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Research paper

Preparation of earthquake-triggered landslide inventory maps using remote sensing and GIS technologies: Principles and case studies

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ABSTRACT

Inventory maps of earthquake-triggered landslides can be constructed using several methods, which are often subject to obvious differences due to lack of commonly accepted criteria or principles. To solve this problem, the author describes the principles for preparing inventory maps of earthquake-triggered landslides, focusing on varied methods and their criteria. The principles include the following key points: all landslides should be mapped as long as they can be recognized from images; both the boundary and source area position of landslides should be mapped; spatial distribution pattern of earthquake-triggered landslides should be continuous; complex landslides should be divided into distinct groups; three types of errors such as precision of the location and boundary of landslides, false positive errors, and false negative errors of earthquake-triggered landslide inventories should be controlled and reduced; and inventories of co-seismic landslides should be constructed by the visual interpretation method rather than automatic extraction of satellite images or/and aerial photographs. In addition, selection of remote sensing images and creation of landslides attribute database are also discussed in this paper. Then the author applies these principles to produce inventory maps of four events: the 12 May 2008 Wenchuan, China M_w 7.9, 14 April 2010 Yushu, China M_w 6.9, 12 January 2010 Haiti M_w 7.0, and 2007 Aysén Fjord, Chile M_w 6.2. The results show obvious differences in comparison with previous studies by other researchers, which again attest to the necessity of establishment of unified principles for preparation of inventory maps of earthquake-triggered landslides.

1. Introduction

Preparation of inventory maps is an essential part of landslide hazard analysis (Harp et al., 2011a; Guzzetti et al., 2012), such as spatial distribution statistics of landslides (Xu and Xu, 2012a; Xu et al., 2014c), susceptibility (Pradhan and Lee, 2010; Pourghasemi et al., 2012; Xu, 2013a), hazard assessment (Pradhan and Lee, 2007; Xu et al., 2012a, b), and river and landform evolution in earthquake-struck areas with widespread and intensive landslides (Parker et al., 2011; Xu and Xu, 2013). A landslide inventory map portrays the location, numbers and other data of occurrence and the types of mass movements that have left discernable traces in an area (Guzzetti et al., 2012). Such maps can be prepared by using various techniques. Qualities (e.g. completeness and validity) of these inventory maps determine the objectivity and accuracy of subsequent research results. Earthquakes often trigger a large number of landslides (Keefer, 1984; Rodriguez et al., 1999; Mahesh et al., 2011; Martha et al., 2015) and a number of inventory maps of landslides triggered by earthquakes have been prepared (e.g. Khazai and Sitar, 2004; Xu et al., 2010, 2014c). It should be noted that there were often obvious differences in landslide inventory maps prepared by different researchers for the same seismic event. In addition to differences of the methods used, one possible reason for this problem is a lack of criteria for the preparation and update of earthquake-triggered landslide inventory maps.

In the current paper, the author describes the principles for preparing inventory maps of earthquake-triggered landslides, focusing on varied methods and their criteria. In the following text, the author uses the terms “inventory” and “inventory map” with the same meaning (e.g. Guzzetti et al., 2012). The principles

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include the following criteria: all landslides should be mapped as long as they can be recognized from images; both the boundary and source area position of landslides should be mapped; spatial distribution pattern of earthquake-triggered landslides should be continuous; complex landslides should be divided into distinct groups; three types of errors such as precision of the location and boundary of landslides, false positive errors, and false negative errors of earthquake-triggered landslide inventories should be controlled and reduced; and inventories of co-seismic landslides should be constructed by the visual interpretation method rather than automatic extraction of satellite images. In addition, selecting remote sensing images and building landslides attribute database are also discussed in this paper. Then these principles were applied to prepare inventory maps for four events in the beginning of the 21st century: the 12 May 2008 Wenchuan, China M_w 7.9, 14 April 2010 Yushu, China M_w 6.9, 12 January 2010 Haiti M_w 7.0, and 2007 Aysén Fjord, Chile M_w 6.2. The results show obvious differences in comparison with previous studies by other researchers, which again attest to the necessity of establishment of unified principles for preparation of earthquake-triggered landslide inventory maps.

2. Overview of principles for preparing earthquake-triggered landslide inventory maps

2.1. Methods

An earthquake-triggered landslide inventory map can be prepared by several methods, including field investigations, visual interpretation of aerial photographs, digitizing paper-based landslide inventories, computer screen-based visual interpretation of high-resolution remote sensing images, and automatic extraction from remote sensing images.

2.1.1. Field investigations

This method was widely used before the remote sensing technology emerged. Based on observations in the field, researchers delineate or locate earthquake-triggered landslides on topographic maps, geologic maps, or other thematic maps, and thus prepare associated earthquake-triggered landslide distribution maps. For example, the 1783 Calabria, Italy *M* 7.0 earthquake is considered to be the first case study with the earthquake-triggered landslide inventory map based on field investigations in the epicenter area (Keefer, 2002). Three limitations of this method should be noted: (1) Landslide inventories based on field investigations often aim at landslides of large or moderate sizes, while those of small sizes are often ignored, resulting in rough and incomplete landslide inventories (Guzzetti et al., 2012). (2) Earthquake-triggered landslides are generally widespread distributed and of high densely in broad earthquake stuck areas, which often result in powerless to prepare detailed landslide inventories only based on filed investigations. (3) The resulting landslide distribution maps with topographic and geologic background (earthquake-triggered landslides are drawn on paper-based thematic maps) can not directly be used in subsequent calculation of the landslide number and area, landslide spatial distribution analysis, and hazard assessments. However, recently, the filed investigation methods were also used in preparing landslide inventory maps related to moderate earthquakes (Alfaro et al., 2012; Jibson and Harp, 2012), or only as a verification tool for a small part of landslides triggered by large earthquakes (Harp et al., 2011b; Xu et al., 2014c). Anyway, it is almost impossible only rely on field investigations to prepare complete and detailed inventories of earthquake-triggered landslides.

2.1.2. Visual interpretation of aerial photographs

With the advent of the remote sensing technology, visual interpretation of remote sensing images, saving a large amount of field work, has become the main method for preparation of landslide inventories. Early remote sensing images are mainly aerial photographs. Using this method, positions or boundaries of landslides are directly plotted on aerial photographs or other thematic maps based on visual interpretation. Landslide inventories based on this method can avoid missing a large number of landslides on small scales and can obtain detailed and comprehensive earthquake-triggered landslide inventories. These landslide inventories are, however, also paper-based materials rather than compute-based digital files of vector format. Therefore, the inventories also can not directly be used for subsequent spatial analysis because it is difficult to obtain precise numbers and areas of landslides in the case that a large number of landslides are triggered by a major earthquake. This method was applied in the analyses of several earthquake events (Keefer, 2002), such as the 1948 *M* 7.3 Fukui, Japan earthquake, the May 31, 1970 *M* 7.9 Rio Santa earthquake of Peru, and the February 4, 1976 *M* 7.5 Guatemala earthquake. It should be noted that field investigations are often an auxiliary tool for visual interpretation of aerial photographs associated with earthquake-triggered landslides.

2.1.3. Digitizing of paper-based landslide inventories

This technique is an advanced stage of paper-based earthquake-triggered landslide inventories. With the development of the computer and geographic information system (GIS) technologies, paper-based landslide inventories can be digitalized for subsequent earthquake-triggered landslide studies, such as spatial distribution analysis, landslides hazard assessment, and evolution of rivers and landforms in areas affected by widespread co-seismic landslides. The resulting digital inventory maps have a high degree of usefulness and play an important role in promoting studies of earthquake-triggered landslides. The first well-known digital inventory map for earthquake-triggered landslides was compiled by Harp and Jibson (1995, 1996), in which large amount of landslides triggered by the 17 January 1994 M_w 6.7 Northridge earthquake were mapped from visual interpretation of aerial photography and selected field verification. Their results of digitalizing landslide inventories showed more than 11,000 landslides triggered by the Northridge earthquake.

2.1.4. Computer screen-based visual interpretation of high-resolution remote sensing images

Computer screen-based visual interpretation of high-resolution remote sensing images (especially high-resolution satellite images) is the most popular method for preparing earthquake-triggered landslide inventory maps currently. With the computer and GIS technologies becoming highly matured and steady development of remote sensing technology, a plenty of commercial satellites come into service and masses of high-resolution satellite images are available. They have greatly improved the methods of preparing earthquake-triggered landslide inventory maps. The conditions based on paper-based remote sensing images are changed into syntheses of computer screen-based landslide visual interpretation based on GIS software and digital satellite images and aerial photographs, and construction of vector landslides inventory maps. In this method, at first, remote sensing images are precisely geographically registered; then landslides can be mapped based on the registered satellite images on a GIS platform. In addition, landslide inventory maps can be prepared based on three-dimensional perspective of the digital elevation model (DEM) for more precise and objective visual interpretation. Recently, this method has become the most popular tool for earthquake-