Assessment and analysis of collapsing houses by aerial images in the Wenchuan earthquake

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Abstract: Information of houses collapsed by the earthquake is one of the important indicators to assess the earthquake damage intensity, and support the emergency decision-making process in rescue and recovery operations. We monitored the house collapse ratio and its spatial variation in the 5.12 Wenchuan earthquake by airborne images, and analyzed its spatial variation relationship with the earthquake intensity, geological structure, stratum lithology and surface rupture caused by the earthquake. The house collapse ratio was derived by visually interpreting ADS40 airborne images acquired from May 15 to May 28, 2008. The results show that the houses were widely damaged in the earthquake-damaged region, especially in Wenchuan County, Mianzhu City, Shifang City, and Pengzhou City and Wenchuan County which experienced the severest damage. We analyzed the spatial variation of the house collapse ratio and its relationship with earthquake intensity, geological structure, stratum lithology and surface rupture caused by earthquake. The results demonstrate that the house collapse ratio and the earthquake intensity have positive relationship, and the ratio of house collapse is controlled by the geological structure, stratum lithology, and building structure too. The house collapse ratios, which are above 50%, mainly distributed along the surface rupture in a SW to NE direction.

Key words: Wenchuan Earthquake, airborne images, house collapse, earthquake intensity, surface rupture

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1 INTRODUCTION

The condition of houses collapsed by the earthquake reflects the damage intensity of earthquake, and is the important information to assess the losses of life and property in the earthquake-hit area. The collapsing house is referred to completely or partially damaged houses which can not be repaired in this paper. It is easy to recognize the collapsing houses in aerial images with the high spatial resolution directly although the damaged degree of houses can not be identified. Many investigations have demonstrated that the ratio of collapsing houses can be obtained by the visual interpretation of aerial images (Fan *et al.*, 2008; Hasegawa, 2001; Yang, 1993, 1994) and the computer auto-recognition (Liu, 2004), while the visual interpretation has shown the great reliability. As the robust approaches of computer auto-recognition are not available at present, the visual interpretation of aerial images is still being mainly applied now although it needs lots of manpower.

The Wenchuan Earthquake with a magnitude of 8.0 struck Sichuan Province, China on May 12, 2008. Many houses collapsed due to the shallow focus earthquake and large seismic intensity, and a heavy loss of life and property was suffered in the earthquake-hit area. The Chinese Academy of Sciences established a working group soon after the earthquake, which aimed to promptly acquire the aerial images and satellite images, and by interpreting and analyzing of pre- and post- remote sensing images to provide the information of damage conditions caused by earthquake disasters such as road blocks, house collapses, secondary geological disasters to the relevant governmental rescue officials. This paper demonstrates the disaster conditions of collapsed house which was one of the results assessed by the aerial images in the working group, and discusses the relationships between the spatial variation of house collapses with the seismic intensity and surface ruptures which were investigated by the field work after the earthquake and reported by Chen (2008), Zhang (2008), Xu (2008).

2 INFORMATION OF HOUSE COLLAPSES OBTAINED BY AERIAL IMAGES

The aerial images with the spatial resolution of 0.5m were obtained from May 15 to May 28, 2008 by ADS40 digital

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sensor boarded on two planes of airborne remote sensing that the Chinese Academy of Sciences posses. The images covered 14 severely damaged counties or cities in Sichuan Province. Fig. 1 shows the area of aerial images, the population centre of residential areas in the earthquake-hit area as well as the locations of residential areas where the collapsing houses were interpreted.

The data volume of aerial images, which covered the large area as shown in Fig.1, is about 2Tbytes. As there is not an effective method of computer auto-recognition for collapsing houses in the large area using the massive aerial data available, the visual interpretation of aerial image by human-computer interaction was adopted to assess the condition of collapsing house in the working group. The ratio of collapsing house were respectively derived over the densely populated area in the anterior mountain plains and the total disaster area of 14 counties with the following methods based on the visual interpretation of collapsing houses status in 0.5m aerial images.

Method 1: Visually estimating the ratio of collapsing houses for the densely populated area in the anterior mountain plains

For regions with dense populations including Pengzhou, Shifang, Mianzhu and Anxian which locations of population centre are shown as the orange color points in Fig.1, we sketched out the polygons of residential blocks and visually estimated the ratio of collapsing houses occupied over each polygon. The ratio of collapsing houses ranges from 0% to 100% by 10% increments. The result is shown in Fig.2.

Method 2: Spatial distribution of the house collapses over large disaster area based on the approaches of sampling and interpolating

There are the residential areas over 40 thousand points including cities, townships and villages in the cover area of aerial images. If we interpreted the house collapses for the total of population regions, it should be impossible to get the information of disaster situation for collapsed house in short time. Therefore we chose 101 bigger residential areas within the 14 counties as the samples shown as dark red color in Fig.1. The collapsed and non-collapsed houses were visually interpreted within a 1km × 1km area around the center of each town in the aerial images. The house collapse ratio was calculated as the ratio of the collapsed houses area to the sum of interpreted collapsed and non-collapsed houses areas. Furthermore, the spatial distribution of house collapse ratios was derived by interpolating the house collapse ratios of 101 samples into raster data with 70 m grid using the inverse distance weighted method.

Method 1 is faster than Method 2 for the same area because the interpretations of collapsed and non-collapsed houses need longer time. However it can be inferred that the collapse ratio of the Method 2 is more accurate because the ratio of collapsing houses statistically calculated by the visual interpretation of collapsed and non-collapsed houses is more confident than visually estimating the ratio of collapsing houses directly. In order to quickly evaluate the damage degree of house collapsed, we adopted directly visual estimation of collapse ratio for the regions with dense populations located in the anterior mountain plains in the earlier stage of assessing earthquake disaster. The

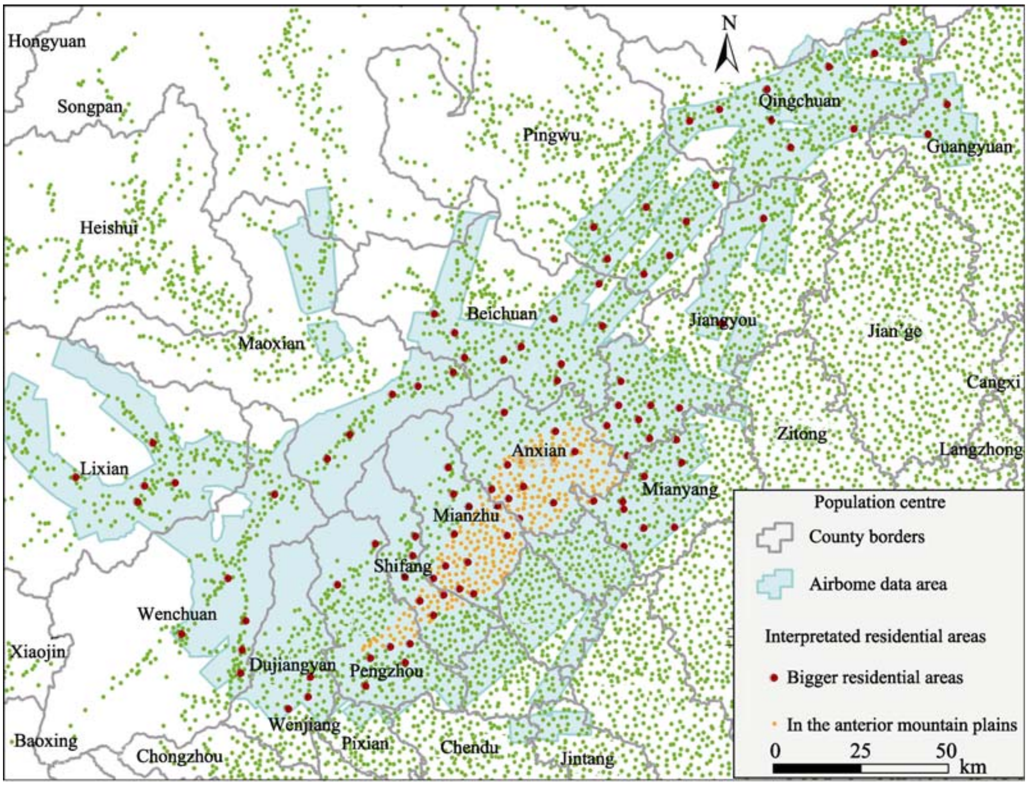

Fig. 1 Cover area of aerial image and the residential areas of visually interpreted collapsed house in the disaster area of the Wenchuan earthquake

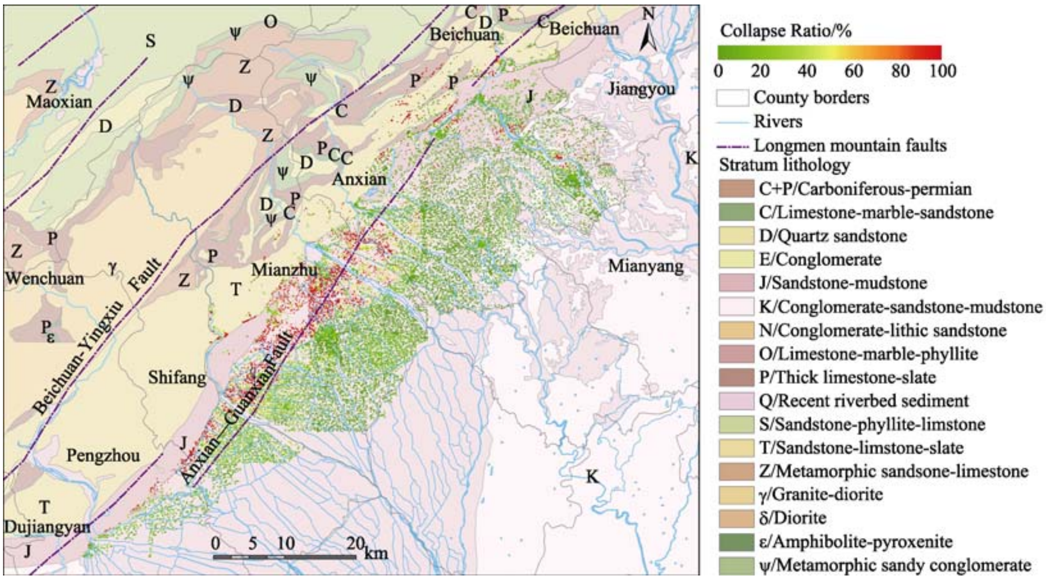

Fig. 2 Spatial variation of house collapse ratio in the counties of piedmont plain

overall situation of house collapses was evaluated by interpolating the ratios of collected samples which collapse ratios were derived from the statistics of visually interpreted collapsed houses and non-collapsed houses for the post-earthquake reconstruction plan in the later stage of our working. Comparing the collapse ratios with two methods in the same region, it was found that their difference is less than 5% as the collapse ratios is above 50%, but the difference is from 5% to 10% as the rang of collapse ratios is between 20% and 50%, that may be affected by the un-certainty of visually estimation of the collapse ratio in Method 1.

3 RESULTS AND DISCUSSION

3.1 Spatial variation of collapse ratio for the densely populated area in the anterior mountain plains

The degree of house damage caused by earthquake is determined by earthquake intensity, the features of the site media for seismic wave propagation, and the earthquake-resistant capability of the building structure. The earthquake intensity is a constant value for an earthquake. But the features of the site media for seismic wave propagation are influenced by the terrain, stratum lithology, geological structure, and hydrology, etc. The earthquake-resistant capability is related to the building structures and types, house foundation, and the construction quality. The lithology in the anterior mountain plains is mainly the quaternary floodplain sediments which stratum is loose, where the population is very dense across Pengzhou City, Shifang City, Mianzhu City and Anxian. Fig. 2 demonstrates the spatial variation of the house collapse ratio interpreted overlapped with the Longmen Mountain Fault and lithology map in the anterior mountain plains.

Based on the analysis of the geographic distribution and its relationships with geological fault and lithology, the following features regarding the collapsed houses were found.

(1) The house damage is severest in Mianzhu City.

The houses in many residential areas of Mianzhu city (100 km northeast of the epicenter), including nine towns extending northeastward from Guangji Town to Gongxin Town, were almost totally collapsed into a flat surface, which means that the collapse ratio is over 80%. The house collapse ratio is higher in the rural areas than in the urban areas, because the design of the building structure in the countryside did not take earthquake resistance into consideration. For example, in Mianzhu City, the house collapse ratio is below 30% in the towns, but reached over 60% in the countryside.

(2) Effect of the Longmen Mountain Fault and stratum lithology is significant.

Shifang City and Mianzhu City, located in the center of the Anxian-Guanxian Fault along the Longmen Mountain Fault, suffered the severest damage. The degree of house collapses decreases significantly from the center to the end of the fault (e.g. Pengzhou City and Anxian). Moreover, some scattered residential areas along the banks of the Anchang River in Anxian have a high house collapse ratio. This phenomenon may be related to the attenuation features of the seismic wave in the anterior mountain plains and the controlling effect from the stratum lithology. The stratum lithology in Anxian consists of sandstones, mudstones, and a mixture of sandstones and mudstones in the modern fluviatile deposits.

3.2 Spatial variation of collapse ratio and earthquake intensity

Fig. 3 shows the spatial distribution of the collapse ratio overlaid with the earthquake intensity and surface ruptures data. The earthquake intensity is from the project team of the national reconstruction plan after the Wenchuan Earthquake, which was provided by the China Earthquake Administration.

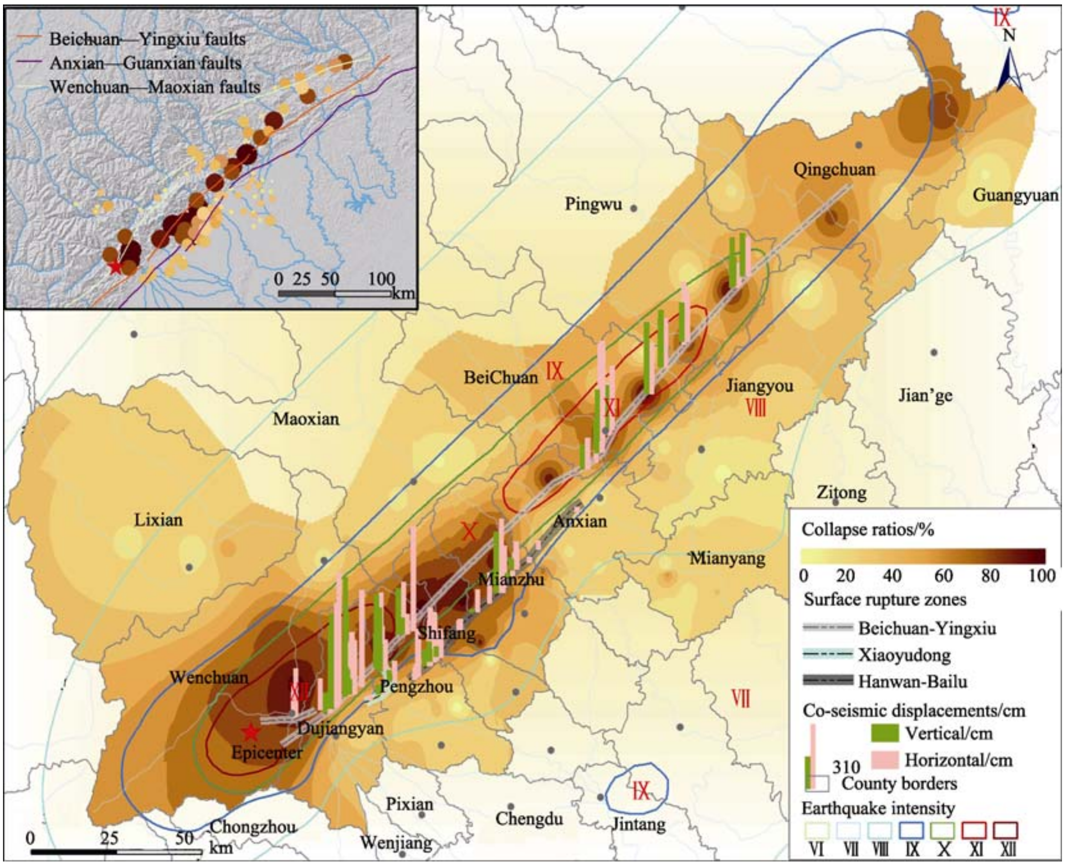

Fig. 3 Map of house collapse ratio interpolated by the samples shown in the left upper corner of map, which is overlapped with earthquake intensity and measured co-seismic vertical (light red bar) and horizontal (green bar) displacements along to Beichuan, Pengguan and Xiaoyudong rupture zones

The data of surface ruptures is referred to the results of field investigation carried by Xu *et al.* (2008).

The following results are obtained regarding the overall spatial variation of collapsed houses by Fig.3.

(1) The severest damage occurred in the places close to epicenter and extended to the north-east, such as Yingxiu Town and Yingxiu Town in Wenchuan County, Tianchi Town and Hongbai Town in Mianzhu City, Beichuan County, and Chenjiaba Town, where the house collapse ratio is over 90%.

(2) Wenchuan County suffered the most extensive damage. Most houses in Mianzhu City, Shifang City, and Pengzhou City suffered house damage with a collapse ratio of over 60%. Because these cities have high residential density as shown in Fig. 1, it can be estimated that the Wenchuan Earthquake had the strongest impact on the residents of these three cities.

(3) In the regions 100 km, 150 km, and 300 km northeast of the epicenter, the houses were widely collapsed. During the propagation of earthquake wave, the rupture was obstructed, thus the distribution of the static-slip displacement was scattered. A rupture vacant zone appeared in the obstructed areas. The spatial distribution of the house collapse ratio in this study shows a similar spatial variability as the rupture process reported by Chen *et al*. (2008).

(4) By the field investigation after the earthquake carried by Xu *et al.* (2008), it was found that three surface rupture zones occurred over the Longmensan tectonic belts on eastern margin of Tibetan plateau in the Wenchuan earthquake, which are Beichuan—Yingxiu, Hanwan—Bailu and Xiaoyudong. This earthquake generated a 240 km long surface rupture along the Beichuan—Yingxiu Fault characterized by right-lateral oblique faulting. Maximum vertical and horizontal displacements of 6.2m and 4.9m, respectively, were observed along the Beichuan—Yingxiu Fault. It can be seen as shown as Fig.3 that the collapse ratios are above 60% along the surface rupture zones of Beichuan — Yingxiu, Hanwan — Bailu and Xiaoyudong. When statistically analyzing the correlation between the collapse ratio and the displacements as shown in Fig.4, it was meaningfully found that the collapse ratio tends to increase with the increment of horizontal displacements, whereas there is not corresponding relationship between the collapse ratios with the increment of vertical displacements. It is necessary to further investigate and verify the relationship between the horizontal and vertical displacements with collapsed house shown in Fig.4.

(5) Linear correlation between collapse ratios with earthquake intensity was shown. The house collapse ratio from 80% to 100% corresponding to the earthquake intensity of 11 (XI) degrees, extends from the epicenter to the northeast, in Yingxiu Town and Yingxin Town in Wenchuan County, Dabao Town

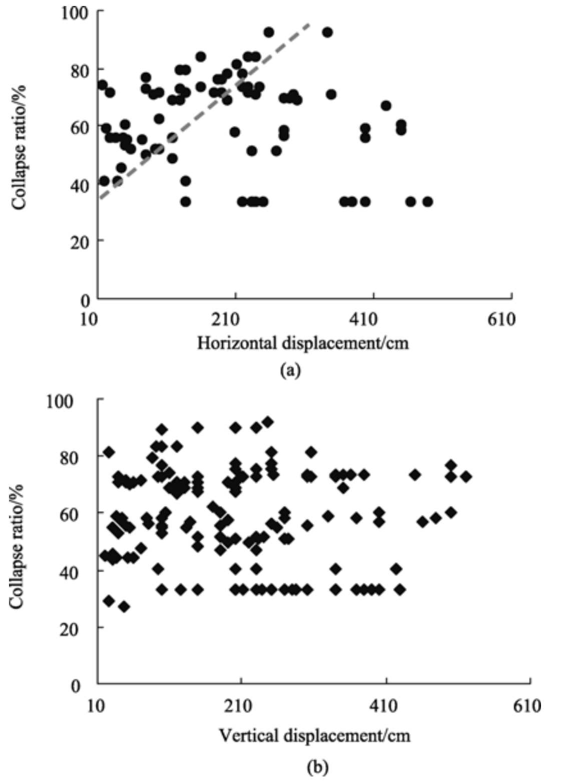

Fig. 4 House collapse ratio and measured co-seismic horizontal (a) and vertical (b) displacements

and Jingtang Town in Pengzhou City, Hongbai Town in Shifang City, Tianchi Town in Mianzhu City, Beichuan Town, Chaping Town, and Chenjiaba Town in Beichuan County, and Nanba Town in Pingwu County. The spatial distribution of the high house collapse ratio along a southwest-northeast direction presents very similar patterns with the earthquake intensity as shown in Fig. 3. Moreover when their relationship was also statistically analyzed by the least square method, a linear relationship between earthquake intensity and house collapse ratio was revealed with the coefficient of determination above 0.9. The linear regression equation is

$$y = 14.664x - 85.218 \quad (1)$$

where x is the earthquake intensity and y is the house collapse ratio. The correlation coefficient r^2 is 0.94, standard deviation is ±5.8. The result was very similar to the Tangshan earthquake (Yang, 1994) shown in following regression equation:

$$y = 17.205x - 101.861 \quad (2)$$

where r^2 is 0.96, standard deviation is ±2.96. Their linear regression coefficients are very near although reasons of the Wenchuan earthquake and Tanshan earthquake are different. Whereas the relationship between earthquake intensity and house collapse ratio showed a power function in Japan based on the statistics of previous earthquakes, and the house collapse ratio is larger in China than in Japan in the low earthquake intensity. It may be reasons why the anti-seismic design of the building structure in China has not standards especially in the consideration.

4 CONCLUSION

The houses in the cities and towns experienced extensive damages and a large number of people were killed or injured in the Wenchuan Earthquake of May 12, 2008. The Wenchuan earthquake had several distinct features, such as a shallow epicenter, high magnitude of 8.0, and a high earthquake intensity of 11 (XI) degrees which is almost close to the climax. The high intensity and strong vibration were the major causes of the house collapsed.

Compared with the ground investigation, we were able to monitor the house collapse in a large region using aerial images. Moreover based on the statistical analysis of correlation between the house collapse ratio derived by the aerial images and earthquake intensity reported by the China Earthquake Administration, it was found that the house collapse ratio present strong correlation with the earthquake intensity. Our results agree well with the analysis of the surface rupture process caused by the earthquake that was performed by seismologists, which implies that the visual interpretation using aerial images is effective. And the results indicate that the earthquake intensity data can be used to give a rough assessment of the house damaged status based on the linear relationship between the house collapse ratio and earthquake intensity in China when high spatial resolution remote sensing data are not obtained. Moreover by incorporating the images with the geological data, we can effectively assess the spatial distribution of house collapse and provide scientific information for evaluating the damage conditions and the earthquake intensity.

The techniques of remote sensing had played a significant role in assisting the disaster relief and post-disaster reconstruction in the Wenchuan Earthquake (Li, 2008; Zhang, 2008). The results of the house collapse assessment shown in this paper have been used as fundamental data in the project of "Evaluating on Resources and Environment Carrying Capacity" which is one of the special projects called for by the National Reconstruction Plan after the Wenchuan Earthquake.

Concluding our experience of remote sensing application in the Whenchuan earthquake, it is urgently necessary for (1) developing the robust method of computer automatic or half automatic recognition of collapsing houses, (2) modifying the functions of visual interpretation and quickly overlapping display with GIS in the human-computer interaction because the quickly visual interpretation by experts is indispensable even so there will be computer automatic recognition available.

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汶川地震房屋倒塌的遥感监测与分析

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摘　要： 地震灾害中房屋倒塌受害程度表征了地震作用下地面运动的强度大小以及地震灾害造成的人员经济损失状况。2008-05-12 汶川大地震震级高达八级，最大烈度接近极限达 11(XI)度，波及区域范围广，造成大面积房屋倒塌。利用航空高分辨率光学遥感图像，基于房屋倒塌的图像目视判读及插值方法获取了大面积受灾区房屋倒塌灾情信息，结合灾区地震烈度和地震地表破裂带相关数据对房屋倒塌受害程度的空间变化特征进行了分析与评价。判明在汶川地震灾区房屋普遍受害，其中以汶川县房屋倒塌受害最重，其次是绵竹市、什邡市、彭州市。房倒率与地震烈度成线性对应关系，房屋倒塌严重区沿龙门山断裂呈西南-东北向分布。

关键词： 汶川地震，航空图像，房屋倒塌，地震烈度，地表破裂

中图分类号： TP79　　文献标识码： A

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1　引　言

地震房屋倒塌状况反映了地震的破坏强度，是受灾人口推测、经济损失评估以及灾后重建规划的重要的灾情信息之一。本文房屋倒塌系指房屋全毁或房屋顶部大部分倒塌，即不可能修复的房屋。高空间分辨率的航空光学图像能直观地反映房屋倒塌的情况但很难识别房屋被破坏的程度。通过航空图像可以容易地目视判别出全毁房屋或屋顶部大部分倒塌的房屋。过去的地震灾害调查表明，利用高分辨率光学图像，基于倒塌与未倒塌房屋的图像特征，通过遥感图像的目视判读(范一大等，2008；Hasegawa 等, 2001；杨喆，程家喻, 1993,1994)或计算机的自动识别方法可以获取房屋倒塌的比率(以下称房倒率)(柳稼航等, 2004)。其中目视判读精度具有一定的可信度，计算机自动识别还处于方法探索研究中，目前没有一个成熟的适用性较强的方法。目视判读虽然工作量大，但它具有一定的可靠性，是目前采用的主要方法。

2008-05-12 四川省发生的汶川 8 级大地震，由于地震震级高、震源浅、烈度大，导致大量的房屋倒塌，加之受灾范围广、受灾区人口居住密度高，造成了巨大的人员伤亡。汶川地震发生后中国科学院成立了“汶川地震灾害遥感监测与灾情评估工作组”，建立从航空航天遥感数据获取、灾情快速判读分析评估到灾情信息综合分析实时上报的遥感灾害监测与灾情评估体制，为减灾救灾部门提供了遥感灾情信息。其中工作组利用航空光学图像提供了灾区有关房屋倒塌灾情信息，针对其部分调查结果，利用汶川地震后陆续发表的有关地震产生的地表破裂过程等调查结果(陈运泰等, 2008；张勇等, 2008；徐锡伟等，2008)，对遥感判读获取的房屋倒塌空间变化与地震烈度及地表破裂带的关系展开分析论述，为灾害应急监测与灾情评价提供遥感应用示范实例。

2　房屋倒塌空间变化信息的获取

汶川地震发生后，中国科学院在 5 月 15 日至 5 月 28 日航空飞行了 0.5m 高空间分辨率 ADS40 数字光学图像，图像覆盖了汶川县至青川县等 14 个地震重灾县市(图 1)。

由于汶川地震受灾区面积大，航空遥感覆盖获

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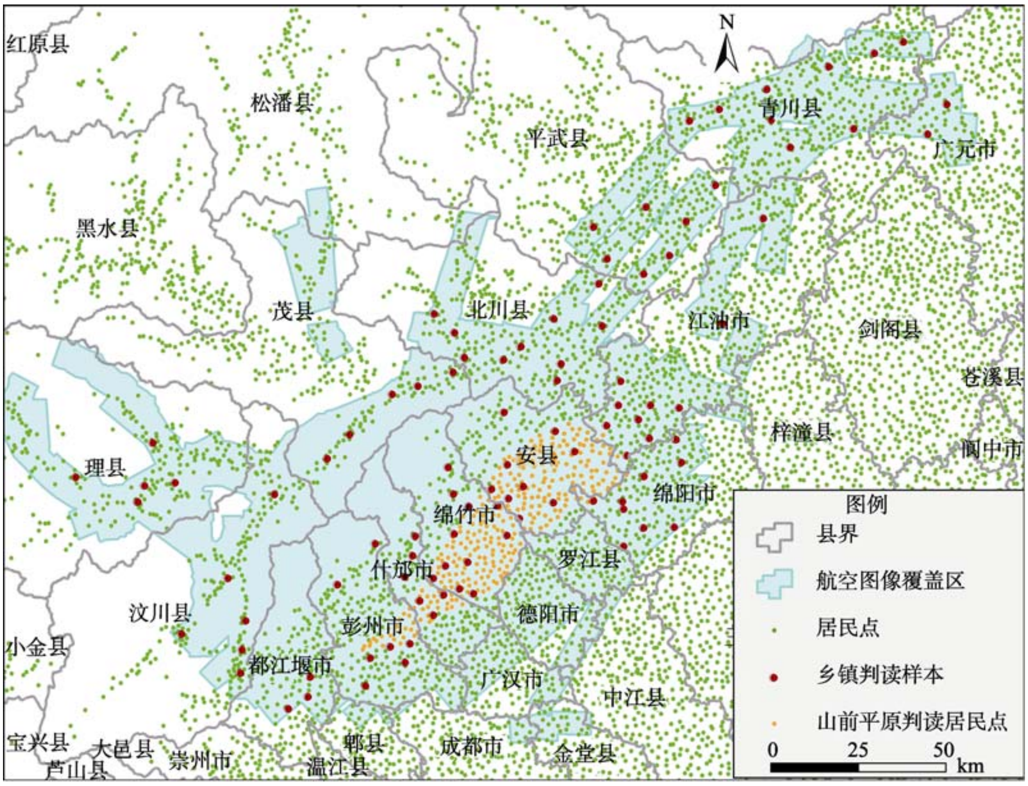

图 1 汶川地震灾区房屋倒塌判读区及样本的分布

取的光学图像数据量达到了约 2 TBytes。鉴于目前还没有一个适用于大范围受灾区以及海量遥感图像的房屋倒塌计算机自动识别方法可以利用，本文作者以图像目视判读为基础，分别获取了下述山前居民点密集区房屋倒塌和灾区房屋倒塌空间分布信息。

方法一 山前居民点密集区房倒率的目视判估

汶川地震发生后，汶川县、绵竹市以及什邡市等地房屋倒塌严重。如图 1 所示绵竹、什邡等县市的山前平原区人口密集，为把握人口密集区房屋倒塌灾情，我们对彭州市、什邡市、绵竹市、安县的山前平原的居民点区(图 1 中橘红色点区)进行了房倒率图像快速目视判估。对山前平原逐个居民点以房屋聚集区为单位勾画出图斑，然后目视判估图斑内倒塌房屋所占比率即得到图斑的房倒率(图 2)。

方法二 基于采样判读插值方法获取灾区房倒率空间分布信息

由于受灾区面积大，仅航空图像覆盖区内居民点就有 4 万个以上(图 1)，若对灾区所有的房屋进行遥感判读，其工作量之大是不可能短时间内快速地得到大面积房屋倒塌受灾情况。我们从图像覆盖区的 14 个县市选取 101 个乡镇乡村样本(图 1 深红色点)进行了房屋倒塌判读，然后采用空间插值信息处理方法进行样本插值得到大面积房屋倒塌信息。样本判读以每个乡镇政府驻地为中心基本在约 1km×1km 范围内，利用灾后获取的高空间分辨率航空图像，分别目视判读勾画出倒塌房屋和未倒塌房屋区，统计倒塌房屋面积占被判读房屋总面积(倒塌房屋面积与未倒塌房屋面积的和)的百分比即为房倒率，由此得到 101 个样本的房倒率。然后利用距离反比插值方法对 101 个样本的房倒率进行插值，得出灾区总体房倒率的空间分布(图 3)。

上述方法一和方法二房屋倒塌灾情信息获取中分别使用了不同的目视判读方法：由目视直接估计房倒率和通过逐一判读倒塌房屋然后统计得到房倒率。在高空间分辨率的航空图像上，依据倒塌房屋的特征可以准确地判读提取出倒塌房屋，但若在一定区域的图斑范围内由目视直接估计倒塌房屋占判读区房屋的比率(房倒率)受判读者主观判估的影响较大。因此，上述由判读倒塌房屋然后统计得到的房倒率(方法二)比由目视直接估计房倒率(方法一)的精度要稳定。但方法二需要逐一判读倒塌房屋，对同样区域面积的判读，与直接目视判估房屋倒塌率的方法比较要耗时很多。两种方法各有利弊，工作组在灾情遥感监测的前期为了快速获取居民点密集区房倒灾情信息采用了目视直接估计房倒率，而

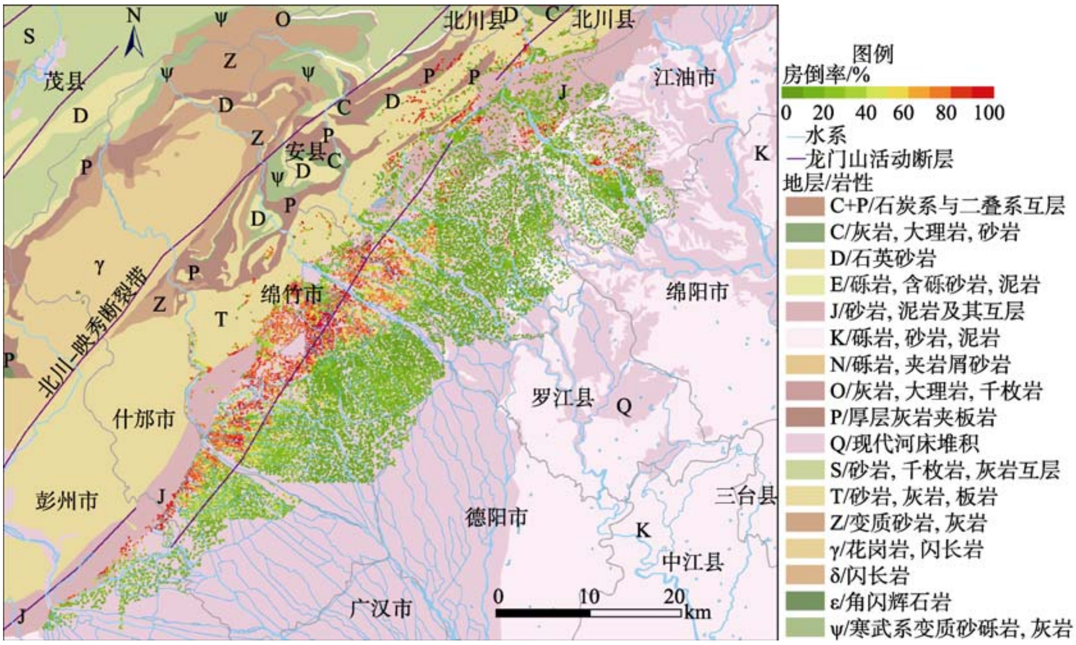

图 2　山前平原居民点密集区房倒率的空间变化

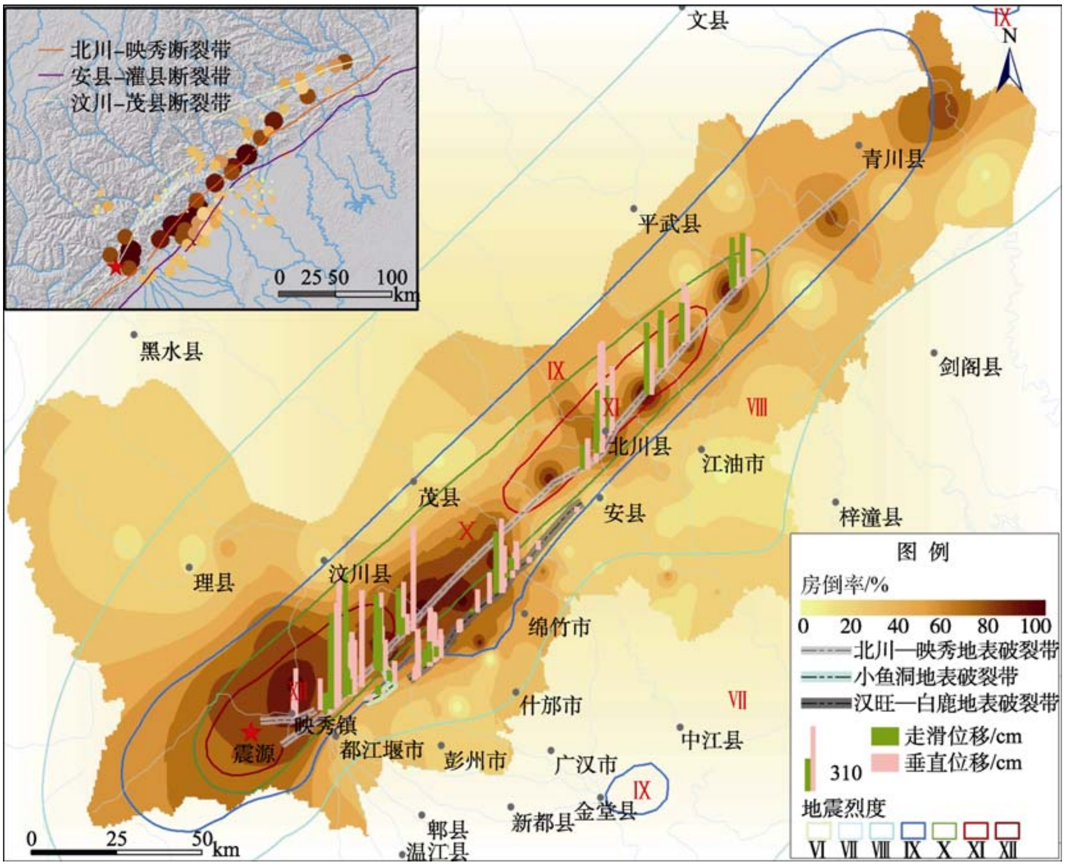

图 3　汶川地震重灾区房倒率插值图与地震烈度、龙门山推覆构造带中段地表破裂带及其同震位移分布

后期为了给灾后重建规划提供灾区总体房倒灾情，采用了样区采样逐一判读倒塌房屋，然后插值得到灾区总体房倒率的空间变化信息。针对相同判读样本区，我们比较了两种方法所得到的房倒率，在房倒率 50%以上的值域，两方法的结果相差很小，均在 5%以下，并且房倒灾情的空间变化规律，两方法

有着一致性的结果；但在 20%—50%值域，两方法的结果相差为 5%—10%，这与判读者对于房倒率在20%—50%之间的目视判估不稳定有关。

3 结果与讨论

3.1 山前平原居民点密集区房屋倒塌的空间变化

地震对房屋倒塌的损毁，通常取决于地震的强度、传播地震波的场地介质特性及其房屋建筑的抗震性能。传播地震波的地介质特性受所处地段的地形地貌、地层岩性、地质构造及其水文地质等条件的影响。另外房屋建筑的抗震性能与建筑结构类型、地基及其施工质量等有关。汶川地震灾区的山前平原主要属第四纪河漫滩的现代河床堆积、地层岩性疏松。该区居民点密集，涉及彭州市、什邡市、绵竹市及安县，图 2 为该区目视判估的房倒率叠加在地层岩性和地质构造的结果。

从图 2 显示的地域分布和与地质构造的关系上分析，房屋倒塌明显呈现出以下的特点。

(1) 地域分布上以绵竹市房屋倒塌最为严重。距震源北东约 100km 处，在强大的地震烈度下，绵竹市从广济镇沿北东向至拱星镇之间的 9 个乡镇大片的民房倒塌，很多居民区被夷成了平地，房倒率达 80%以上。另外房倒率有农村房屋比城镇高的趋势；以绵竹市为例，县城城区平均房倒率低于 10%，乡镇平均房倒率低于 30%，农村平均房倒率高于60%。这与农村房屋建筑没有抗震设计有关。目前农村相当数量房屋属于自建住房，没有一定的抗震设计和建筑标准，缺乏灾害防灾能力。在恢复重建过程中，农村住房质量和抗防震问题应该给予高度的重视。

(2) 在房屋倒塌与龙门山断裂带活动断层及地层岩性的关系上，龙门山安县—灌县断裂带纵贯该区，此断裂带中心部什邡、绵竹房屋倒塌严重，中心向两端彭州、安县房倒率明显下降。如图 2，绵竹市的山前为现代河床堆积，岩性并没有很大的变化，但房倒率却有着明显的空间变化，初步推测该区的房屋倒塌与地震波的破裂过程及断裂带有关。但在安县沿安昌河两岸明显地零星散布有房倒率高区，这与该地段沿河区松软的砂岩、砾岩、泥岩及现代河床堆积的地层岩性有关。

3.2 房倒率的空间变化与地震烈度

图 3 为基于 101 个乡镇乡村的房倒率判读结果(左上角的缩小图)进行距离反比插值，得出的灾区总体房倒率空间分布与地震烈度、地表破裂带及其同震位移叠加的结果。地震烈度数据来自于国家汶川地震灾后重建规划“资源环境承载能力评价”项目组；地表破裂带及其同震位移数据源于徐锡伟等(2008)实地调查发表的汶川 M_s8.0 地震地表破裂带基本参数一览表。

分析图 3 所示地震灾区房倒率的空间分布，呈现了以下的变化特征。

(1) 由震源附近汶川县映秀镇和银杏乡、向北东延伸绵竹市的天池、红白、至北川县城及陈家坝，房屋震害严重，倒塌率均在 90%以上；

(2) 房屋倒塌以汶川县受害覆盖范围最大；绵竹市、什邡市和彭州市山前平原地带的房屋倒塌严重，倒塌率大于 60%以上的乡镇分布很多。该区居民点密集、人口众多，高房倒率导致灾区该 3 市的受灾人口最多。

(3) 房倒率大于 60%的值沿西南—北东向呈波动性变化分布。

由震源向北东方向约 100km 房屋普遍倒塌，并在约 150km 及 300km 处再次出现房屋普遍倒塌。陈运泰等(2008)对于汶川地震破裂过程分析研究中指出由于破裂在传播过程中遭遇了多个障碍体的阻挡，整个断层面上的滑动位移分布比较零散，受阻挡区域出现破裂空区。本文得出的房屋普遍倒塌的空间分布规律与陈运泰等(2008)报告的破裂过程有着非常相似的空间变化规律。

(4) 房屋倒塌严重区主要沿着地震产生的地表破裂带分布。

徐锡伟等(2008)的震后应急野外考察表明，汶川地震在青藏高原东缘龙门山推覆构造带上产生了 3 条地表破裂带：北川—映秀地表破裂带、汉旺—白鹿地表破裂带、小鱼洞破裂带，其中沿北川—映秀的断裂展布的北川—映秀地表破裂带是汶川地震的主体地表破裂带，长约 240km，最大垂直位移620cm，最大右旋走滑位移 490cm。图 3 显示了房屋率大于 60%以上的区域主要分布在北川—映秀地表破裂带、汉旺—白鹿地表破裂带和小鱼洞破裂带上的小鱼洞镇附近。分析地表破裂带上调查的走滑位移量和垂直位移量与房倒率关系(图 4)，发现房倒率随水平位移量的增大有着增加的趋势，但与垂直位移量没有显示出对应的关系，解释该现象还有待对地震运动对房屋产生的破坏力进一步的研究分析。

(5) 房倒率与地震烈度呈线性对应关系。

如图3，由震源向北东延伸，房屋普遍倒塌的汶川县映秀镇、银杏、彭州市大宝、经堂、什邡市红白、绵竹市天池、北川县城、茶坪、陈家坝、平武

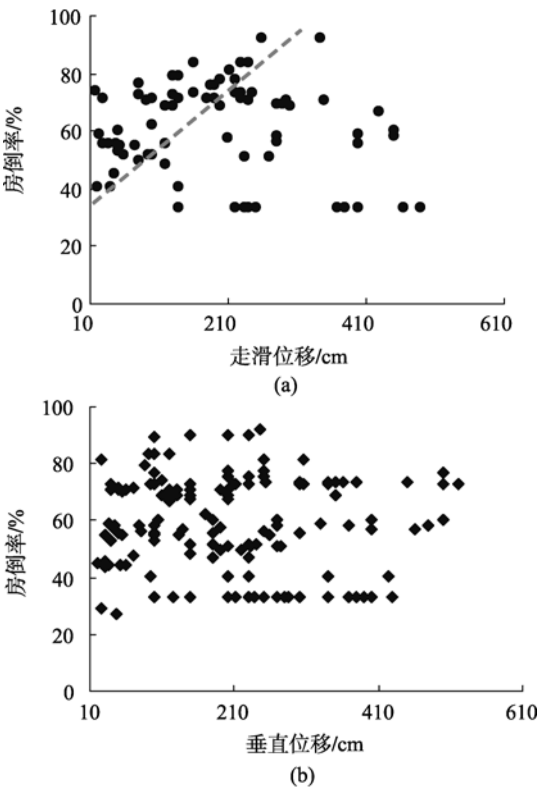

图 4 房倒率与走滑位移量和垂直位移量的关系

县南坝等倒塌率达 80%以上对应了地震烈度 11(Ⅺ)度。并且地震烈度 10(Ⅹ)在彭州市、什邡市、绵竹市的等值线与房倒率为 60%的等值线非常吻合。利用最小二乘法对地震烈度与房倒率判读样本进行直线相关分析发现房倒率与烈度有着很好的线性关系，其关系式为

$$y = 14.664x - 85.218 \tag{1}$$

其中 x 为烈度，y 为房倒率，相关系数 r^2=0.94，剩余标准差为 S=±5.8。该结果与杨喆等在唐山地震中房屋倒塌与地震烈度的直线拟合分析得到的下式(杨喆，程家喻, 1994),

$$y = 17.205x - 101.861 \tag{2}$$

其中 r^2=0.96；S=±2.96 有着近似的线性系数值。虽然两次地震有着不同的成因特点，但房屋倒塌与烈度显示了相似的线性关系结果。在日本根据历次大地震灾害的统计分析，地震强度与房倒率并不呈线性关系，而呈现出随地震强度的增大房倒率呈缓慢增加然后急剧增加的乘幂函数关系。在低地震烈度下中国房倒率呈现出比日本高的趋势。虽然两国地质条件不同，但这与中国特别是农村的建筑结构防震设计及质量管理等方面远没有日本严格规范有很大的关系。日本的地震频度和强度非常高，对各类工程抗震设防水平和抗震能力建立规范标准是日本政府为提高公众的减灾意识、减轻地震灾害的主要手段之一。

4 结论与讨论

在“5.12”汶川大地震中，城镇住宅和农村住宅大量倒塌，死伤人数多，显著特点是震源浅，震级高达八级，烈度最高达到 11(Ⅺ)度，最大烈度已经接近极限。烈度大、震动强是造成房屋倒塌严重的主要原因。

本文汶川地震房屋倒塌的遥感监测与评价的结果表明，为快速获取大面积地震灾区房屋倒塌灾情信息，针对上万个居民点，采取样本选择进行图像房屋倒塌判读然后利用数据插值处理方法，可以快速有效地得到灾区房屋倒塌灾情全局空间变化信息。该方法虽然是目视判读，却也不失为房屋倒塌灾情评价的有效手段之一。与地面调查相比，房倒率空间变化遥感监测信息为灾区提供了更科学宏观的灾情分布信息。另外，基于本文房倒率与地震烈度及地表破裂带关系的研究结果表明，在提供地震灾情信息的科学服务中，遥感监测结果结合地震烈度、地面地震实测、人口等其他数据，可以为地震灾害人员救助及灾后重建等提供全局性的判断决策依据。在汶川地震的救灾减灾中，遥感空间信息技术发挥了重要作用(李德仁等，2008；张继贤等，2008)。

为使遥感技术能够实现快速准确地为地震灾害监测与评估提供科技服务，总结本次汶川地震房屋倒塌灾情评价的遥感应用经验，我们认为今后有必要在以下的两方面展开深入的研究与技术开发：(1)鲁棒性计算机房屋倒塌信息自动或半自动快速提取方法的研究开发；(2)即使有房屋倒塌的计算机自动识别，专家的遥感图像快速目视判读分析和自动识别结果的确认分析还是不可缺少的，因此需要改进图像与 GIS 数据快速叠加显示和人机交互判读功能。

致 谢 汶川地震房屋倒塌的航空图像判读中，中国科学院对地观测中心与数字地球科学中心的储成赞、陈爱莲、吴燕华等学生参与工作，特此致谢。

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