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UCT Journal of Research in Science ,Engineering and Technology

UCT . J. Resea. Scien. Engineer.Techno.(UJRSET)

Volume 1,Issue 1

1(1): *07-11(2013)*

ISSN XXXX-XXXX

GIS Modeling of Earthquake Damage Zones Using ETM Data and Remote Sensing- Bojnoord, Khorasan Province

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ABSTRACT

The devastating earthquake that occurred in Khorasan Shomali Province, Iran, on the 12th May 2008, caused widespread damage and devastation to rural communities and economy. The terrain of the entire region has been weakened and is now highly susceptible to long-term slope instability that will trouble this region for many years to come. However, the actual intensity caused by the earthquake ranged between VIII and XI. The seismic intensity map is practical for regional guidance but lacks the detail to provide an adequate representation of the true damage level, in terms of current status and future potential in such a seismically active and populated region, especially when the hazards and risks are likely to be multiple and cascading in high relief areas. This paper presents a GIS based approach to earthquake damage zone modeling using satellite remote sensing and DEM data. The novelty is to take into account the coseismic ground deformation as an important modulating factor in modeling the susceptibility of earthquake related geohazards, together with conventional multi-criteria factors which draw on geological and topographical variables such as rock competence, slope, proximity to drainage, and fracture density. The modulating effect of the earthquake greatly enhances the susceptibility in the areas where the majority of the ensuing landslides and debris-flows actually took place. When this susceptibility model is further modulated by the mapped surface disruption caused by the earthquake, it is directly linked to seismic intensity and we call it "earthquake damage". The output earthquake damage map represents both the current damage status as well as the future damage (hazard) potential.

Original Article:

Received 11 Nov. 2013
Accepted 23 Dec. 2013
Published 30 Dec. 2013

Keywords:
Geohazard,
GIS Model,
Remote Sensing,
ETM,
Earthquake

1. Introduction

The A devastating earthquake occurred on 12th May 2008 in Iran County near the western edge of the Chengdu basin in Khorasan Province, Iran. This was followed by thousands of aftershocks, for a period of more than a month, causing tremendous damage and loss of human life, and the widespread destruction of infrastructure and a total economic loss of over 110 billion USD [2]. These effects were induced both by direct earthquake shaking and by large earthquake-triggered geohazards. The most common forms of the earthquake induced geohazards in the region are landslides and mudflows [2].) which account for 15% of deaths [4]. The Beichuan county town is a typical example. It is situated in the main rupture zone along the Yingxiu–Beichuan fault [3], which lies in the central part of the Longmenshan complex fault system (Fig. 1), and in a deeply incised valley surrounded by very steep mountainous slopes. The town was completely destroyed by the strong earthquake and the ensuing massive landslides which involved entire mountain slope collapse (Fig. 2). There have been abundant publications on the Wenchuan earthquake including dedicated special issues of Tectonophysics [14], International Journal of Remote Sensing and Bulletin of the Seismological Society of America [10].Whilst the majority of the work published focuses on co-seismic rupture processes, fault geometries, slip patterns and stress evolution in relation to the earthquake, there are many papers presenting studies on the distribution of earthquake induced geo hazards [1], and their relationship with key geo-environmental factors and earthquake rupture zones [7], and on the GIS modeling of geo hazard susceptibility using satellite remote sensing and field inventory data [6]. Satellite remote sensing images have been widely used to identify the main processes of denudation, i.e. all forms of mass movements, in addition to providing geomorphologic and landscape categorisation using DEMs (Digital Elevation Models). Several GIS models for landslide and mudflow susceptibility after the earthquake have been proposed using similar sets of geological and topographical factors in the form of multiple variables in weighted linear combination. However, none of these models fully integrates the earthquake deformation as a controlling factor for susceptibility mapping of landslides and mudflows in the region seriously damaged by the Wenchuan earthquake. We believe that modelling the earthquake induced hazards and damage is quite different from conventional geohazards susceptibility modelling for general cases; it should be considered in line with seismic intensity zonation. Seismic intensity is widely used to assess damage levels induced by an earthquake. Unlike the earthquake magnitude scales, which express the seismic energy released by an earthquake, seismic intensity denotes how severely an earthquake affects a specific place. The China Seismic Intensity Scale (CSIS) is a national standard and is called ‘Liedu’ in Chinese. It was formally established by the China Earthquake Administration (CEA) in 1980 but has been in use since the 1960s. Liedu is similar to European Macroseismic Scale 1998 [5].aswell to the Modified Mercalli intensity scale [4,6,12]. that categories seismic impacts into 12 degrees of intensity. Table 1 shows the Liedu scale of the most recent update in 2004 from the National Standard GB/T 1772–1999 [13]. Before the earthquake, the maximum intensity expected in the Wenchuan regionwas VI–VIII Liedu, but the actual intensity caused by the earthquake ranged between VIII and XI; this matches our field observations in Beichuan Town. The particular devastation in Beichuan Town was, however, a combined result of destructive shaking and massive landslides triggered by the earthquake because the town was in a deeply incised valley surrounded by the high, steep mountain slopes (Fig. 2): it is extremely prone to widespread and large scale slope failures. Our field investigations have shown that many areas along the Yingxiu–Beichuan fault were subject to the same level of earthquake shock but experienced far less significant damage than Beichuan because their locations were not independently prone to geohazards. For effective hazard management and prevention of earthquake-induced damage, the lesson to be learnt is that the seismic intensity zonation system should be enhanced by the characterization of localised variation of damage levels that an earthquake may produce. In this paperwe present a study of the GIS based modelling of earthquake damage zones, using the Beichuan area in the Wenchuan earthquake zone as an example (Fig. 1). The novel idea shown here is the combination of measurements of earthquake deformation, as derived from differential interferometric SAR (DInSAR) data, with a geohazard inventory and geo-environmental conditioning factors (such as slope, lithology, drainage and fracturing) derived from broad-band multispectral satellite imagery and DEM data.Whilst the differential SAR interferograms derived from cross-event ALOS (Advanced Land Observation Satellite) PALSAR (Phased Array type L-band Synthetic Aperture Radar) image pairs provide broad-scale co-seismic deformation zones relating to seismic intensity, far more detailed damage levels within each deformation zone can be mapped using local geo-environmental factors via amulti-criteria GISmodel. By incorporatingmeasurable variables of co-seismic deformation and geo-environmental conditions, within a GIS model, the resultant map characterises not only the destruction immediately after an earthquake but also the future potential of damage caused by the earthquake; this result no longer represents a conventional measure of seismic intensity based on descriptive assessment, and thus we call it earthquake damage. TheWenchuan earthquake will impose notable, long-term damaging impact; [20] expect significant earthquake-induced geohazards to continue for as many as 20 years. [16]observed large increases in the number of potential geohazard sites, which places significant importance of this study on modelling and mapping the geohazard susceptibility as a consequence of earthquake damage in the region. For instance, on 14th August 2010, devastating slope failures and mudflows occurred in the area around the epicentre of the Wenchuan earthquake after days of heavy rain. Local news coverage suggested that the effects of these failures were worse than those caused by the earthquake in 2008 [19]. This study of earthquake damage zonation will contribute to a framework for refining the existing seismic intensity scale mapping system, from the regional scale down to a local scale.

2. The Models

Place Many studies, as well as our own field investigations, indicate that slope failures (mainly landslides and debris flows) are the dominant but not exclusive forms of geohazard triggered by the Wenchuan earthquake [18] In this paper we use the word ‘geohazard’ as a general term to represent the all forms of catastrophic slope failure, to emphasise the hazardous aspect of this natural process of surface evolution. Multi-criteria modelling is a typical GIS approach for synthesizing multi-source data to describe a complex target theme, such as geohazards [2]. Several GIS models for susceptibility mapping of the Wenchuan earthquake induced landslides and debris-flows have been proposed with similar sets of geological and topographical factors in a form of multi-variable linear combination [12]. These published susceptibility models established relationships between variables based on statistics of mapped geohazard inventory data but the physical-geomorphologic principles are often ignored. Fundamentally, none of theseworks included themost influential factor, co-seismic deformation of the Wenchuan earthquake, into their models. Indeed this factor changes the nature of the initial susceptibility model to make it link to the seismic intensity. Our basic principles for geohazard GIS modelling are that geohazard susceptibility cannot be quantitative at regional scale; it has to be subjective and arbitrary at certain levels; and it can never be entirely objective. Secondly, since this is a regional, qualitative study and one based on only limited field observations,we have insufficient ground information to make anymeasurement or description of ‘human’ factors such as vulnerability and exposure, and so our modelling is limited, at this stage of our work, to the calculation of hazard rather than risk [11]. These are fundamental assumptions for suchmodelling. Whilst a simple model seems rather crude and arbitrary, from our own experience we suspect that a complex and apparently quantitative model may never really work at all. There is thus a fine balance for the modelling: too crude and the model will fail to effectively categorise the theme, whilst too much detail may make the model too narrow and localised, thereby restricting its applicability. In addressing this balance, we have adopted a simple, numerical yet qualitative model as defined below. The GIS-based modelling of susceptibility to geohazards and the modelling of current damage levels are two separate but closely linked issues. Given various geo-environmental conditions relating to geohazards, an earthquake will intensify the overall susceptibility to those geohazards. We therefore consider the GIS modelling of susceptibility to earthquake related geohazards as a conventional geohazard susceptibility model modulated by seismicity, hence:

$$Egh = G*S \qquad (1)$$

Here Egh represents the susceptibility of earthquake related geohazard, whilst G and S are the geohazard susceptibilitymodel and seismicity respectively. The modulation relationship between G and S represents the fact that the two variables co-exist all the time and intensify each other.

There are no weights specified for any of the additive items in the above formulae. As a numerical qualitative (not quantitative) modeling process, each variable is assigned a sequence of ranks, the range of which determines the relative contribution of the variable to the model and so effectively acts as a weighting scheme. For instance, the rank range of drainage (Dr) is 0–2 and that of fault/fracture (Ff) is 0–4 for rock-slides indicating that Ff has a higher contribution than Dr for mapping the susceptibility to this type of geohazard. As the relative importance of different variables is implemented via their ranking scale, it is unnecessary to further complicate the models with an extra hierarchy of weights. It is difficult to derive quantitative weights of various variables. A complex statistical approach [1,8,13] may appear to be quantitative but it could be misleading without consideration of basic principles and might not stand up to simple reality checks. The fate of the final result of such an approach is sealed from the start. If a variable that is in fact not directly relevant is put into the system, a statistical procedure will produce a weight for it anyway and the weight could be significant.

3. Derivation of input variables

3.1 Imagery and DEM data

Source data for this study are from JAXA's (Japan Aerospace Exploration Agency) ALOS, Landsat TM (Thematic Mapper) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (Global Digital Elevation Model) as listed in Table 2. For the multi-criteria GIS modelling, all the chosen variables are derived from satellite imagery and DEM data as raster layers (2D array data in pixels). This ensures objective and full data coverage to the study area, not biassed by accessibility to field investigation and local data

3.2 Rock competence map

Lithology has a background control on susceptibility in that certain rock types are less resistant or are unlithified, and are therefore likely to be more erodable and more easily dissected, transported and re-deposited. The mechanical properties of rocks (such as the degree of fracturing and weathering) are far more influential here than any specific rock type. We therefore consider the physical competence of rock formations as a fundamental factor in influencing geohazard occurrence. Searching the satellite data archives, to identify suitable images for regional lithological mapping, reveals that the best cloud-free multispectral images of the study area are two Landsat TM scenes (see Table 2). Fig. 3 shows a colour composite of Landsat TM image bands 5, 3 and 1, displayed in red, green and blue enhanced using the Direct Decorrelation [12,14], of the study area within the Mianyang metropolitan district. The band combination in this image is generally effective in differentiating major rock types [12]) by enhancing the rich spectral variation and sharp textual features of lithological units and their boundaries. This image was therefore used for the majority of geological interpretation. Rock competence can be quite reliably mapped from this colour composite via visual interpretation of colour, texture and landforms, in combination with field investigation carried out in the summers of 2008 and 2009.

According to our field investigation and publications [15], mediumto thickly bedded limestone and sandstone formations as well as metamorphic rocks are dominant in the mountainous region of the study area. These rocks are usually highly competent butmay becomeless competentwhen heavily fractured andweatheredwithin and near fault zones, such as those which form valleys and residual hills around the flanks of large mountains along the Yingxiu–Beichuan fault zone.We have classified these rock units into two broad rock competence groups, hard (high competence) and relatively soft rocks (medium to low competence), rather than differentiate on the basis of lithological type. Towards the south-east of the mountain range, near the Chengdu Plain, there is a belt of narrow thrust folds characterized by inter-bedded limestone and sandstone. This belt is classified as high to medium competence. Further to the south-east, in the lowerright corner of the study area, there lies the western margin of the Chengdu Plain which comprises low-lying Tertiary sandstones and unconsolidated Quaternary deposits of low competence, which form alluvial terraces and platforms. In summary, the study area can thus be mapped into four classes of rock competence (Fig. 4):

- High competence: thick layers of limestone, sandstone and metamorphic rocks
- High-medium competence: folded, inter-bedded limestone and sandstone
- Low-medium competence: highly fractured and weathered rocks
- Low competence: Tertiary sandstone and Quaternary unconsolidated sediments.

3.3 Slope

Slope is the single most important variable controlling mass wasting process, such as rock-slides and debris-flows. As the gradient of elevation, a slope layer can be easily derived from a DEM, using a 3×3 slope angle kernel.

3.4 Proximity to drainage

Proximity to drainage has an indirect influence on slope instability since undercutting by rivers at the toes of slopes is a common trigger of debris-flows and the channels themselves tend to form the preferential pathways for the debris-flows. Here the area affected by fluvial erosion is decided by the magnitude of the river channels and water flow capacity which is in turn controlled by rainfall intensity. For instance, a small stream can swell dramatically to carry a significant amount of water and sediment during a heavy storm. The average annual precipitation in the region is about 800–900 mm and the highest recorded rainfall, in a 24-hour period, is ca. 334.7

mm, and this occurred during 2008 [2]. In consideration of this, we generated a drainage network buffer map (Fig. 7) from the ASTER GDEM with four stream-order levels which are given different buffer widths and rank values, as listed in Table 5. We give higher order streams wider buffer zones and higher ranks because large river channels affect larger areas and are more likely to trigger bank collapse and landslides. According to the failure mechanism and materials involved, fluvial erosion has a more significant influence on debris-flows than rockslides. We therefore assigned the debris-flow buffer zone twice the rank of that for the rock-slides (Table 5). As the relationship between proximity to drainage and the other variables is a linear combination, the areas outside drainage buffer zones are assigned a zero value.

3.5 Fracture density

Proximity to faults and fractures (mapped as structural lineaments) also favour the occurrence of geohazards since these zones of brittle deformation provide the passage of water and facilitate weathering and weakening of the rocks. In the context of seismically triggered geohazards, the proximity of a fault is particularly relevant if it ruptured during the earthquake. Field evidence indicates that faults and fractures have direct impact on surface damage. A location close to the epicentre of an earthquake could escape from destructive rupture if it is not in the immediate vicinity of an active fault or fracture, whilst one situated at a distance from an epicentre could experience very severe damage and destruction if it lies on an active fault.

3.6 Mapping the earthquake induced geohazards

In this heavily vegetated region, the earthquake induced geohazards are typically characterised by broken ground which is stripped of vegetation, in the AVNIR-2 images taken shortly after the earthquake, as illustrated in Fig. 2. As a result such areas can be quite accurately mapped using Normalised Differential Vegetation Index (NDVI).

4. Earthquake damage zone modelling and assessment

With all the input variables prepared, the earthquake damage zone modelling comprises two steps as defined in Eqs. (4) and (5): susceptibility mapping of earthquake related geohazards forms the first step, using all the variables except the layer of mapped earthquake induced geohazards which is applied in the second step to produce the final map of earthquake damage zones.

4.1 Susceptibility mapping of earthquake related geohazards

Applying different variable rankings for rock-slides and debrisflows, as described earlier, to Eq. (4), the corresponding susceptibility maps were derived as shown in Fig. 13. The initial value range for rock-slide susceptibility is [0–117] and that for debris-flow [0–90].

The slightly wider value range of rock-slide susceptibility is caused by the fact that rocks of high and high-medium competence can form very steep slopes (see Tables 3 and 4) and therefore the score of high susceptibility for rock-slides should be higher than that for debris-flows. These value ranges were then sub-divided into four susceptibility levels via multi-level thresholds based on the natural break points in the image histograms: corresponding to classes of Low, Medium, High and Very High susceptibility to geohazards. From these two maps, we can observe:

- The spatial distribution of the classes of both geohazard types is strongly controlled by co-seismic deformation in the first order;
- The High to Very High susceptibility classes have quite different distributions in the two maps, with strong control exerted by the lithology-slope modulation. In the case of rock-slides, the High to Very High susceptibility classes occur mainly in rock formations of high-medium and high competency, whilst for debris-flows, the High to Very High susceptibility classes occur dominantly in lithologies of low-medium competency, and in highly fractured and weathered rocks.

The differences in distribution of the medium to low susceptibility classes between the two types of geohazards are controlled mainly by fracture density in the case of rock-slides and by drainage buffer zones for debris-flows.

4.2 Mapping the earthquake damage zones

An earthquake damage zone map should present both the current damage caused by the earthquake (the seismic intensity) and the future potential damage from geohazards under the changed geoenvironmental conditions caused by a major earthquake event. For instance the massive Wenchuan earthquake and its aftershocks fractured otherwise stable mountain formations rendering this high relief region susceptible to frequent major rock-slides and debris-flows for many years to come. We therefore proposed to model earthquake damage zones by modulating the geohazard susceptibility with the mapped earthquake induced geohazards as defined in Eq. (5). The final map of earthquake damage zones is shown in Fig. 15. Considering that this earthquake damage zone map is different from the earthquake related geohazard susceptibility map (Fig. 14a) only in areas of existing, mapped geohazards where the score is doubled, we applied the same thresholds to classify the earthquake damage zone into four levels: Low, Medium, High and Very High. This simple approach assures that the mapped geohazards in the areas of the highest susceptibility level are saturated at the same level whereas those at lower susceptibility levels are raised to higher levels.

5. Conclusion

In this paper we have presented a multi-variable modelling procedure for the mapping of susceptibility to earthquake related geohazards and of earthquake damage zones, based on the case study of the Beichuan area where extreme devastation and destruction were triggered by theMs 8.0Wenchuan earthquake event. The proposed GIS model for earthquake damage zone mapping is novel in its combination of geohazard susceptibility factors with co-seismic deformation. In developing this new model, we step away from the conventional descriptive approach of seismic intensity, by incorporating measurable variables of co-seismic deformation and geological/topographical conditions to characterise not only the destruction immediately after an earthquake but also the future potential for damage as a consequence of the earthquake.

The result fromthismodel no longer strictly refers to seismic intensity, though it is closely related, and we call it earthquake damage. The model has been designed on the basis of our understanding of the relationships between the main influential variables, using combined ddition and multiplication (modulation) operations which are different from models based on weighted linear combination and geometric mean that have been used in previous work of this type. The most important variable for modelling the susceptibility of earthquake related geohazards and earthquake damage zones is the co-seismic deformation. The DInSAR data generated from ALOS PALSAR cross-event fringe pairs enabled us to derive this variable, and its contribution to the corresponding mapping is significant. Our study demonstrates that under the circumstance of a strong earthquake, co-seismic deformation takes the first order regional control in causing earthquake induced geohazards and susceptibility to future geohazards, whilst other variables can be used effectively to categorise local hazard levels. The final map of earthquake damage zones fairly accurately reflects the ground reality and matches the geohazards inventory compiled by the State Key Laboratory of Geohazard Prevention, Chengdu University of Technology. The importance of the map is not only to show what has already happened but also to indicate where geohazards are most likely to happen in future, as a long term impact of the Wenchuan earthquake in the Beichuan region.

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