (GDACS), USGS-ShakeCast, Istanbul earthquake rapid response system, and Rapid response and disaster management system in Yokohama, Japan, etc. (Erdik et al., 2014). These seismic loss estimation systems generally include three parts: the ground motion intensity measure (IM), building inventory and fragility, and direct economic losses and casualties. The ground motion IM can be obtained from the real-time monitoring data of seismic network directly or calculated using ground motion prediction equations (GMPE). The building inventory data can be determined by using either a detailed building database or macroscopic statistical data. The seismic damage of buildings can be predicted using the damage probability matrix (DPM) method or the capacity spectrum method. Economic loss and casualties are mainly calculated using empirical models.

However, the main problems existing in these systems are: (a) The dynamic characteristics of ground motion are not comprehensively taken into account; (b) The DPM method is difficult to apply in the areas where historical earthquake data are lacking or in quickly developing areas where there are large differences between the inventories of current and historical buildings; (c) The capacity spectrum method cannot easily represent the concentration of damage to different stories and the time-domain properties of ground motions (e.g., the velocity impulse of ground motions). (d) The earthquake loss prediction method relies on historical seismic damage data, and the repair time cannot be provided in these systems.

2 Real-Time Regional Time-history Analysis

Based on the above background, a real-time regional time-history analysis method is proposed in this work based on the city-scale nonlinear time-history analysis and the corresponding regional seismic loss prediction. The framework to conduct the real-time regional time-history analysis is illustrated in Figure 2. The procedures proposed in this method are as follows:

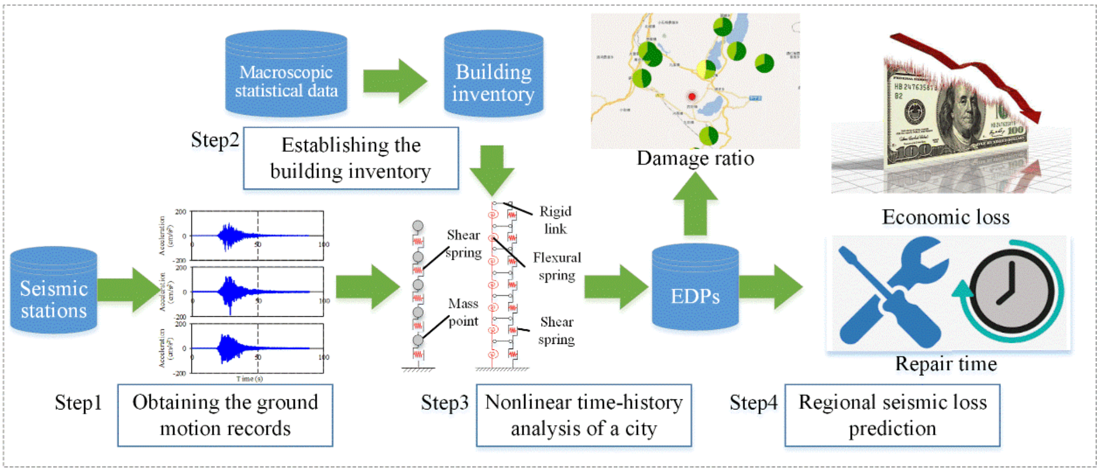


Figure 2. Framework for real-time regional time-history analysis

(1) Obtaining the ground motion records from the seismic stations

The ground motion records can fully describe the features of the ground motions without any information loss. The densely distributed seismic stations make it possible to obtain the ground motion records in a timely manner. After an earthquake, the ground motion record near to the epicenter can be quickly obtained through the seismic stations, and information such as the station's latitude, longitude, and recording time can be collected simultaneously.

(2) Establishing the building inventory database for the target region

Based on the Sixth National Population Census, this work constructs a virtual building inventory database of regions in mainland China. Specifically, according to the Sixth National Population Census, the number of buildings in the target region classified by the number of stories, structural type, and year built can be obtained. The building is divided into 33 categories according to the number of stories, structural type, and year built in this work, and the proportions of the 33 buildings can be determined by solving the indefinite equations that describe this problem. Then, the building inventory database of each region can be established to serve the subsequent seismic damage prediction. Note that if the statistical data of each building can be obtained for the target region, then these data can be directly used to establish the analysis model.

(3) Conducting the city-scale nonlinear time-history analysis to predict the seismic damage of the target region

Most of the urban buildings can be divided into two types: ordinary multi-story buildings and ordinary tall buildings. In general, multi-story buildings often exhibit shear deformation modes under earthquakes, while tall buildings will deform in flexure-shear modes. So the MDOF shear model will be used for the multi-story buildings (Figure 3A), and the MDOF flexural-shear model will be adopted to tall buildings (Figure 3B). For the MDOF model, the masses of the buildings are concentrated on their corresponding stories, and the nonlinear behavior of the structure is represented by the nonlinear inter-story force-displacement relationships (Figure 3C). The trilinear backbone curves recommended in the HAZUS report are employed to model the inter-story force-displacement relationships. Based on the building inventory, the corresponding parameter determination method for buildings in China and the United States is also proposed (Xiong et al., 2016, 2017; Lu et al., 2014). The reliability of this method is further validated by comparing the simulation results with earthquake site investigations, experimental results, and a large number of numerical results (Lu & Guan, 2017). With high efficiency, this method can be used well in post-earthquake emergency response. There exists an inherent uncertainty in the seismic performance of buildings, which is considered by incorporating the parametric uncertainty of the building backbone curve in this method.

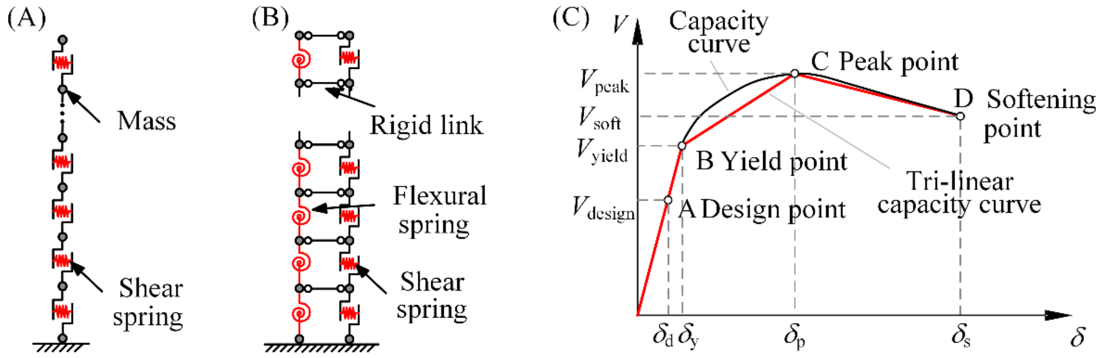


Figure 3. (A) MDOF shear model; (B) MDOF flexural-shear model; and (C) Trilinear backbone curve adopted in MDOF model (Xiong et al. 2016, Xiong et al. 2017).

The nonlinear time-history analysis of the buildings in the target area is implemented using the ground motions obtained from the seismic network. Subsequently, the time histories of the seismic response of each story in every building can be obtained. According to the engineering demanding parameters (EDPs) and the damage criteria proposed by Lu & Guan (2017), the damage state of each building in the region is determined, based on which the destructive power of the ground motion to the target area is evaluated.

To make full use of the real-time earthquake ground motions obtained from the densely distributed seismic stations, the destructive powers of ground motions obtained from different seismic stations can be evaluated by inputting the ground motions one-by-one into the building models of the target region. The distribution of building damage ratios under different station records can be given subsequently, which provides an essential reference for post-earthquake rescue work. For example, the destructive powers of ground motions of the 2018-08-13 M5.0 Yunnan Tonghai earthquake can be illustrated intuitively in Figure 4.

The human response to the floor acceleration is of great importance for the resilience assessment of communities under moderate seismic actions. Based on the comfort criteria (Simiu & Scanlan, 1996) and floor acceleration computed by the nonlinear time-history analysis, the human response to different ground motions can be obtained. The distribution of human comfortableness under the ground motions of the 2018-11-26 M6.2 Taiwan Strait earthquake is shown in Figure 5. Although the damage ratio of buildings under this earthquake is very small, the ratio of human uncomfortableness is still high.

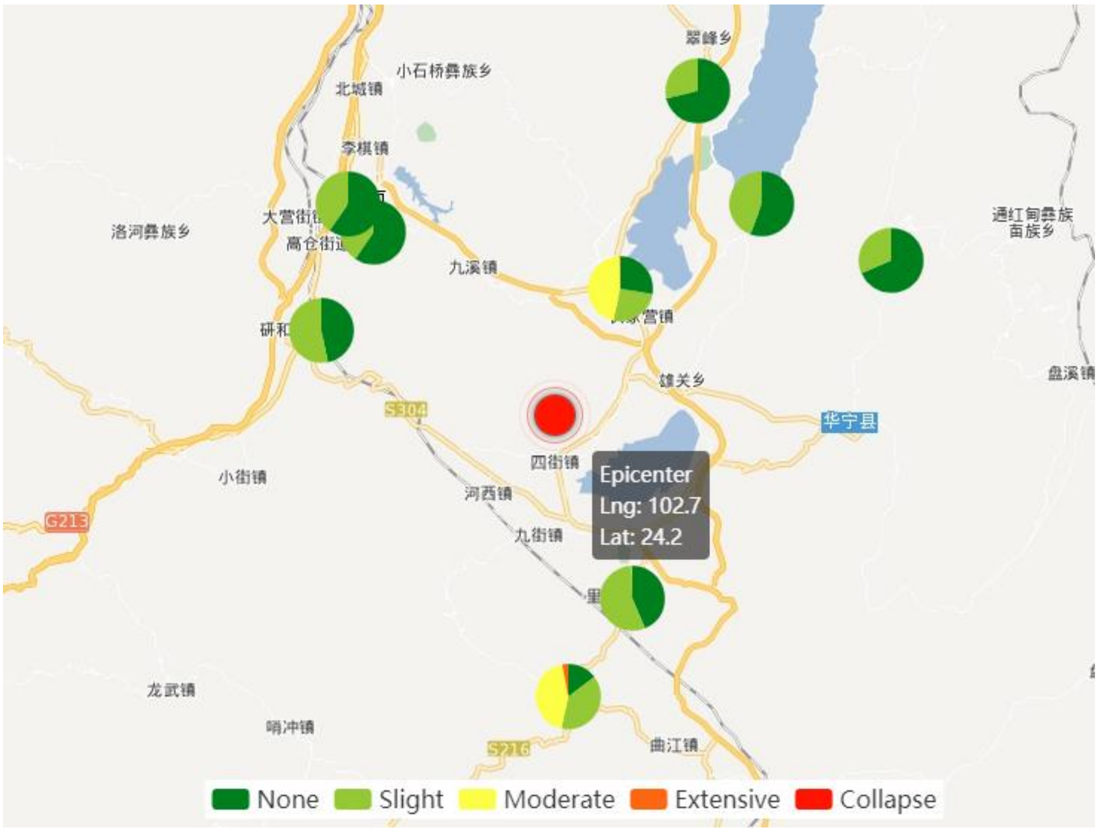


Figure 4. The destructive powers of ground motions of 2018-08-13 M5.0 Yunnan Tonghai earthquake

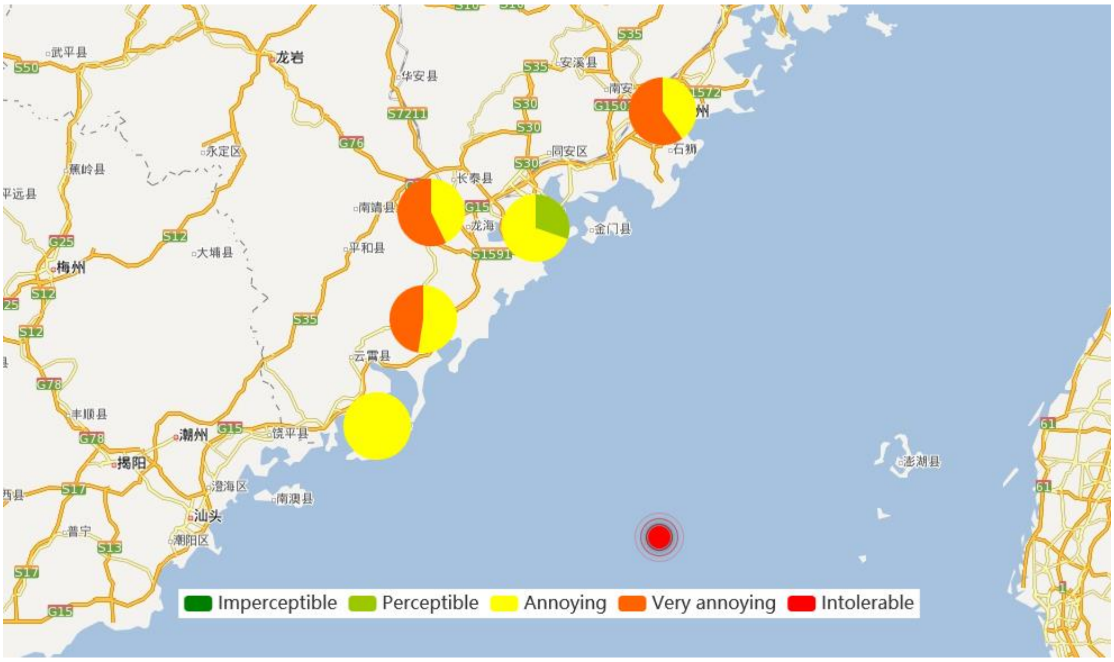


Figure 5. The distribution of human comfortableness under the ground motions of 2018-11-26 M6.2 Taiwan Strait earthquake

(4) Performing the regional seismic loss prediction to assess the seismic economic loss and repair time for the target region

Based on the FEMA P-58 method (Next generation seismic performance assessment method of buildings) and the city-scale nonlinear time-history analysis, a practical approach for regional seismic loss prediction is proposed

(Zeng et al., 2016). The main process of the method is as follows: (a) analyze the building response to determine the EDPs on each story of each building using the nonlinear MDOF models; (b) calculate the economic loss and repair time of components based on the building performance models and the fragility data provided in the FEMA P-58 document. The flowchart of the repair cost calculation is shown in Figure 6. Using this method, the damage states of components on different stories can be obtained, and the loss caused by the floor displacement, acceleration, and residual displacement can be considered. With high efficiency, the economic loss and repair time of the earthquake-stricken areas can be calculated quickly using this method.

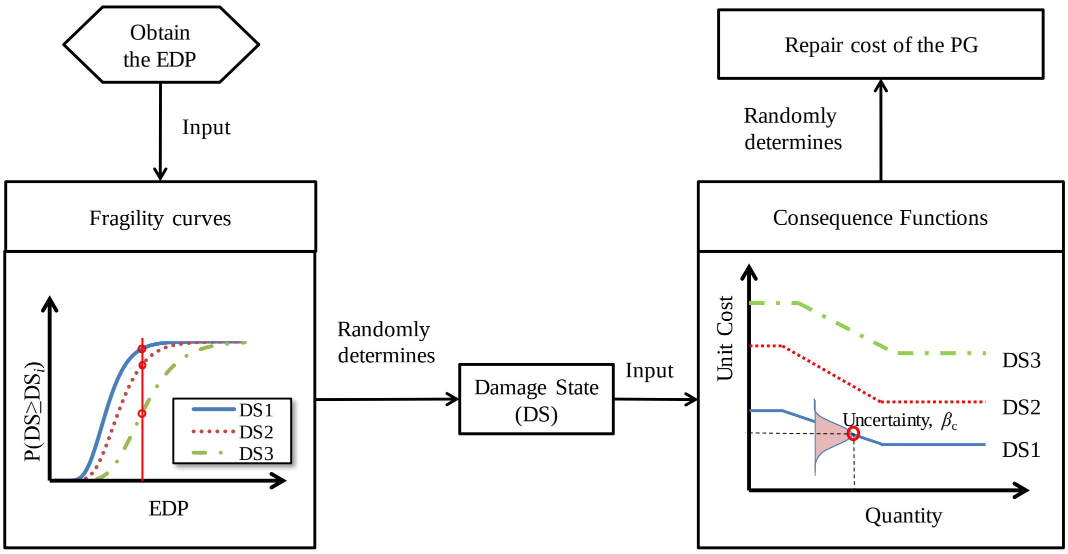


Figure 6. Calculation of repair cost for a building component using the FEMA-P58 methodology (Zeng et al., 2016)

One of the key challenges of using the FEMA-P58 method in a region is the assembly of performance models (PGs). The performance model of buildings contains the basic information with both the structural and nonstructural PGs. The types and quantities of building components can be obtained using the following three methods: (a) the field survey data and building design drawings, (b) building information models (BIM), and (c) geographic information system (GIS) database.

(a) Field survey data, and building design drawings

The type and quantity of each structural PG can be obtained from the structural and architectural drawings of the building. The nonstructural PGs can be determined using the field survey. Note that it requires some efforts to collect the information. However, it can be implemented in parallel by groups of people with basic knowledge of architectural and structural engineering.

(b) Building information models

The detailed building data can be automatically obtained from the building information model in which the building components have different levels of developments (LODs). The determination of the component type and the development of a component vulnerability function when the information is incomplete are proposed to produce an acceptable loss prediction (Lu et al., 2019). The modeling rules and the information extraction for BIM are also proposed to obtain the component information (Lu et al., 2019).

(c) GIS database

The building component type is estimated via the potential fragility classification number (FEMA, 2012). For example, the classification tree of the gypsum wall board (GWB) partition is shown in Figure 7. Meanwhile, the structural component quantity is estimated based on the statistics from the available literature and design drawings. The nonstructural PGs information can be identified according to the normative quantity information provided by

Appendix F of FEMA (2012). A tool to estimate the number of nonstructural PGs is also provided in FEMA P-58. Based on that data and basic GIS information such as floor area, number of stories, and occupancy, the structural and nonstructural PGs can be estimated.

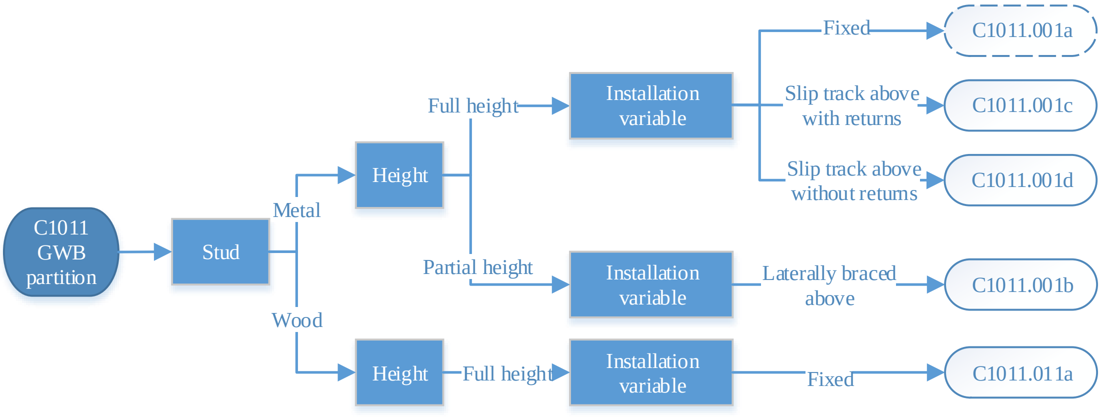


Figure 7. The classification tree of the gypsum wall board (GWB) partition component

City information model (CIM) is defined as the integration of GIS and BIM (Xu et al. 2014). With the development of this model, the CIM of the earthquake-stricken area can be pre-established, which will provide valuable data for the community resilience assessment.

To facilitate the abovementioned analysis and popularize the methods proposed in this work, an automatic report system is developed correspondingly. The system includes data preparation, calculation, and a post-processing module, which plays an important role in each earthquake emergency response.

3 Applications in Earthquake Emergency Response

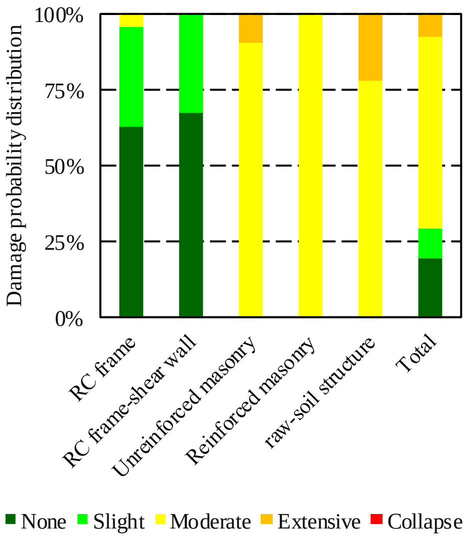
The real-time regional time-history analysis proposed in this work has been applied to many earthquakes in China and other countries and regions around the world, as listed in Table 1. The seismic damage assessment of the 2017 Jiuzhaigou earthquake is a typical application case (Lu et al., 2017). After the earthquake, several sets of ground motion records were obtained from the seismic network, and the seismic damage prediction of the target regional buildings was performed quickly by using the proposed method. Seismic results of a typical town and country in the Aba region under the ground motion from the Jiuzhaigou Baihe station is shown in Figure 8. The analytical results show that the buildings in the disaster area may be damaged to some extent, but the ratio of collapse is very small, which is consistent with the actual post-earthquake site investigations (Dai et al., 2018). The results provided a useful reference for the earthquake emergency response and scientific decision making of earthquake disaster relief.

To demonstrate the resilience assessment method for a region, the seismic economic loss and repair time of Tsinghua Campus (Zeng et al., 2016) were calculated. The ground motion recorded at the Jiuzhaigou Baihe station is input to 619 buildings of Tsinghua Campus. The distribution of the median building loss ratios and repair/rebuilding times are as shown in Figure 9. The total loss ratio is 0.576%, which is very small. The repair time of the campus is 15 days with parallel repair strategies. The results provide a valuable reference for the resilience assessment of Tsinghua Campus.

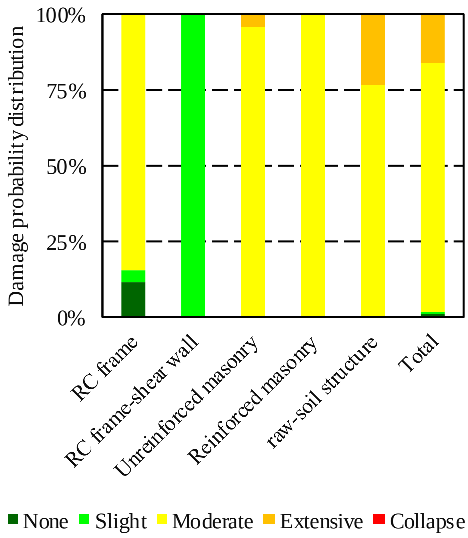
Table 1. Applications of the real-time regional time-history analysis method

ID	Earthquake name	ID	Earthquake name
1	2016-12-08 M6.2 Xinjiang Hutubi earthquake	13	2018-10-16 M5.4 Xinjiang Jinghe earthquake

2	2016-12-18 M4.3 Shanxi Qingxu earthquake	14	2018-10-31 M5.1 Sichuan Xichang earthquake
3	2017-03-27 M5.1 Yunnan Yangbi earthquake	15	2016-04-16 M7.3 Kumamoto earthquake
4	2017-08-08 M7.0 Sichuan Jiuzhaigou earthquake	16	2016-08-24 M6.2 Italy earthquake
5	2017-09-30 M5.4 Sichuan Qingchuan earthquake	17	2016-11-13 M8.0 New Zealand earthquake
6	2018-02-12 M4.3 Hebei Yongqing earthquake	18	2017-09-20 M7.1 Mexico earthquake
7	2018-05-28 M5.7 Jilin Songyuan earthquake	19	2017-11-23 M7.8 Iraq earthquake
8	2018-08-13 M5.0 Yunnan Tonghai earthquake	20	2018-02-06 M6.5 Hualien earthquake
9	2018-08-14 M5.0 Yunnan Tonghai earthquake	21	2018-06-18 M6.1 Japan Osaka earthquake
10	2018-09-04 M5.5 Xinjiang Jiashi earthquake	22	2018-09-06 M6.9 Japan Hokkaido earthquake
11	2018-09-08 M5.9 Yunnan Mojiang earthquake	23	2018-10-26 M5.4 Japan Hokkaido earthquake
12	2018-09-12 M5.3 Shanxi Ningqiang earthquake	24	2018-11-26 M6.2 Taiwan Strait earthquake

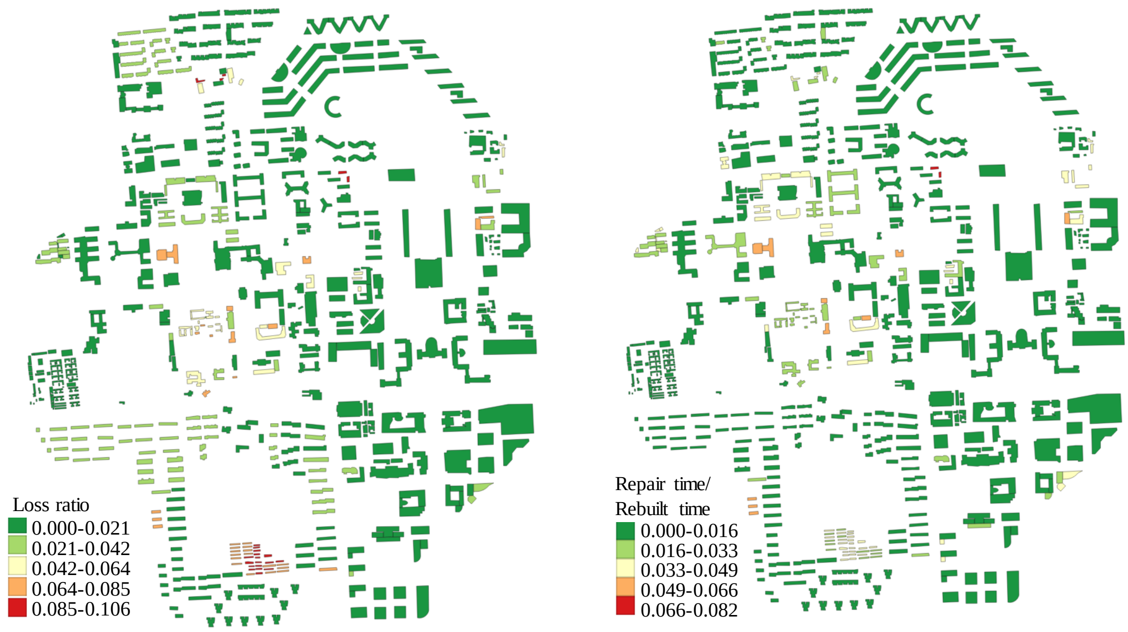


(a) Typical town in Aba region



(b) Typical country in Aba region

Figure 8. Seismic results of typical town and country in Aba region under the ground motion from the Jiuzhaigou Baihe station



(a) Median building loss ratios (b) Median building repair/rebuild time

Figure 9. Distribution of median building loss ratios and repair/rebuild time for Tsinghua Campus

4 Conclusions

Based on the city-scale nonlinear time-history analysis and the regional seismic loss prediction, a real-time regional time-history analysis method is proposed in this work. The main conclusions are as follows:

(1) The uncertainty problem of ground motion input is solved properly with the proposed method based on the real-time ground motion obtained from the seismic stations;

(2) The amplitude, spectrum, and duration characteristics of ground motions as well as the stiffness, strength, and deformation characteristics of different buildings are fully considered in this method based on the nonlinear time-history analysis and MDOF models;

(3) Using the real-time regional time-history analysis and the corresponding report system, the assessment of the earthquake's destructive power, repair time, and economic loss can be obtained shortly after the earthquake event, which provides a useful reference for scientific decision making of earthquake disaster relief. This work is of great significance to enhancing the resilience of the earthquake-stricken areas.

6 References

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