Urgent monitoring and analysis on Yushu Earthquake using remote sensing

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Abstract: At 7:49 am on April 14, 2010, an earthquake (Ms 7.1) originated (33.2°N, 96.6°E) near Jiegu Town, Yushu Tibetan Autonomous Prefecture, Qinghai Province, China. After the earthquake, we analyzed the geological structure of the disaster region based on the "Beijing-1" images. Using the aerial images after earthquake with high resolution (0.4m) and SPOT ortho-images, we monitored urgently the disaster situation, including the damage degree of the buildings, the damage degree of the lifelines, the field disasters and the secondary disasters. The result could provide the important basis for emergency management and rescue mission.

Key words: Yushu Earthquake, remote sensing, urgent monitoring

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1 REMOTE SENSING APPLICATION IN EARTHQUAKE DISASTER

Earthquake is one of the major natural disasters in China. In particular, the sudden, devastating disaster caused by a strong earthquake will bring great harm to life and property. But the occurring time and location of the earthquake still can not be predicted timely and accurately before the earthquake, so that active defense measures should be taken to reduce the disaster degree. Therefore, rapid and comprehensive access to disaster information after the earthquake is of great significance to carry out rescue actions and reduce disaster losses.

Remote sensing technology provides a quick effective approach to access the disaster information and loss after the earthquake, owing to its advantage of the quick dynamically all-weather monitoring with large amount of information and a short update cycle (Wei *et al*., 2008). Especially with the development of the high-resolution satellite sensors and aerial remote sensing technology (including altitude unmanned aerial vehicles and other platforms), remote sensing technology has substantially enhanced its capacity of the rapid access to disaster information.

Some countries, such as Japan and the United States, have carried out the study and monitoring of the disaster information after the earthquake based on the multi-source remote sensing data that can be rarely affected by the destroy from the earthquake (Tahayt *et al.*, 2009; Miyagi *et al.*, 2009; Peltzer *et al.*, 2001; etc). For instance, Nioki and Furmio (2000) used aerial remote sensing image to investigate the damage of Kobe Earthquake in Japan. In Turkey Earthquake, Athens Earthquake in Greece, Sumatra Earthquake Tsunami in Indonesia, and Haiti Earthquake, remote sensing technology were used to investigate and assess the damage situation and the losses after the earthquake.

In China, remote sensing technology was introduced to investigate and assess the damage of earthquake since the mid of 1960's. With the support of national key scientific and technological project in the period of the 8th Five-year Plan of China, aerial photography was carried out to monitor and map the earthquake damage situation for Xingtai Earthquake in 1966, Tangshan Earthquake in 1975, Lancang—Gengma Earthquake in 1988 (Wei *et al.*, 2008). Based on the analysis to those typical examples of the destructive earthquakes, the monitoring methods, grading classification standards and application technology system on the earthquake damage were developed using the aerial remote sensing images. It was the first time of the rapid production to seismic intensity envelope line with human-computer interaction and Geographical Information System (GIS). At the same time, the "technical specifications for earthquake remote sensing survey" was developed. All the

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First author biography: WANG Litao (1979—), male, Associate Professor. He graduated from the Institute of Remote Sensing Applications, Chinese Academy of Sciences. He is interested in the remote sensing applications on hazard and enviromnet. E-mail: wanglt@irsa.ac.cn achievements from the study made the foundation for seismic monitoring application using remote sensing technology (Zhu *et al.*, 1998; Wei *et al.*, 2008). The satellite remote sensing data were firstly used to monitor and evaluate the earthquake damage situation from the Ms 7.6-magnitude earthquake at Nantou County, Taiwan, in September 2l, 1999 (Wei *et al.*, 2000). During the course of Wenchuan Ms 8.0 earthquake in 2008, the comprehensive utilization of multi-source remote sensing data not only timely provided the disaster information and the important scientific basis for the earthquake emergency rescue, loss assessment and post-disaster reconstruction layout, but also accumulated a large number of technical methods and practices (Fan *et al.*, 2008; Wang *et al.*, 2009; Wei *et al.*, 2008; Wang *et al.*, 2008, 2009; Chen *et al.*, 2008).

2 EARTHQUAKE URGENT MONITORING PROCESSES USING REMOTE SENSING TECHNOLOGY

After decades of practice and application, there are a lot of monitoring technology, methods and indicators accumulated on earthquake damage in China, which were used in Wenchuan Earthquake and played a big role. In investigation and assessment of earthquake damage, five indicators are needed to be interpreted from remote sensing images (Wei *et al.*, 2008): the damage degree of houses and buildings, the damage degree of structures with a seismic fortification criterion, the damage of lifeline, the field disasters of earthquake and the secondary disasters. In the urgent monitoring phase after the earthquake, the damage degree of houses and buildings, the damage to lifeline engineering and survey of secondary disasters are very important information and of great significance for the rational deployment of the rescue force, reducing people’s property damage, reducing harm from secondary disasters.

In the earthquake urgent monitoring using remote sensing, manual interpretation, change detection and other methods are used to analyze and extract the damage indicators from the remote sensing data with different resolutions and different spectral information in order to assess the disaster situation. The main technical processes include: analysis of geological tectonic and environment background, quick process of remote sensing data, quick interpretation of damage indicators, rapid assessment of the disaster situation and rapid mapping using GIS and remote sensing (Fig. 1).

After the earthquake, the three elements of an earthquake (epicenter location, magnitude and occurrence time) would be published by China Earthquake Administrator. Referring to the three elements, the regional data should be collected, including the basic data (society, economy, population, roads and etc.) and remote sensing image before the earthquake. Using those data, the analysis on the geological tectonic and environmental background would be made to help understand the background of the earthquake and evaluate the approximate range of the hardest hit region, which is the foundation and prior knowledge of urgent monitoring work. As soon as obtaining the remote sensing data, the quick process should be carried out, including geographic coding, image enhancement, image fusion and image mosaic. Then, combining with prior knowledge and remote sensing images before earthquake, the damage indicators would be interpreted rapidly by manual interpretation, edge extraction, change detection and other methods. The disaster situation could be investigated and assessed quickly, including the damage degree of housings and buildings, the damage degree of lifeline and the survey of secondary disasters. Supported by GIS technology, disaster monitoring results could be mapped, and the assessment reports be written, which would provide qualitative / quantitative and intuitive decision basis for the earthquake emergency rescue.

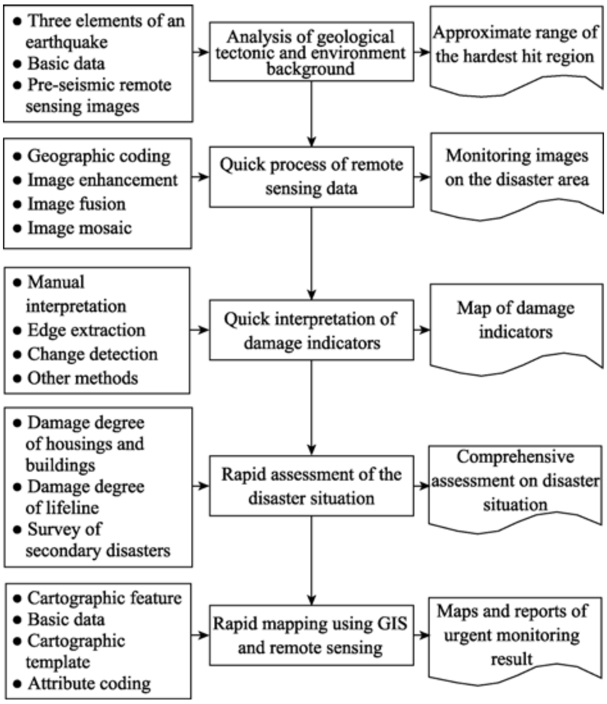

Fig. 1 Urgent monitoring flow for Yushu Earthquake based remote sensing

3 REMOTE SENSING MONITORING OF YUSHU EARTHQUAKE

At 7:49 am on April 14 2010, an earthquake originated (33.2°N, 96.6°E) near Jiegu Town, Yushu Tibetan Autonomous Prefecture, Qinghai Province, China. According to the three elements of Yushu Earthquake published by China Earthquake Administrator, we collected the basic data on Yushu Autonomous Prefecture and the remote sensing images before the earthquake (including SPOT-5 ortho-image and “Beijing-1” data) to make geological tectonic analysis and other infrastructure work.

After the disaster, two aerial surveys, respectively on April 14,2010, and April 15,2010, were carried out to obtain the remote sensing images with the resolution of 0.4m from the Center for Earth Observation and Digital Earth (CEODE), Chinese Academy of Sciences (CAS). In this paper, we used those aerial images to carry out urgent monitoring of Yushu earthquake combined with SPOT ortho-image and “Beijing-1” data.

According to the characteristic of the frame aerial camera (such as high geometric, radiometric resolution, high ground cover overlap), we used a fast process method based on a multi image auto-matching technology and completed rapidly the preprocessing of post-disaster aerial images and ensure the smooth implementation of disaster quick assessment.

3.1 Geological tectonic analysis of Yushu Earthquake

From the figure of Geological tectonic and environment background for Yushu earthquake based on “Beijing-l” microsatellite (Fig. 2), it was found that there were several fault zones in the occurring region of Yushu Earthquake, such as Ganzi—Yushu active fault zone, Wudaoliang—Qumarlai fault zone, Ulan Ul Lake—Yushu fault zone. The Yushu Ms7.1 earthquake lied in the Ganzi—Yushu active fault zone with the distribution of north west—south eastern. This fault zone with the overall performance of the valley landscape form is a giant fault zone of Late Quaternary with the characteristic of sinistral strike-slip and vertical differential activity (Wen *et al.*, 2003). Ganzi—Yushu fault zone lying at the southern end of the Xijir Ulan Lake—Yushu fault zone is the northwestward extension of Xianshuihe fault sensu lato and the northern boundary of the eastward extrusion of the Sichuan—Yunnan rhombic block of the Qinghai-Tibet Plateau. Its structure is relatively complex. According to the difference of its activity characteristic, it can be divided into three segments: The southern segment is composed of a set of echelon sinistral faults and the fault activity gave rise to the Ganzi pull-apart basin. The seismc activity is strong at the Yanqiao area. The central segment is mainly characterized by strong strikce-slip movement and a number of downfaulted basins occur at the north side of the fault. The north segment, which turns north from Dengke, consists of a principal fault and a number of feather faults that intersect the main faults obliquely, with sinistral strike-slip faults predominating. The downfaulted basins related to the fault are located at the western side of the fault. The seimic activities are scattered and weak (Peng *et al.*, 2006). According to the earthquake recorder, there have been several earthquakes, but few earthquakes with more than magnitude 7 in this fault zone.

According to remote sensing image analysis, combined with

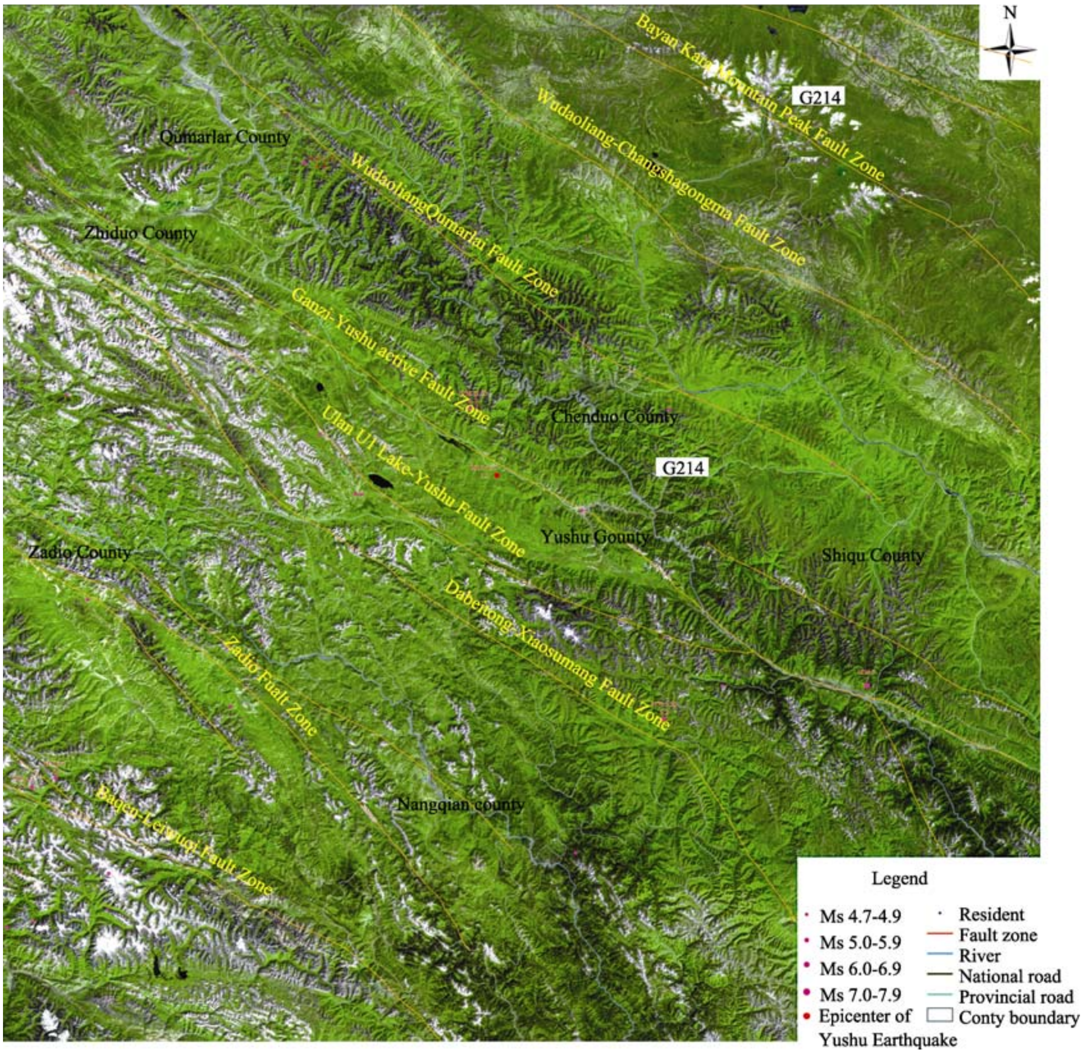

Fig. 2 Map of geological tectonic and environment background for Yushu Earthquake based on “Beijing-l” microsatellite
(Note: this figure is offered by Twenty First Century Aerospace Technology Co., Ltd.)

the local socio-economic development and population distribution and other basic data, the macroscopical epicenter was located in the Ganzi—Yushu active fault, in the southeast of the instrumental epicenter and in the western of Jiegu Town, which is the seat of the local government of Yushu County and Yushu Tibetan Autonomous Prefecture. In the Yushu earthquake region, population distribution was of relative concentration. Except in Jiegu Town, the housing and building were scattered in the valleys (Fig. 3). So it was thought that the main damage of housings and buildings should be concentrated in Jiegu town, Yushu County. In Yushu Earthquake region, there were two main roads of the provincial highway (S308) and the national highway (G214), and a reservoir dam located in the south, 10.5 km from Jiegu Town, which should be the emphases of lifeline engineering surveying.

3.2 Damage degree of housings and buildings

For the reason that the earthquake occurred in the Ganzi—Yushu active fault zone and had foreshock, main shock and aftershock, it would cause enormous damage to housing construction with lower civil engineering structure. According to the interpretation and comparative analysis between the high-resolution remote sensing images before earthquake and after earthquake, it was found that: the old civil structure housing almost fell destroyed completely, the texture of which could not be recognized from the aerial images after earthquake without the assistance of the images before earthquake (Fig. 4). A small part of the brick building were collapsed. The other were uncollapsed but had damage in the structure (Fig. 5). The texture of brick buildings could be recognized only from the

Fig. 3 Scattered buildings at the westnorth of Jiegu Town


(a)
(b)

Fig. 4 Remote sensing images of the civil structure housing before (a) and after (b) the earthquake aerial images after earthquake.

According to the interpretation result based on remote sensing images, the overall collapse rate of the housings, buildings and infrastructure in Jiegu Town was about 60%. The distribution of housing collapsed was shown in Fig. 6. Taking Victory Road as the boundary, lower rate of housing collapsed in the eastern region for locating far away to the Ganzi—Yushu active fault zone, except for the old civil structure housings. In the western region of Victory Road, especially in the southern section (Fig. 6 (a)), the damage was so serious that almost all of the

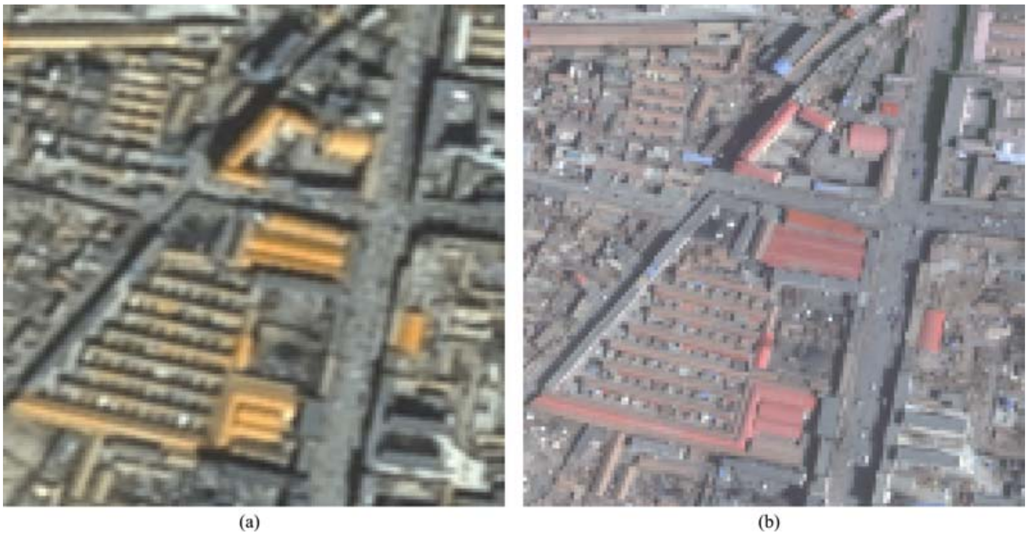

Fig. 5 Remote sensing images of the brick building before (a) and after (b) the earthquake

Fig. 6 Map of collapsed housing in Jiegu Town, Yushu County

(a) Region of the south of Jiegu Town; (b) Building of frame construction along the Provincial and county roads; (c) Collapse of housing on the alluvial fan

1 Civil structure housing almost fell destroyed completely; 2 Few brick buildings collapsed; 3 Few civil structure housings collapsed

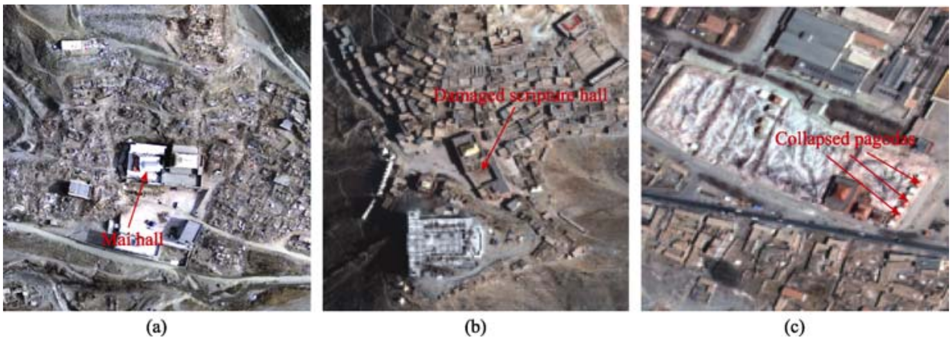

Fig. 7 Damage of Heritage in Jiegu Town, Yushu County
(a) Thrangu Gompa; (b) Kyegu Monastey; (c) Gyanak Mani

civil engineering structures housing fell destroyed completely. Some of the brick building was also collapsed, Many of the uncollapsed ones suffered serious damage to the structure, which are difficult to repair. For frame structure, the office buildings for government and the services buildings along the provincial and national highway were almost in good condition (Fig. 6(b)).

From after-seismic aerial images, the interpretation result showed that the collapse rate of the housings on an alluvial fan in the west side of Jiegu Town (Fig. 6 (c)) reached up to 86%. There might be two reasons: (1) In that alluvial fan after years of weathering, the surface was relatively flat and solid, but the lower soil had been eroded, so that the structure was not stable enough. (2) The region was near the fault zone. Therefore, for the post-disaster reconstruction and the future residential land, we should keep away from the alluvial fan.

3.3 Heritage damage investigation

Yushu County is located in the beautiful Three Rivers region and also the Tibetan gathering area. There are many heritage sites on Tibetan culture in Jiegu Town. Some of the heritage sites were severely damaged in this earthquake (Fig. 7), as illustrated by interpreting the post-disaster aerial remote sensing images with the resolution of 0.4 m. The structure of the main hall at the famous Thrangu Gompa was seriously damaged, and the subsidiary buildings were collapsed (Fig. 7(a)). The buildings at the Kyegu Monastey were partially collapsed, including the scripture hall (Fig. 7(b)). At the Gyanak Mani, the national cultural heritage, some buildings were collapsed in the earthquake. Three of the eight pagodas had been broken down. The damage degree of the other pagodas could not be recognized due to such factors as resolution and imaging perspective impact (Fig. 7(c)). For the reason of lying more near the fault zone, the Thrangu Gompa was influenced by the earthquake and had relatively severe loss.

3.4 Survey of field disaster and secondary disaster

After the earthquake, the field disaster (such as faults, cracks, collapses, landslides, debris flows and river bank collapse) and the secondary disaster (such as dammed lakes, cross dam collapse, fires and toxic gas leaking) will directly bring great harm to the people, the casualties caused by which would be even more than the earthquake itself if improperly disposed (Wei *et al.*, 2008). In Wenchuan Earthquake, the disaster once caused a large number of landslides, debris flow, and dammed lakes (Wang *et al.*, 2008), which brought a big threat to the people.

But in Yushu Earthquake, for the reason of geological structure, magnitude and other reasons, we only found some small-size field disasters and secondary disasters according to the interpretation result of remote sensing images (Fig. 8). Also, those field disasters and secondary disasters did neither cause serious damage to the national highway, provincial highway and water conservancy facilities, and nor jam the river leading to dammed lakes.

3.5 Investigation of lifelines and key projects

Within the range of after-seismic aerial images, the interpretation result showed that the provincial highway (S308) and the national highway (G214) and other main roads were not severely affected and seriously damaged by the earthquake disaster. There were some sections impacted by minor landslides and seismic subsidence. For example, the landslides covered little parts of the provincial highway in Fig. 8(a), and seismic subsidence led to part of the national highway collapsed in Fig. 8(b).

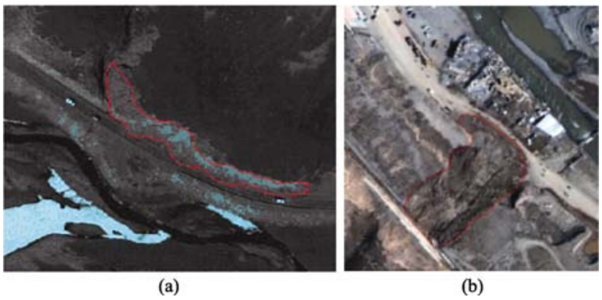

Fig. 8 Field disasters of Yushu Earthquake
(a) Landslide; (b) Seismic subsidence

The reservoir dam located in the south, 10.5 km from Jiegu Town Yushu County, was largely intact (Fig. 9).

4 CONCLUSION

Using high-resolution aerial images after the disaster, combining with the remote sensing images before the earthquake

Fig. 9 Aerial image for The reservoir dam located in the south, 10.5 km from Jiegu Town

("Beijing -1" microsatellite data, SPOT orthoimage), we carried out the urgent monitoring work for Yushu Earthquake, including the analysis of geological structure, the damage degree of the housings and buildings, the damage degree of lifelines and the survey of secondary disasters. According to the investigation and assessment results, the hardest hit region by the earthquake lied in Jiegu Town, Yushu County. For the reason that the earthquake occurred in the Ganzi—Yushu active fault zone and had foreshock, main shock and aftershock, it caused enormous damage to housing construction with lower civil engineering structure, and some damage to some heritages. But the earthquake did not cause the large-scale field disasters and secondary disasters, which neither caused serious damage to the national highway and the provincial highway and water conservancy facilities, nor blocked the river leading to the dammed lakes.

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青海玉树地震灾情遥感应急监测分析

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摘 要： 2010-04-14 7 时 49 分，中国青海省玉树藏族自治州结古镇附近(北纬 33.2°，东经 96.6°)发生了 Ms7.1 级地震。利用灾后高分辨率航空影像，结合震前北京一号小卫星、SPOT 正射影像，在分析地质构造背景基础之上，从房屋建筑物损坏情况、生命线工程的损毁程度以及次生灾害的调查等方面开展了灾情遥感应急监测工作，为地震应急决策救援提供宏观、科学(定性、定量)的辅助决策依据。

关键词： 玉树地震，遥感，应急监测

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1 遥感技术在地震监测中的应用

地震灾害尤其是强烈地震，所带来的突发性、毁灭性的灾难，给灾区人民生命财产带来极大的危害。震后快速、全面地获取灾情信息，对于及时开展救援行动、降低灾害损失具有重要的意义。

遥感技术具有获取信息快、信息量大、手段多、更新周期短，能多方位和全天候地动态监测等优势，为快速完成地震灾害调查与损失评估提供了一种新的高效技术手段(魏成阶等, 2008)。尤其是随着高分辨率遥感卫星和航空(包括无人机等超低空平台)遥感技术的发展，使得遥感技术在快速获取灾情信息的能力得到实质性的提高。

日本、美国等国家充分利用航空、航天遥感等对地观测技术在地震发生后，准确、全面地获取灾情图像信息，并对后续次生灾害进行动态监测(Tahayt 等, 2009; Miyagi 等, 2009; Peltzer 等, 2001)。日本的 Nioki Ogawa 和 Furmio Yamazaki(2000)利用阪神地震航空遥感影像较好地判读震害。土耳其地震、希腊雅典地震、印度尼西亚地震海啸、南亚地震、海地地震等发生后，均采用了遥感手段及时、全面地获取灾区灾情信息，进行震害损失评估。

中国于 20 世纪 60 年代中期开始使用遥感技术获取地震灾情信息，最早利用航空摄影进行不同比例尺的震害制图工作，为航空遥感技术引入中国强烈地震灾害的调查评估领域积累了丰富的经验(魏成阶等，2008)。通过“八五”国家科技攻关计划的支持，以 1966 年邢台地震、1976 年唐山地震、1988 年澜沧—耿马地震等破坏性地震为典型震例，展开航空遥感获取震害信息和典型震害解译方法、分级分类标准及其应用技术系统的研究，制定了《地震灾害航空遥感调查技术规范》。实现了在 GIS 支持下，通过人机交互方式完成地震烈度包络线的快速生成，为遥感技术在震害监测方面的深入应用奠定了基础(朱博勤等, 1998; 魏成阶等, 2008)。1999-09-2l 中国台湾省南投县发生 Ms 7.6 级强烈地震，魏成阶等(2000)成功地采用卫星遥感监测评估了这次地震震害。在 2008 年汶川地区发生 Ms8.0 级大地震中，中国遥感工作者综合利用多源遥感数据，积极开展地震灾情遥感监测工作，为震后的应急救援、损失评

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估及灾后重建提供了科学数据，同时也积累了大量的技术方法和实践经验(范一大等, 2008; 王世新等, 2009; 魏成阶等, 2008; 王晓青等, 2008, 2009; 陈世荣等, 2008)。

2 地震灾情遥感应急监测技术流程

经过几十年的应用实践和监测研究，中国在地震灾害监测的技术方法和指标研究方面积累了大量经验，在2008年汶川地震中也得到了广泛实践和应用。根据以往应用实践，利用遥感图像进行震害监测，可从5个方面进行判读(魏成阶等，2008)：房屋建筑物的损坏情况，具有明确抗震标准的构筑物的损坏程度，生命线工程的损毁程度，震后的场地灾害以及由此引发的次生灾害。在应急监测阶段，房屋建筑物损坏情况、生命线工程的损毁程度以及次生灾害的调查则是重要的灾情信息，对于合理部署救援力量，降低人民财产损失，减少次生灾害的危害具有重要的意义。

在地震灾情遥感应急监测中，通过人工解译、变化检测等方法，分析不同分辨率、不同波谱信息的遥感数据，提取灾情判识因子，进行灾情的分析评估。其主要技术流程包括：地质构造背景分析、遥感数据快速处理、判识因子解译、灾情快速评估以及灾情快速制图等步骤(图 1)。

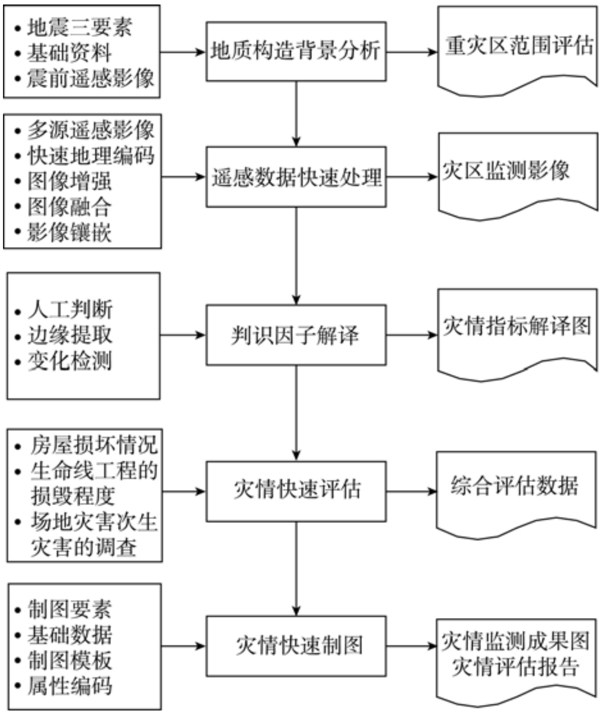

图 1 地震灾情遥感应急监测技术流程

地震发生后，由国家地震局公布的地震三要素(震中位置、震级大小、发震时间)出发，收集相关的基础资料(社会、经济、人口、道路等)及震前遥感影像，通过地质构造背景分析，了解地震发生的背景，初步评估重灾区大致范围，为灾情应急监测工作的开展提供先验知识。在获取灾后遥感影像，在保证精度的前题下，开展遥感数据快速处理，获取灾区的标准影像数据。结合先验知识以及震前遥感影像，通过人工判读、边缘提取及变化检测等方法，提取灾情指标的判识因子。在此基础上开展灾情信息的快速评估，包括房屋损坏情况、生命线工程的损毁程度以及次生灾害的调查，并在GIS技术支持下，生成灾情监测成果图，编写评估报告，为地震应急救援提供宏观、科学(定性、定量)的辅助决策依据。

3 玉树地震灾情遥感监测分析

2010-04-14 7 时 49 分，中国青海省玉树藏族自治州结古镇附近(北纬 33.2°，东经 96.6°)发生了 Ms7.1 级地震。根据国家地震局提供的地震三要素，收集了青海玉树自治州的相关基础资料，其中有震前 SPOT 2.5m 正射影像、“ 北京一号 ”小卫星影像数据等震前遥感影像，用于地震灾区的地质构造分析等基础工作。

灾情发生后，中国科学院对地观测与数字地球科学中心分别于 2010-04-14 和 2010-04-15 对地震灾区进行了两次航空调查，获取了 0.4m 分辨率的遥感图像。本文利用该数据与震前高分辨率遥感图像对比分析，与中分辨率的北京一号小卫星数据进行复合分析，开展了玉树地震灾情遥感应急监测工作。

针对灾后框幅式航空数字影像的特点，例如高几何、辐射分辨率，高地面覆盖重叠率等，采用了基于多影像处理的框幅式航空数字影像快速处理技术，完成了灾后航空影像的快速地理编码、图像增强、影像镶嵌等预处理工作，保证了灾情评估工作的顺利开展。

3.1 玉树地震地质构造背景分析

以“ 北京一号 ”卫星数据为底图，对玉树地震区的地质构造背景进行了分析(图 2)。该地区分布有玉树—甘孜活动断裂带、五道梁—曲麻莱断裂带、乌兰乌拉湖—玉树断裂带等多条地震断裂带。青海玉树 Ms 7.1 级地震发生在北西—南东方向展布的玉树—甘孜活动断裂带上。该断裂带在地貌上总体表现为河谷形态，是一条晚第四纪强烈活动的左旋走

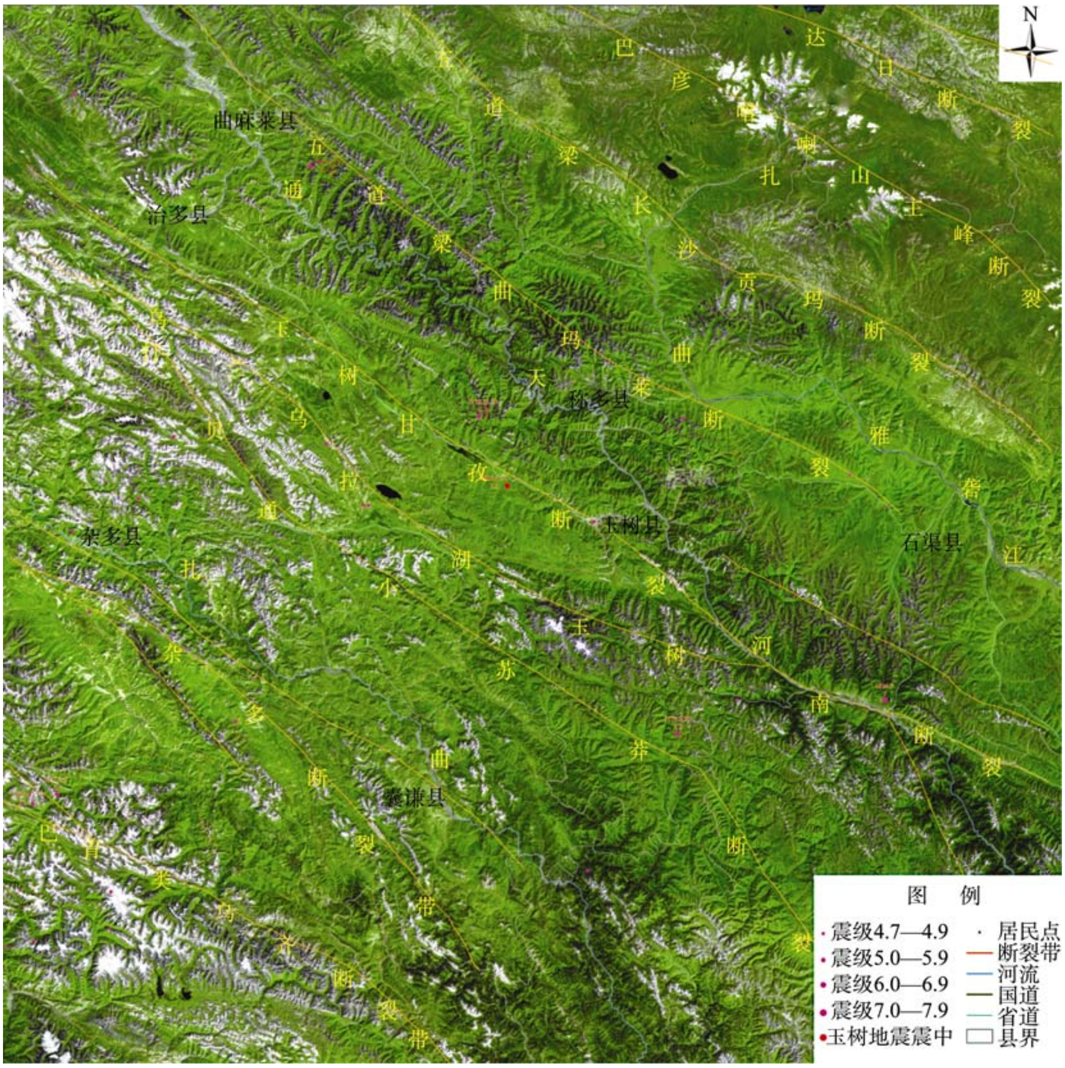

图 2　北京一号小卫星玉树地震地质构造背景分析图

(注：本图由国家科技部国家遥感中心数据管理与产业发展部，二十一世纪空间技术应用股份有限公司提供)

滑断裂，兼有垂直差异活动的巨型断裂带(闻学泽等，2003)。该断裂带位于西金乌兰湖—玉树断裂带的南端，是青藏高原川滇菱形块体向东挤出的北部边界，其结构较为复杂，根据其活动性的差异可分为 3 个段落：南段由一组斜列的左旋断裂组成，断裂活动形成甘孜左阶拉分盆地，岩桥区地震活动强烈；中段以强烈走滑运动为主，并在断裂北侧形成一系列断陷盆，现今无地震记录；北段自邓柯向北转折，由主干断裂及一系列羽状断裂斜截复合，且以左旋走滑为主，与断裂有关的断陷盆地发育在断层的西侧，地震活动分散，且活动性较弱(彭华等，2006)。根据地震历史记录，在该断裂带上很少有 Ms 7 级以上地震发生。

根据遥感图像显示，结合当地社会经济发展及人口分布等基础信息，初步判读此次地震的宏观震中应定位于玉树县结古镇西部，位于仪器监测震中东南的玉树—甘孜活动断裂带上。由于玉树地震发生区域人口分布相对集中，在玉树县政府所在地结古镇外，房屋建筑多零散分布于山谷地区(图 3)，因此房屋建筑物的主要损毁应集中于玉树县结古镇。而穿越结古镇的省道(S308)和国道(G214)及结古镇南 10.5km 通天河支流上的水库大坝则应作为生命线工程重点调查。

3.2　房屋建筑倒塌损毁分析

由于此次地震有前震、主震和余震，通过玉树—甘孜活动断裂带活动性分析，初步判断地震将给低层土木结构的房屋建筑造成巨大损坏。根据地震前后高分辨率的遥感影像对比分析：震区内的低矮老旧土木结构建筑基本倒平全毁(图 4)，从震后影像上无法分析其纹理信息，必须以震前高分辨率影像作为辅助数据进行判识；砖混结构房屋建筑只有少部分倒塌，多为结构受损，在影像上可判识出其纹理信息(图 5)。

图 3　在结古镇周边(西北 14km)零散分布的房屋

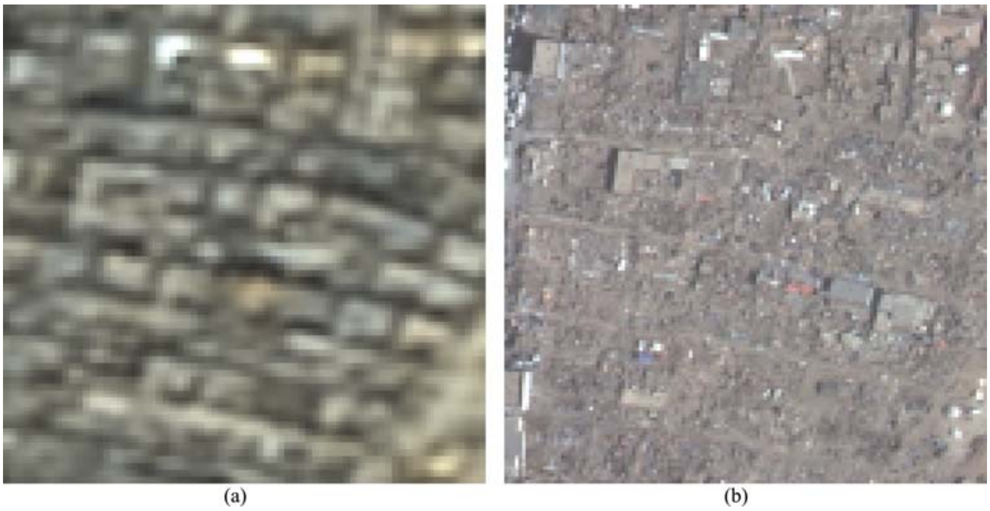
(a)　(b)

图 4　土木结构建筑震前(a)和震后(b)遥感影像

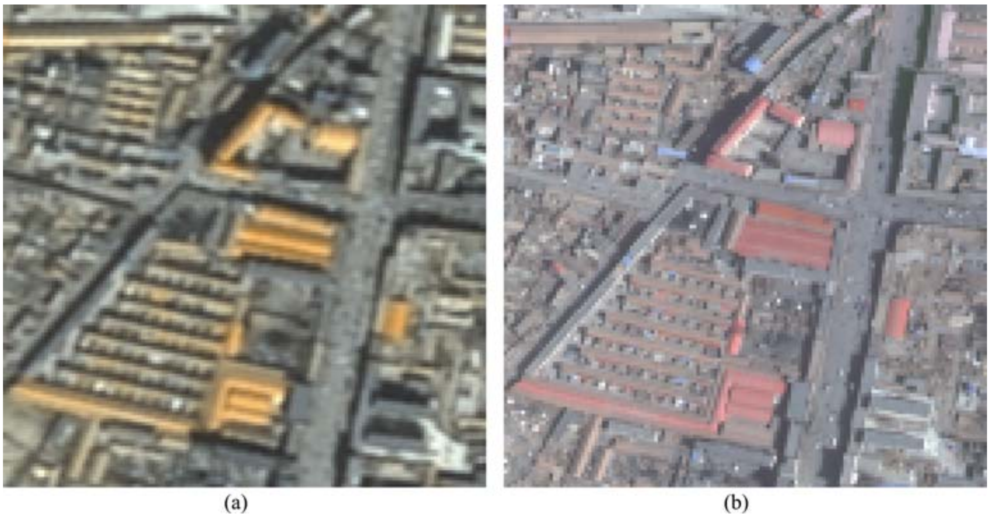
(a)　(b)

图 5　砖混结构房屋建筑震前(a)和震后(b)遥感影像

(a) 震后; (b) 震前

根据判识监测结果分析，玉树县结古镇房屋建筑及其附属基础设施总体倒塌率为 60%左右，房屋倒塌的总体分布情况为(图 6)：以胜利路为界东部地区多为砖混结构房屋，离玉树—甘孜活动断裂带较远，房屋倒塌率较低，除了老旧土木结构房屋倒塌外，砖混结构房屋只有零星倒塌；胜利路以西、胜利路南段地区房屋倒塌严重(图6(a))，土木结构房屋建筑大多倒平全毁，砖混结构房屋建筑有少部分倒塌，即使未倒塌的也多为结构严重破坏，难以修复。玉树县行政机关和沿国道省道的服务业楼房以框架结构为主，基本完好(图 6(b))。

在结古镇西侧(图 6(c))，一处冲积扇区域发生大量房屋倒塌，根据航空遥感影像解译结果，其房屋倒塌率达 86%。这是由于冲积扇地区土质松软，结构不够稳定，且该地区位于地震断裂带附近，因此在地震中造成灾难性后果。在灾后重建和今后批准住宅用地时应尽量避开冲积扇区。

3.3　文物损坏遥感监测

玉树地处美丽的三江源藏族聚集区，在结古镇拥有很多藏族文物古迹。此次地震部分文物收到严重损毁(图 7)。从灾后 0.4m 航空遥感影像上分析，其中著名的禅古寺大殿结构严重损毁，其附属建筑全部倒塌(图 7(a))；结古寺建筑也有部分倒塌(图 7(b))；全国重点文物保护单位新寨嘉那嘛呢的佛塔、护法殿堂等附属建筑在地震中倒塌，从影像中可清晰判识出 8 个佛塔中 3 个已倒塌，其他佛塔损坏情况由于受到分辨率和成像角度等因素影响无法判识(图 7(c))。此次禅古寺损失较为严重，主要原因为其地处结古镇南部，位于地震断裂带附近，受地震影响较大。

(a)　　(b)　　(c)

图 6　玉树结古镇房屋倒塌分布示意图

(a) 结古镇南部受灾严重地区；(b) 沿国道省道的服务业楼房以框架结构建筑；(c) 冲积扇上的倒塌房屋

1 为土木结构房屋倒平全毁；2 为砖混结构房屋少部分倒塌；3 为土木结构房屋少部分倒塌

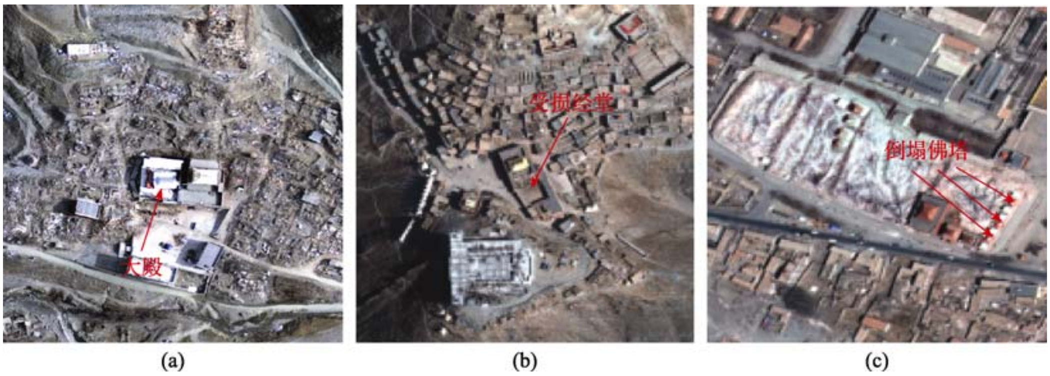

图 7 玉树结古镇文物损毁情况

(a) 禅古寺; (b) 结古寺; (c) 新寨嘉那嘛呢

3.4 场地灾害、次生灾害调查

在地震发生后，形成断层、地裂缝、崩塌、滑坡、泥石流、河流崩岸等场地灾害，以及由地震场地灾害堵塞河流引发的堰塞湖、水库大坝跨塌、火灾、有害气体泄漏等次生灾害，会给人们带来巨大的伤害，如果处置不当其造成的伤亡甚至超过地震本身(魏成阶等，2008)。如在 2008 年汶川大地震中，灾区形成大量滑坡、泥石流，并堵塞河流引发大量堰塞湖(王世新等, 2008)。

玉树地震中，由于地质结构、震级等原因，根据遥感监测结果分析，并未形成大规模的场地灾害和次生灾害(图 8)，对国道省道及水利设施造成严重损毁，也未堵塞河道形成大范围堰塞湖。

3.5 生命线及重点工程遥感监测

通过航空遥感影像监测分析，在航空遥感影像监测范围内，省道(S308)和国道(G214)等主干道路未受地震场地灾害严重影响，未出现道路严重损毁情况，部分路段受滑坡和震陷轻微影响，如图 8(a)山体滑坡掩盖部分省道路面，图 8(b)震陷导致国道部分路面塌陷。

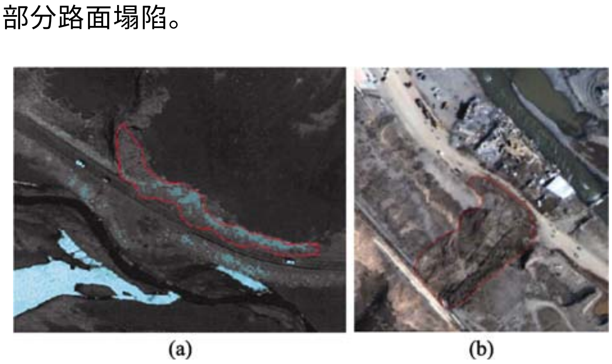

图 8 玉树地震场地灾害

(a) 滑坡; (b) 震陷

位于玉树县结古镇南 10.5km、通天河支流上的水库大坝基本完好(图 9)。

图 9 水库大坝航空影像

4 结 论

利用灾后高分辨率航空影像，结合震前北京一号小卫星、SPOT 正射影像，在分析地质构造背景基础之上，从房屋建筑物损坏情况、生命线工程的损毁程度以及次生灾害的调查等方面开展了灾情遥感应急监测工作。从监测结果分析，此次玉树地震的重灾区为玉树县结古镇。由于有前震、主震和余震，并且处于玉树—甘孜活动断裂带的活动性分析，地震给低层土木结构的房屋建筑造成巨大损坏。同时，对该地区的文物建筑也造成一定程度的破坏。但地震后并未形成大规模的场地灾害和次生灾害，未对国道省道及水利设施造成严重损毁，也未堵塞河道形成大范围堰塞湖。

致　谢：文中所用的航空影像数据由中国科学院对地观测与数字地球科学中心提供，所用 SPOT 影像由北京视宝卫星图像有限公司提供，所用北京一号卫星影像及地质背景分析图由二十一世纪空间技术应用股份有限公司提供。

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