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Structural damage distribution induced by Wenchuan Earthquake on 12th May, 2008

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Abstract. Based on the reconnaissance of buildings in Dujiangyan City during 2008 Wenchuan earthquake, China, structural damage characteristics and the spatial distribution of structural damage are investigated, and the possible reasons for the extraordinary features are discussed with consideration of the influence of urban historical evolution and spatial variation of earthquake motions. Firstly, the urban plan and typical characteristics of structural seismic damage are briefly presented and summarized. Spatial distribution of structural damage is then comparatively analyzed by classifying all surveyed buildings in accordance with different construction age, considering the influence of seismic design code on urban buildings. Finally, the influences of evolution of seismic design code, topographic condition, local site and distance from fault rupture on spatial distribution of structural damage are comprehensively discussed. It is concluded that spatial variation of earthquake motions, resulting from topography, local site effect and fault rupture, are very important factor leading to the extraordinary spatial distribution of building damage except the evolution of seismic design codes. It is necessary that the spatial distribution of earthquake motions should be considered in seismic design of structures located in complicated topography area and near active faults.

Keywords: Wenchuan earthquake; spatial distribution; building damage; near-fault earthquake; topography

1. Introduction

The Wenchuan Earthquake, which took place on May 12th, 2008, is the most severe earthquake ever happened in China since the 1976 Tangshan Earthquake. The earthquake is caused by the fracture of the Longmenshan fault due to the collision between two tectonic plates, the Indian plate and the Eurasian (comprising the continents of Europe and Asia) plate. The epicenter of Whenchuan earthquake is located in Wenchuan County (31.0°N, 103.4°E). The principal earthquake lasts for nearly 2 minutes with seismological surface fault of nearly 300km long and the focal depth of approximately 10 km. The earthquake causes severe casualties and property

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loss, and also it brings many buildings, bridges and dams to damage or even collapse.

Dujiangyan City is only 21 km away from the epicenter and 8.6 km in perpendicular distance to the Longmenshan fault, thus this city belongs to the near-field earthquake zone. According to the seismic intensity distribution published by China Seismological Bureau for the Wenchuan Earthquake, Dujiangyan City is under the seismic intensity of IX~X, which means that the structures are under severe destruction. Buildings in Dujiangyan City includes several representative structural types, so several typical seismic damage are revealed, which provides a great background for seismic performance evaluation of urban buildings. Dujiangyan City is a fan-shaped radial area back against a mountain, and the seismic damage of buildings becomes gradually slighter with the increase of distance away from the mountain. Field survey and reconnaissance have been made by a large number of engineers and researchers to investigate and explore why so tremendous disaster of human lives and engineering structures happened in this severe earthquake. Many researches on building damage and collapse are focused on the influence of structural type, construction age and use purpose on seismic damage and collapse (Lin *et al.*2009, Chen and Booth 2011, Li and Li 2012). A statistical analysis of seismic damage of multi-aged buildings in Wenchuan earthquake is performed and a preliminary result shows that the seismic capacity of masonry buildings increases drastically after the year 2000, and the multi-aging effect in consideration of seismic design code evolution is notable (Lin *et al.* 2009). The data recorded in previous earthquakes also shows that topographic condition has a remarkable influence on the distribution of seismic intensity (Finn *et al*. 1995), leading to notable spatial distribution of structural seismic damage. The site selection and seismic design of engineering structures are highly dependent on seismic intensity. Thus, researches on spatial distribution effect of structural seismic damage and the spatial variation of earthquake motions are of vital significance for practical engineering. The former researches mainly focuses on the effect on structural type and construction age evolution of buildings in high intensity regions, and seldom presents the effect and evidence of spatial distribution of seismic motions induced by geology and especially topography. This study is concerned with damage grads and damage indexes of structures, as well as the urban evolution and spatial distribution of earthquake motions. The evidence of spatial structural damage and potential cause are provided and analyzed comprehensively. The regularities and possible influence factors of urban seismic damage distribution are investigated, aiming to provide references for future seismic design and predictions for seismic damage.

2. Survey of building damage in Dujiangyan City

The radial expansion of Dujiangyan City is revealed obviously from the topographical map (see Fig. 1) the inner and outer ring roads are the main roads of the city. Most of the buildings in the inner ring road are old buildings, while relatively new buildings spread between the inner and outer ring road, Very few buildings are distributed outside the outer ring road, where most agricultural lands are located. The seismic damage of buildings within the outer ring is randomly surveyed in the several areas as shown in Fig. 1.There are about 8000 buildings within the outer ring road and the overall area is about 16.2 km^2. The surveyed area (blue area in Fig. 1) is approximately 5.3 km^2, about 1/3 of the total area. There are 2026 buildings in the surveyed area and these buildings were comprehensively examined in August, 2008. The reconnaissance of these selected buildings fundamentally reflects the representative circumstances of building damage in Dujiangyan City during the Wenchuan earthquake.

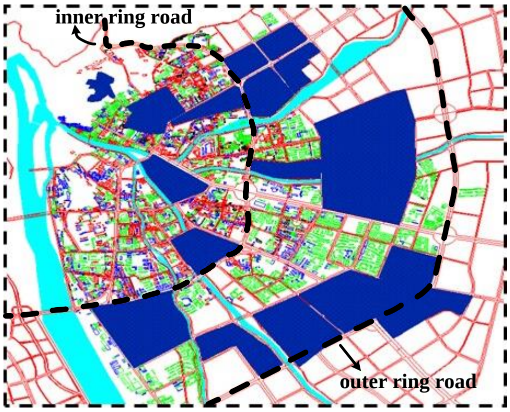

Fig. 1 Seismic reconnaissance region

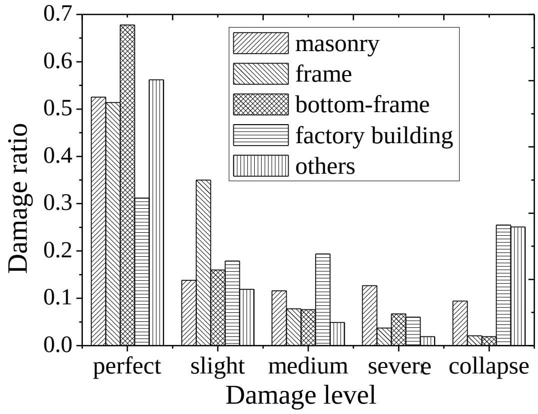

Fig. 2 Proportion of structural damage of buildings

Buildings in Dujiangyan City mainly consist of multistory masonry structures, multi-story reinforced concrete structures, masonry structures with bottom RC frames, single-story industrial plants and other old low dwellings. Among all these structures, the great majority of buildings are multistory masonry structures, with the percentage of 53.2%. According to the classification of function of buildings, these buildings are mainly for residential and commercial purpose, government buildings, hospital, education buildings and factory, *et al*. It is found that 60% of the surveyed buildings are used for residence, and almost all these buildings are multistory masonry structures; about 15% of the surveyed buildings are for both commercial and residential purpose. Most of these structures are multistory reinforced concrete structures, with the bottom frame structures for commercial purpose and the upper part with multistory masonry structures for residence. Almost all kinds of the buildings are damaged to variable levels according to the National Evaluation Specification (PRCMC 1990). The damage level is classified into five levels: almost in perfect condition, slight damage, moderate damage, severe damage and collapse. The proportion of each type of structural damage is presented in Fig. 2. It can be seen that single-story industrial plants, multistory masonry structures and buildings of other structural type are damaged heavily in severe damage level and collapse level. The frame structures and bottom-frame structures are relatively slightly damaged. It can be observed that the frame structure performs better in earthquake than other structures.

The Post-earthquake field works part 3 : Code for field survey (GB/T18208.3-2000) is adopted in this study to present the comparison of damage level between different structures. The formula in the specification provides the corresponding relationship of seismic damage grade and damage index as follows

$$d_{ij} = \sum d_{ij} n_{ij} / \sum n_{ij} \tag{1}$$

Where d_{ij} is the damage index of buildings of structural type "i" with damage grade "j"; n_{ij} is the number of buildings of structural type "i" with damage degree "j". The damage index corresponding to each damage level adopts the median value of the given range in Appendix A1 of the Post-earthquake field works part 3: Code for field survey (GB/T18208.3-2000) for ease of calculation, which means that the five damage levels, respectively almost in perfect condition, slight damage, moderate damage, severe damage and collapse, correspond to a damage index of 0.05, 0.2, 0.425, 0.70 and 0.925. Thus, the average damage index for masonry structures, frame structures, masonry structures with bottom RC frames, industrial factory buildings and other structures is 0.279, 0.176, 0.163, 0.410 and 0.315, respectively. It can be observed that the industrial factory buildings are most severely damaged; the second is other structures including old single-story dwellings and others collapsed structures whose structural type are unable to be judged, thus the average damage index is relative large; while frame structures and masonry structures with bottom RC frame are relatively slightly damaged.

3. Summarization of typical structural damage

3.1 Damage of multistory masonry structures

The multistory masonry structure is widely applied in Dujiangyan City for residential and commercial buildings, especially, for those built before the year 2000. It is found from the investigation that the main failure mode of multistory masonry structures includes damage of bearing wall and non-bearing wall, destruction of constructional column and ring beam and collapse or partial collapse of the structure.

Red bricks were used for most of the multistory masonry buildings built before 2000. Because the earthquake action is largely inflicted on walls and the masonry walls are relatively weak in shear strength, they are likely to reach shear failure. Failure of walls mainly appears as single diagonal crack or X-shape crack. The survey of the Tangshan Earthquake in 1976 shows that multistory masonry structures without constructional column and ring beam are most severely damaged (Liu and Yang 1996). Since then, the seismic design code of China requires setting up constructional column and ring beam to enhance seismic performance of buildings. However, lots of masonry buildings investigated in Dujiangyan City have no constructional column or ring beam, leading to collapse of part or the whole of the walls, as shown in Fig. 3. It is worth noting that periphery through transverse crack appears in some multistory masonry structures shown in Fig. 4, which can be regarded as one kind of horizontal shear failure or vertical tensile failure caused by strong earthquake motion. Quite a lot of masonry buildings especially those built before 2000 were severely damaged or even collapsed, while there are still some masonry buildings including the old ones being in good condition or slightly damaged. Its reason needs further research.

Fig. 3 Structural damage caused by not installing constructional column

Fig. 4 Masonry structure with cut-through horizontal fracture or crack

Fig. 5 Collapse of an infilled wall of the second hospital in Dujiangyan City

Fig. 6 The lantern-shaped damage of frame column

3.2 Damage of multistory RC frame structures

Multistory RC frame structures are also widely applied in Dujiangyan City for residence and the first floor is usually used for business shop. This kind of structure is usually built after the year 2000, and was found slightly damaged in Wenchuan earthquake. Multistory RC frame structures have a relatively small lateral stiffness thus a large horizontal deformation would occur under severe earthquake motion, leading to a failure of non-structural components even columns and beams of the main structure. In this study, damage degrees of multistory RC frame structures are quantitatively investigated and presented in the following analyses.

The relatively small lateral stiffness caused large inter-story drifts. And infilled wall of multistory RC frame structures provides low shear strength for seismic resistance and reveals a poor ductility during earthquake motions. Thus the wall reaches a status of shear failure due to large horizontal deformation during the earthquake. This failure is more likely to occur when there is a lack of strong connection between the infilled wall and the RC frame. Structural collapse of infilled walls of a hospital in Dujiangyan City is shown in Fig. 5, resulting in unexpected troubles in medical relief after the earthquake. The field investigation shows that damage of the beam-column connection and the column base is a universal phenomenon. Also, the longitudinal reinforcing bars are exposed after local spalling of concrete cover or even buckled as lantern-shaped, as shown in Fig. 6. The reason of this failure can be attributed to the following factors, failure of stirrup number at the connection; strengthening of floor-beam leading to a shift of the failure zone from beam to column. But the failure zone is expected to appear in the beam under the conventional concept of “strong column and weak beam”. Strong vertical earthquake motion may be another reason of this failure mode of columns. In addation, besides the common failure in the beam-column connection zone and the column base, some frame girders are found failure with oblique section rupture. Like multistory masonry structures, many stairways and some lintel beams are also found damaged.

3.3 Damage of bottom-story frame structures

The bottom-story frame structure is secondly widely applied except the multistory masonry structure, and this type of buildings was also found relatively severely damaged. Generally, the first one or two floors of this kind of structure are reinforced concrete frame structures used for commerce; other floors are multistory masonry structures used for residence. Due to the small lateral stiffness of the bottom frame, a weak story is likely to form. Under strong earthquake motion, the bottom frame yields large horizontal deformation causing the exposure and buckling of reinforcing steel in the frame column and the oblique section rupture of the frame girder. Because of the infilled walls are usually made from brittle materials. The damage of infilled walls is mainly caused by relatively large inter-story drifts. Shear cracks, including single diagonal crack, X-shaped diagonal crack and crack at the beam-column connection are observed at the bottom frame infilled wall. Failure of infilled walls directly threatens the safety of people and apparatus, and may lead to great casualties and economic loss. Generally, infilled walls are more severely damaged than the frame column, whose damage degree is severer than that of the frame girder.

In the investigation, it is found that bottom-story of some buildings is a combination of half frame structure and half masonry structure. The structural bottom floor facing the main road is frame structure for commercial purpose while the other part of the hybrid bottom-story structure is masonry structure for residential purpose or warehouse. Other than the bottom-story, the upper part is the multistory masonry structure for residence. Under earthquake motion, without constructional column or ring beam, the bottom masonry structure will generally be first damaged and lose its bearing capacity due to its low shear strength. If there is further strong earthquake motion, only the bottom frame structure is at work and the whole structure may be severely damaged or even collapse. Thus this kind of structure should be abandoned in structural design or at least adopt enough structural constructional measures to balance the load of the frame and masonry structure. Fig. 7 and Fig. 8 show the damage of this hybrid structure. It can be seen that the masonry structure is relatively more severely damaged. The bottom-story frame structure and bottom-story hybrid structure were relatively severely damaged. Some bottom frames failed with partial or whole collapse, causing great casualties and economic loss. The possible reasons of this collapse include unreasonable structural design, lack of constructional column or ring beam or other structural measures, e.g., unreasonable stirrup settlement, insufficient lateral bearing capacity, and the strength degradation of building material. However, a large proportion of bottom-story frame structure, especially those built after 2000, performed well in the earthquake and were almost in good condition or slightly damaged. Further researches of these buildings can help to improve the seismic design method of bottom-story frame structure.

Fig. 7 Damage of masonry structure part in bottom-story hybrid structure

Fig. 8 RC frame structure part in bottom-story hybrid structure

Fig. 9 Damage of bent column in single bent frame structure

Fig. 10 Damage of envelop enclosure system in single bent frame structure

3.4 Damage of single story bent structures

In Dujiangyan City, the single story bent structure is mainly used for industrial factory while a few for large span structures like school sports buildings. Generally speaking, this kind of structure is also severely damaged. From the investigation, most of these structures were built before 1990s. Due to strength degradation of structural material, unreasonable design and other factors, many single story bent structures are damaged to variable degrees. The damage can be classified into two types: failure of main bearing structure and failure of building envelop. Bent frame column is the main bearing component of the single story bent structures. If the bent column is severely damaged and the longitudinal linkage of the roof is not strong enough, collapse of partial of the roof, or even a progressive collapse would happen. Fig. 9 reveals that the exposure and buckling of reinforcing steels at the bent column base of a printing house. Also, crack of the building envelop like the enclosure wall and severe collapse of the roof observed in the field survey. The main reason is that there lacks a reliable connection between the enclosure wall and the bent column, also the out-of-plane instability or the shear failure of the walls may contribute to the failure. Additionally, some bent structures lack wind-resisting column, which makes the enclosure walls more likely to collapse, as shown in Fig. 10.

3.5 Damage of other structures

In the inner ring, there are a lot of single story old dwellings, which are greatly damaged in the earthquake. These dwellings were approximately built in 1970s. Most of them are masonry structures with slope tile roofs, without seismic design or reasonable structural measures. Thus they are very likely to be severely damaged, or even collapse. The failure mode of these buildings included: failure of tile sliding due to insufficient connection between the tile and the purlin, destruction or collapse of walls due to unreasonable design without considering seismic design and strength degradation of structural materials, collapse of the roof due to collapse of bearing walls. There are also some high-rise structures like the water tower and chimney. These structures belong to flexible structures with large height and long natural period which are likely to be damaged due to resonance with long period earthquake motion. The investigation shows that high-rise structures generally perform well in the earthquake as they are almost in good condition except that only some slight cracks appears on several water towers. This shows that the earthquake motion in

Dujiangyan City are mainly short-period, with little long-period component. However, this can be resulted by energy dissipation through the waggle of water in the tower, reducing the seismic damage.

4. Spatial distribution of building damage in Dujiangyan City

Dujiangyan City is fan-shaped and the First Ring Road divides this city into two parts: the inner ring and the outer ring. The north-west part of the city is backed against the mountain and the terrain in north-west part is high while the south-east part is relatively low. Distinctive spatial distribution characteristics of seismic damage of buildings are observed from the earthquake survey: structures in the inner ring are more severely damaged than those in the outer ring. The further the structure away from the mountain, the more slightly it was damaged. To further quantitatively investigate this spatial distribution pattern, the urban zone of the city is divided into two parts: the inner ring backed against the mountain with a radius of about 5 km and the outer ring farther away from the mountain with a radius of 9 km.

From the reconnaissance data of buildings in Dujiangyan city, the major structures in the city are multistory masonry structures, which were severely damaged during the earthquake. In this study, the spatial distribution pattern of multistory masonry is taken as an example to carry out the quantitative and comparative investigation. The survey covers 1065 multistory masonry structures which are evenly distributed in both rings: 392 in the inner ring and 673 in the outer ring. Fig. 11 shows the proportion of masonry structures built in inner and outer regions during different construction periods, reflecting the evolution of urban building construction age at the same time. It can be seen from the masonry buildings investigated that most of those in inner ring were built in 1980s and 1990s and very few buildings were built after 2000, while those built in the outer ring are gradually increasing in these stages.

According to seismic damage level of multistory masonry structures in inner ring and outer ring, the damage index of buildings in inner ring is higher than that of buildings in the outer ring. The average structural seismic damage index of inner ring is 0.395 while the index for the outer ring is 0.212 in accordance with Eq. (1). The average damage index in inner ring is 1.86 times of that in outer ring, reflecting that the buildings in inner ring region are more seriously damaged than that in outer ring in Dujiangyan city.

As the structural seismic damage reveals a multi-aged characteristic, which means that buildings built in different stages differ from others remarkably in anti-seismic capacity. According to the evolution characteristic of the seismic design criterion of China, the building structures are divided into four groups: before 1980s, 1980s, 1990s, after 2000. Buildings in the same stage are regarded to have the same seismic capacity, thus the spatial distribution pattern can be analyzed on the same seismic capacity level.

Figs. 12-15 show the seismic damage statistics of multistory masonry structures during these four stages in the inner ring. It can be seen that no matter which stage the structures were built, nearly all the structures in inner ring are more severely damaged than those in the outer ring, especially for those buildings before the year of 2000, which revealed a strong spatial distribution pattern. Structures built after 2000 were all slightly damaged no matter whether they are located in the inner ring or the outer ring These figures also reveal that those structures built before 1980s are most severely damaged while those built after 2000 are slightly damaged or in perfect condition. However, it is noteworthy that those built in 1990s are relatively more severely damaged than those built in 1980s. Further studies need to be carried out to dig the deep-seated reason for this phenomenon.

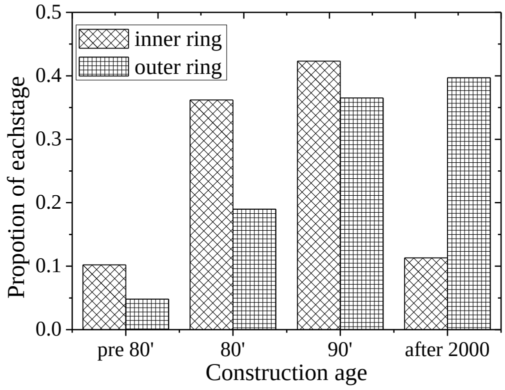

Fig. 11 Proportion of masonry buildings in inner and outer region during each stage

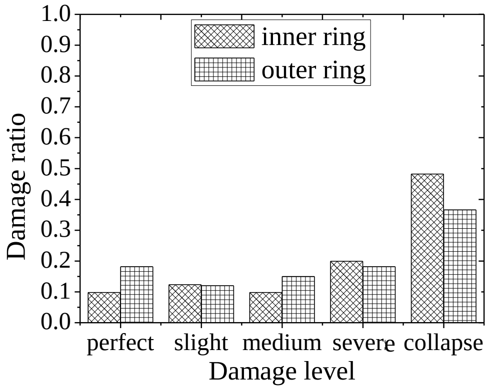

Fig. 12 Damage ratios of masonry buildings in Pre80s'

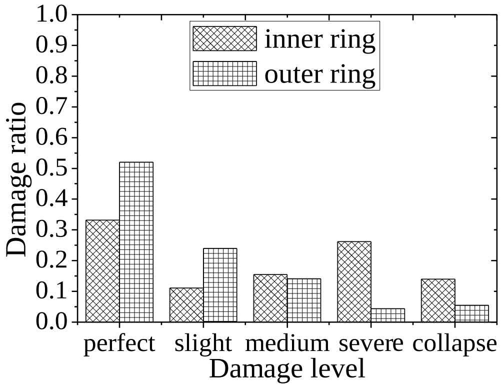

Fig. 13 Damage ratios of masonry buildings in 1980s'

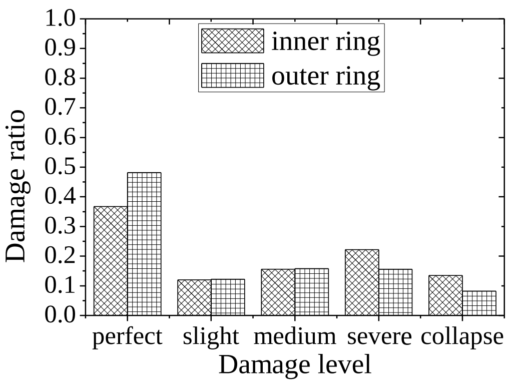

Fig. 14 Damage ratios of masonry buildings in1990s'

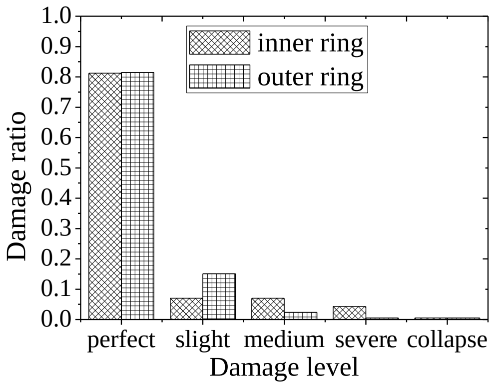

Fig. 15 Damage ratios of masonry buildings after 2000

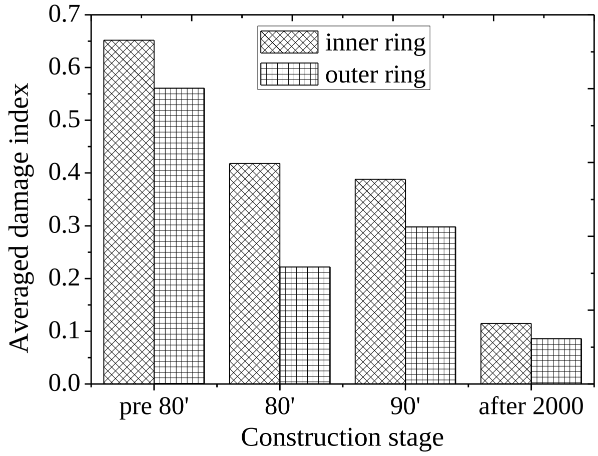

Fig. 16 Averaged damage index of masonry buildings of inner and outer ring part in each age

The seismic damage index of all the investigated multistory masonry structures calculated by Eq. (1) is shown in Fig. 16. Nearly all the structural seismic damage in both rings become slighter when the building age is relatively newer In the inner ring, the seismic damage index of structures built before 1980s, in 1980s and in 1990s are 5.7, 3.6 and 3.4 times of that of structures built after 2000, while in the outer ring, the seismic damage index of the former three changes into 6.5, 2.6 and 3.4 times of structures built after 2000. Comparing the seismic damage index between the inner ring and outer ring on the same seismic capacity level, the seismic damage index of buildings built before 1980s in inner ring is 1.16 times, 1.88 times, 1.30 times and 1.34 times of the indexes for structures in the corresponding construction stage in outer ring, respectively. Thus, it can be observed that the further the structure is away from the mountain, the slighter it is damaged, and the spatial distribution effect in virtue of terrain influence may be a vital factor of seismic damage of buildings.

5. Analyses and discussions of spatial distribution effect of building damages

5.1 Influence of urban construction age evolution

With the evolution of the construction age of buildings, new buildings and old buildings are distributed in different places in the city. Along with the update of the seismic design specifications, newly built structures reveal a better seismic capacity than the early built structures. Fig. 16 shows that the seismic damage index of old buildings can reach 6.5 times that of new buildings. This distribution is the most important factor affecting the spatial distribution pattern of the urban building damage (Lin *et al.* 2009). A study on severe damages and collapses of buildings in moderate to severe earthquake intensities caused by the Wenchuan earthquake was carried out, it is concluded that the seismic design of buildings strictly follows the Code for Seismic Design of Buildings (GB50011-2001) of China, the quality construction and seismic capacity of buildings is assured (Wang 2008). Three different levels of safety margin of buildings structures, referred as fundamental safety margin, integrated safety margin and accidental safety margin, is proposed by

Ye *et al.* (Ye *et al.* 2008). They also put forward that lack of unexpected safety margin in current seismic design code is the main reason of the severe building damage in the Wenchuan earthquake, more researches on the integrated and accidental safety margin should be performed in future structural design. Take the code for design of concrete structures in China as example, along with evolution of the structural design code over the past more than 40 years, several major changes and modification have been made through persistent theory research, experimental verification and engineering practice in 5 generation of code in building material, structural detail, design methodology, performance level (Xu 2010). Structural reliability and seismic performance are remarkably enhanced following the evolution of structural design code in China (Jin *et al.* 2010).

5.2 Spatial difference of earthquake motions

As is known to all, the spatial difference of earthquake motions may lead to a spatial distribution of urban seismic damage. However, reasons for spatial difference of earthquake motions are very complicated, including the effect of topography, geology, earthquake propagation and even structural property of buildings and so on. And some research results reveal that the local topographic or lithology may strongly affect ground motion in areas of highly variable topography (Kaiser *et al*. 2013). The potential causation of spatial distribution of building damage in this city is briefly analyzed herein.

5.2.1 Influence of topography

According to the former research (Geli *et al*. 1988), topography is a significant factor influencing the seismic damage of a certain area. For instance, the basin edge effect imposes more severe damage to structures at the basin edge, which can be attributed to the reason that the shear wave changes into surface wave when incident wave propagates to the highland at the basin edge. At the same time, the incident seismic wave and the reflecting seismic wave reflected by highland at basin edge might be superposed, leading to more serious structural damage. The field data recorded during the 1971 San Fernando Earthquake (Oakeshott 1975), 1980 Fruili Earthquake (Brambati *et al.* 1980), 1985 Chile Earthquake (Celebi and Hanks 1986) and the 1994 Northridge Earthquake (Wennerberg *et al*.1994) authenticated the influence of topography on earthquake motions. The seismic data recorded from Matsuzaki seismograph station (PWRI 1986) is also consistent with this phenomenon. Jibson (1987) utilized peak ground acceleration data during five earthquakes at this seismograph station as the function of rising terrain and normalized the acceleration data to the top of mountain. The regression curve shows that the acceleration changes from the foot of the mountain to the top of the mountain along with the mountain slope: the amplification coefficient of peak ground acceleration at the top of the mountain is 2.5 times of that at the foot of the mountain, whose altitude is only 200 m less than that of the top of the mountain shown in Fig. 17. Although the peak ground acceleration range of in the 5 earthquakes is limited, the influence of topography to earthquake motion is obviously reflected. It is revealed that the basin topography has an amplifying effect on ground motion and would magnify the structural damage in 1303 Hongtong earthquake in the eastern China (Gao *et al*. 2004), that is to say the basin has close relation with distribution of damage, and several studies have been performed by American scientists in Los Angeles and Japanese Scientists in some basins in Japan (Wald and Graves 1998, Satoh *et al.* 2001). In the 2010 Haiti earthquake, the seismic waves affected by surface topography resulted in distinct topographic amplification and led to more severe building damage on a prominent ridge top rather than at nearby soft soil sites (Hough *et al*. 2010). Gallipoli *et al*. (2013) installed temporary accelerometer stations to study the role of site amplification in building damage enhancement, and two of the monitored sites reveal an aggravation factor for slopes and ridges, in which one reflects the spatial distribution of amplification as a function of the site along a slope and the other proves validation of stratigraphic and topographic amplification

The geologic structure system of Dujiangyan City belongs to Cathaysoid tectonic system, located through Longmenshan region of western Sichuan to the top of the Minjiang River Alluvial Fan of Chengdu Plain. Its geomorphic unit belongs to the first bottom of the Minjiang River Alluvial Fan. The north-west part of the city adjoins the Yulei Mountain making the terrain of north-west high and the south-east low. Its downtown is fan-shaped and divided into two parts by the First Ring Road, with a staircase distribution of high mountains, middle mountains, low maintains, hills and plains. As the inner ring is near the mountain with high terrain, this could likely be one of the causation that the structures in inner ring was more severely damaged than those in outer ring, as shown in Fig. 16. In addition, the impact degree of this factor should be further verified by the strong motion records from seismograph stations.

Due to lacking strong motion records from 2008 Wenchuan earthquake, a simulated main shock in Dujiangyan district is synthesized by taking time-history of small earthquake as Empirical Green’s function (Li and Zhang 2011). The small earthquake is simulated by stochastic method at the base of limited aftershock seismic records from ambulatory seismostations. It is conclude that severe earthquake motion occurred during Wenchuan earthquake with approximate peak ground acceleration (PGA) of 400 gal, and it also provide an evident that the PGA in northwest district (the inner ring area in Fig. 1) is significantly larger than that in southeast district (the area nearby outer ring in Fig. 1) of Dujiangyan city. An iso-elevation contour map around Dujiangyan city is provided in Fig.18 to show the topography condtion of Dujiangyan district. Northwest Mountain areas topography may be one important factor to affect earthquake ground motions in Dujiangyan city. The surrounded area by the dotted line is Dujiangyan city (shown in Fig. 1), and surveyed area of building damage is located in this surrounded region. It is obvious that the northwest part and western part of this iso-elevation contour map are mountainous area. So the surveyed area located in inner ring road is more close to the mountainous, resulting in more severe earthquake motions within inner ring road than that around the outer ring road.

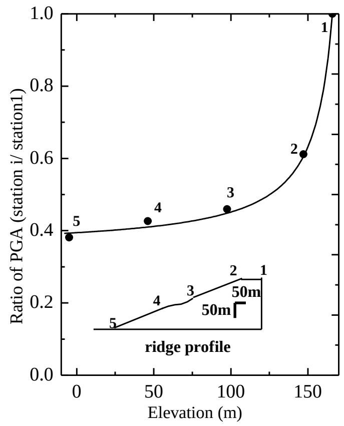

Fig. 17 Relative distribution of PGA along a ridge flank from Matsuzaki array in Japan (Jibson 1987)

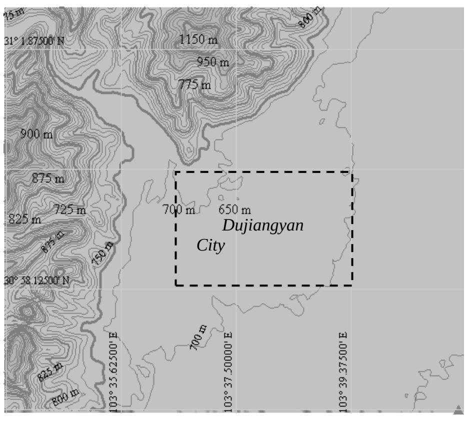

Fig. 18 Iso-elevation contour map of Dujiangyan district

5.2.2 Influence of local site

In earthquakes happened all over the world, more and more evidence have been found that the prominent variance of seismic motions is related to local site condition. Three earthquakes have occurred near Lorca town, located in Murcia province of Spain, in 1999 (Mula), 2002 (Bullas) and 2005 (La Paca) with magnitudes (M_w) of 4.7, 5.0 and 4.8, respectively, and the special relevance of local site effects are contributed to the ground motion amplification cause by shallow geology and the spatial distribution of building damage (Navarro *et al*. 2000, Benito *et al*. 2006, Navarro *et al*. 2007). During 2003 Colima (Mexico) earthquake, the ground motion amplifications revealed in narrow high-frequency bands which may impose severe effects on the extent of building damage and its spatial distribution, and clear spectral peaks had been found in a short period range in the heavily damaged area, but these peaks did not appear at the slightly damaged area (Navarro *et al*. 2008). Similar phenomenon, that is of the prominent relevance to building damage distribution and local site effects, was also verified in another two earthquakes occurred on May 11th, 2011 with epicenter located near Lora Town of Spain (Navarro *et al.* 2012). In seismic design criteria of China, the geological condition of Dujiangyan City is the second type site. However, different distance to the mountain may have different geological condition and site condition. Generally speaking, places near the mountain are bedrock site, and the mountain which the city backs against is made of rock resulted from tectonics. Thus site condition in the inner ring is likely to be harder than that in the outer ring. The seismic damage of high-rise structures in the city is relatively slighter, meaning that the long seismic periodic component is relatively less than the short seismic periodic component. Thus the seismic motion intensity in the inner ring with harder condition might be larger than that in the outer ring. This might be one of the important factors leading to the spatial distribution of seismic damage. If the geological prospecting and site condition data can be acquired, the influence degree of this factor can be further investigated.

5.2.3 Influence of directivity effects during fault rupture

In near-fault regions, long-period pulse-like ground motions with high amplitude and short duration will be caused by forward directivity during fault rupture, and the direction of pulse-like motions is always perpendicular to the fault surface. Extensive researches on the characterization of pulse-like ground motion and its influence on engineering structures resulted from rupture direction effects have been performed in recent decade (Yahyai *et al.* 2011, Casey and Liel 2012). Some research results have shown that pulse-like ground motions have important roles in the distribution of damages over the structural height. Most of rupture direction effect are accumulated in lower 1/3 of 1/2 of structural height and the growing rate of ductility demand at lower parts of buildings height in near fault regions is two times higher than that in far-filed regions (Gerami and Abdollahzadeh 2014). Previous researches have demonstrated that the prominent influence of pulse-like ground motions on structural seismic behavior in near-fault regions, and further investigation on the formation mechanism and implication in anti-seismic design of engineering structures are in progress. The Wenchuan Earthquake caused by the Wenchuan-Yingxiu fault rupture of Longmenshan Fault Zone belongs to near-field earthquake and Dujiangyan is only 21 kilometers from the epicenter. Existing researches show that when fault ruptures, the near fault seismic ground motions might have some distinctive characteristics such as the forward directivity effect and hanging wall effect (Abrahamson and Somerville 1996, Mavroeidis and Papageorgiou 2002, Vladimir and Douglas 2004, Xie *et al.* 2012). As the seismogenic fault of the Wenchuan Earthquake is located at the north-west of the city, the structures in inner ring is more close to the epicenter and rupture fault. Thus the propagation of fault rupturing and the influence of near-fault ground motion effects may be another important factor influencing the spatial distribution of seismic damage.

6. Conclusions

In this investigation, statistical analyses of the seismic damage investigation of structures in Dujiangyan City are presented. Taking the multistory masonry structures for instance, there are two main factors influencing the spatial distribution of building damage, the urban building construction age evolution and the spatial difference of earthquake motion, and comprehensive investigation and potential reasons for the influences are discussed.

The evolution of construction age is the most primary factor influencing the spatial distribution of structural seismic damage. The average damage level of old buildings constructed by former design codes with insufficient seismic bearing capacity is more severe than that of new buildings constructed by current codes. In China, as a result of evolution of structural design criterions, massive dwelling buildings and factory plants are constructed in different ages, revealing multi-aging effect. The strength increase of building material, adoption of reliability design methodology, more rationality of structure system of modern design code in China greatly improve the seismic resistant capacity of modern engineering structures. It is recommended that the performance evaluation and structural retrofitting should be performed on existing buildings constructed by obsolete design guidelines to strengthen structural safety.

The spatial distribution of earthquake motions may be another important factor influencing the spatial distribution of building damage. Comparing the seismic damage of buildings during each construction age, the average seismic damage index of buildings in inner ring is evidently larger than that in outer ring with maximum amplification coefficient of 1.89. It is the evidence that the spatial distribution of earthquake ground motions induced distinguished structural damage in different area away from the mountain. But in current seismic design code of China and many other countries, effects of spatial distribution in a certain city especially near a mountain is seldom considered in structural design of buildings, which should be attracted more attentions in the future structural design.

The causation of the spatial difference of earthquake motions is substantially complicated, including the topography, geology, site condition and propagation of seismic wave generated by rupture fault and other factors. The specific causation needs further studies and analyses according to the geological diversities and strong earthquake observation records. A valuable evidence of multi-aging effect of buildings and spatial distribution of earthquake motions are potential reasons for severe structural damage of buildings. Amplification effect of earthquake motions near fault rupture and mountain topography may be very prominent factor to affect earthquake ground motions. Relevant evidence is provided by seismic inversion method, seismic survey of building damage and topography of Dujiangyan district. So it is necessary that the amplification effect should be considered in seismic design of structures located in complicated topography and near active faults. Site selection of new-built buildings and engineering structures should be considered the spatial distribution of earthquake ground motions. Not only non-uniform excitation of ground motions be further investigated in engineering structural design, topography effect, directivity effect of fault rupture and local site effect also should be involved in seismic analysis, design and reinforcement, especially for engineering structures in mountainous area and near potential active earthquake fault.

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