Towards an Improved Method for Earthquake Induced Landslide Susceptibility and Hazard

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1. Introduction

The occurrence, type and abundance of landslides in an area depend on the characteristics of the triggers and on the predisposing conditions (Guzzetti et al., 2007). Natural conditions that control the location, abundance and type of landslides include the local and regional geomorphological and lithological setting, the incidence and abundance of geological discontinuities, the type and depth of the soil, the extent and type of the vegetation cover, and the mechanical and hydrological properties of the rocks and soils (Zaruba and Mencl, 1982; Crozier, 1986; Turner and Schuster, 1996). Natural conditions exhibit some differentiations regionally. These conditions result in variations in regional landslide distributions. Although the geologic, geomorphologic, climatic and tectonic conditions are different at every region, the natural conditions may not show a homogeneous structure even at small areas bounded by physiographic, lithologic and climatologic conditions. For this reason, the regional significance of the landslide distributions at medium-scale studies has to be presented. There exist some limitations for the determination of significance of the natural conditions. The result of this is arising from the differences in landslide types, dimensions and spatial and temporal intensities (Van Westen et al., 2005; Gokceoglu et al., 2005; Guzetti et al., 2007). In addition to the spatial and temporal differences, the information obtained from the natural conditions has been deformed by the landslide and also differ (Suzen and Doyuran, 2005; Gorum et al., 2008). Additionally, slope instabilities are triggered and controlled by seismic, meteorological, geologic and various morphologic conditions. These conditions can change rapidly depending on the spatially varying climatic, anthropogenic and tectonic effects.

Earthquakes are one of the main triggering factors of landslides and rapidly changes of surface with generate landslides. Largest earthquakes have capable to trigger thousands of landslides throughout areas of more than 100,000 km^2 (Keefer, 1984) and also these landslides can cause extensive damage and loss life. Usually their damage effects and casualties considered within the earthquakes. Conversely, it is known that earthquake induced landslides may have been destructive rather than earthquakes. For example, 12 May 2008 the magnitude (M_w) 7.9 Sichuan Earthquake which is occurred in China triggered more than 11,000 landslides and these events have threatened 805,000 persons and their properties.

Earthquake induced landslides have been documented from at least as early as 1789 BC in China (Hansen and Franks, 1991) and 372 BC in Greece (Seed, 1968). The first scientific identification of earthquake induced landslides and their systematic documentation was undertaken in the Calabria region of Italy after the 1783 earthquake swarm and first basic inventory for earthquake induced landslides accomplished in 1957 for Daly City after the California earthquake (Keefer, 1994). On the other hand the first large inventory attempt done by Harp et al. in 1981 for Ms 7.5 Guatemala earthquake (1976). However, the knowledge of this phenomena have become more detailed and comprehensive with time as increased resources and new tool, such as aerial photography, Geographic Information Systems (GIS) and Remote Sensing (RS) technologies, have been available (Soeters and Van Westen, 1996; Keefer, 2002).

The widespread use of these tools enabled to determine the landslide distribution in large areas and understand better the relation between earthquakes and landslides. Understanding the distribution dynamics of the landslides induced by earthquakes is important to reduce the hazards caused by earthquake induced landslides. It is possible to find plenty of study in similar context in the literature since 1980s. These studies that focus on regional and medium scale landslide distribution relations pioneered to the present landslide hazard studies induced by earthquakes. Most of these studies are based on deterministic approach, while there are also some statistics based studies. According to the results of distribution and statistics based studies, the type and locality of landslides caused by earthquakes are affected by the differences in seismic parameters and distribution of geological characteristics and topographic factors. Therefore, it is prerequisite a comprehensive understanding of seismic parameters, geological and geomorphologic dynamics and the relations between them for better understanding landslide distribution induced after the earthquakes. In this respect, the prediction of landslide occurrence where and under which conditions is the key feature for the regional and medium scale landslide hazard studies.

1.1. Brief Literature Review

Earthquake-induced landslide hazard zoning known to have experienced earthquake-induced slope failures during historical earthquakes, or areas identified as having past landslide movement including both landslide deposits and source areas, or areas where the geological materials are susceptible to earthquake-induced slope failure. Zonation refers to the division of the land surface into areas and the ranking of these areas according to the degree of actual or potential hazard from landslides or other mass movements on slopes (Varnes, 1984). The objective of earthquake-induced landslide hazard assessment is to evaluate the location of landslide susceptibility zones where landslides could be induced by future strong earthquake shaking. The procedure of slope stability analysis and hazard zonation requires an evaluation of spatially varying terrain, geological and hydrological conditions, and spatial distribution of existing landslides.

The Geographic Information System (GIS) has been described as “a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes” (Burrough,1986). Over the past three decades, GIS has attracted great attention in the assessment of natural disasters. Government agencies and research institutions have expended great effort in landslide hazard mapping. A large amount of research on landslide hazard zonation techniques can be found in publications by Varnes (1984), Hartlen and Viberg (1988), Guzzetti et al. (1999), and Van Westen (2000). Many scientists and engineers have attempted to assess landslide hazards and their spatial and temporal distributions. The literature on this subject is voluminous.

From the literature reviews on GIS application to landslide hazard assessment, it appears that most of the studies focused on using statistical methods to assess and predict the landslide susceptibility (Carrara,1983; Chung and Fabbri,1999; Carrara et al.,1991, Van

Westen, 1993) and the remainder focused on integrating the GIS technique with a deterministic model for slope stability analysis (Van Westen,1993 and 2000; Jibson,1998; Xie et al.,2003a and 2003b;). For earthquake-induced landslide hazard assessment, there are two components which are commonly used: pseudo-static slope stability analysis and Newmark displacement method. For deterministic and probabilistic approaches, most research employs the infinite slope model, Newmark displacement, and Monte-Carlo simulation to estimate the factor of safety and displacement, or failure probability (Jibson and Harp, 1998; Christian and Urzua,1998; Luzi et al., 2000; Refice at al.,2002; Khazai and Sitar,2002).

In the last two decades, research has established that GIS provides an excellent tool for landslide hazard zonation. However, seismic-induced landslide susceptibility assessment inherits complex uncertainties of terrain, seismic, geologic and geomorphic parameters. Most existing GIS-based analysis models can only assess approximate landslide hazards. For deterministic analysis of slope stability, assumption of current analysis models such as the infinite slope model, are only applicable for shallow slope sliding prediction. In fact, circular slope failure and deep slope sliding occur more commonly than otherwise in earthquake prone areas and these types of landslides usually are the major cause of property damage and fatalities. More accurate analysis and better techniques are needed to improve the mapping of landslide hazards and the prediction of seismic-induced slope instability. It is essential to develop a reliable analysis model that considers failure modes, structural-geological and geomorphological parameters, and uncertainties to achieve the accuracy needed for seismic-induced landslide hazard zonation.

Looking to researches on earthquake-induced landslide studies in near future; one of these investigations was performed in Umbria-Marche, Italy by Esposito et al. (2000). Esposito et al. (2000) carried out a research on surface deformations that includes landslides that were triggered by the 1997 Umbria-Marche seismic event. Researchers worked in the area that is about 700 km^2 and near the epicenter where the seismic event occurred. Researchers noted that the most frequently occurring slope failures are rock falls and rotational and planar slides. Consequently, it has been revealed that the reactivation of old landslides will be decreased as the distance to the epicenter becomes shorter.

In their work, which assesses the susceptibility of the landslides that were triggered by the 1994 California Earthquake, Parise and Jibson (2000) noted that analyzing and determining the character of these landslides were important since they give hints about the area that would be susceptible when the next earthquake happens. In their study, they analyzed the distribution, density and the geometry of the landslides that were triggered in Santa Susana which is close to the epicenter. In addition, in the study, horizontal and vertical displacements were determined using GPS, landslides were mapped using aerial photos, and digital elevation models were generated using GIS.

Wasowski and Del Gaudio (2000) used a probabilistic approach while they evaluated the mass movements induced from earthquakes in Caramanico Terme, Italy; where earthquakes and land slides are two important geological hazards. In addition, they also noted that the magnitude of the slope failures triggered by earthquakes is between VI and IX. Mass movements are in the form of rotational failures or rock falls. Field surveys and historical records helped detecting the areas that trigger rock falls, and are susceptible for seismic activities. Historic and pre-historic rock fall records and their expansion areas Historic and pre-historic rock fall accumulation and their expansion/creep areas helped the determination of potential hazard zones. Researchers noted that the time probabilistic estimation was only possible by the well documentation of the seismic history at low magnitude levels in limited time intervals.

Wasowski et al. (2002) investigated the factors that control seismic slope susceptibility in the Slopes of Valley Sele. It was denoted that most of the slope failures were caused by 1980 Irpina Earthquake. It was also noted that hydrological conditions and differences in slope gradient are two important parameters that cause difference in the distribution of reactivated landslides that are caused by seismic effects. In the scope of the study, 1/25000 scale topographic maps were digitized and the digital elevation model of the region was generated. Furthermore, a landslide inventory was obtained by studying the types, location and failures prior to the occurrence of the landslides that happened during 1980 earthquake. The study also revealed that the existing landslides being triggered by the 1980 earthquake were to be reactivated.

Capolongo et al. (2002), in their study in which they aimed to assess the threats from land slides that are triggered by earthquakes, used a GIS based analysis for the slope deformation model that was induced from a seismic effect in the Southern Apennines, Italy. In the study, geologic, geotechnical, geomorphologic, and seismic data were also included in the model of standard slope stability. This model evaluates the landslide potential that occurred during the 1980 Irpina earthquake in the Valley of the Sele River. The researchers used an approach of probability and Newmark displacement analysis method in their work. In the study, experiment results were applied to both for deterministic and probabilistic approaches of the Newmark analysis, and the results are highly uncertaint/ambiguous for the areas that represent complex geological structures. As a result, the researchers note that these values are affected from regional and environmental factors, and the performance of the model is affected adversely/negatively.

Del Gaudio et. al. (2003) offered an approach taking time probability in to account for the seismic induced landslide hazard. Those researchers recommended a new technique including time factor for the seismic induced landslide hazard assessment. For this purpose they initially made a seismic hazard assessment to determine the probability of the occurrence of various seismic shaking levels. They identified the Arias Intensity for measuring the shakes. Some of the empirical equations based on Newmark Model are used for defining the critic slope acceleration (a_c) for the seismic effect that triggers the landslides. The researchers enabled assessing the seismic induced landslides with their study.

Del Gaudio and Wasowski (2004), in which time probabilistic evaluation of the landslide hazard in Irpina, southern Italy caused by a seismic activity was made, aimed to map the landslides that were triggered by the earthquakes using the model of Newmark over a regional scale. Regional probabilistic hazard maps for Irpina were made considering two failure types which are landslide debris flows and rock falls. It was noted that seismic activity levels in Italy the zones that are out of active seismic zones do not cause landslide hazards.

Agnesi et al. (2005), with a multidisciplinary approach, aimed at evaluating the mechanism of the landslide which was triggered by the earthquakes of Cerda (Sicily, Italy). Although the study area is homogenous from the point of view of geology and geomorphology, the fact that recorded landslides are not available in the vicinity of the study area showed the importance of seismic data for the land slides which are triggered by seismic activity. The data from GPS, geology, geomorphology, geophysics and geochemistry were obtained and analyzed to investigate the cause and effect between earthquakes and landslides. According to this, the situation can be interpreted such that the remnant land slide body was triggered by an earthquake.

Nicoletti (2005) noted an inconsistency between the distribution of the landslides that were triggered by the earthquakes and historical seismic activity in the southeastern Italy, Sicily. Although most of the landslides triggered by the earthquakes are located to the west of the study area, historical seismic activity was mostly observed in the eastern part. This study evaluates the model of landslide and earthquake and in the case a larger landslide occurs to the west of the study area a) the activity of the eastern part b) the seismic activity that occurs in a higher magnitude and lower reoccurrence period. Consequently, regional earthquakes are likely to happen in the western part in which landslides occur however these are larger than historical observations and they have longer reoccurrence period.

Ingles et al. (2006) carried out a research on the displacements of earthquake induced landslides using Newmark model, in which the effect of the vertical component of ground shaking was investigated. With the model developed the ground acceleration which is not parallel to the slope that is called vertical acceleration parameter depends on the seismic state of the slope (magnitude, earthquake source distance and type of fault), and the vertical acceleration affects the upper and lower parts of the slope. Consequently, the displacements D that were developed in this study were larger than the results D_N that were obtained from the Newmark Approach. The difference $D-D_N$ is larger for some potential landslides and important for seismic stability analyses for the slopes. This also verifies the importance of vertical ground acceleration.

2. Problem Definition and Research Objectives

2.1. Problem Definition

The location, type and abundance of earthquake induced landslides in an area depend on the characteristics of the seismic parameters and on the predisposing conditions. The latter control include the local and regional morphological and lithological setting, the frequency and orientation of geological discontinuities (including bedding planes, faults, joints, and cleavage systems), the morphology and morphodynamics of the surface and the mechanical and hydrological properties of the rocks and soils. A large variety of studies on the earthquake induced landslide distributions have shown that local and regional geologic and geomorphologic conditions are very important in terms of presence, distribution and typology of landslides (Keefer, 1984; Crozier et al., 1995; Rodriguez et al., 1999; Keefer, 2000; Jibson, et al., 2000; Chigira et al., 2003; Wang et al., 2003; Khazai and Sitar, 2003; Chigira and Yagi, 2006). Understanding the role of the predisposing conditions in controlling earthquake-induced landslide distribution and their pattern is important to determine landslide susceptibility and hazard. In order to better understand the future behavior and next generation area of the landslide events and their distributions, before and after earthquake (event) inventory mapping based on detailed geomorphological structural geologic analysis with using high resolution aerial photographs-satellite images and extensive field works are essential.

Regional earthquake induced landslide studies analyze the landslide distribution based on seismic parameters and local geologic and geomorphological conditions which are very important for understanding the future landslide events. Many studies have certain difficulties to explain the distribution of landslides which concentrate in certain areas or that occur at a distance from epicenter or fault rapture and covering large areas. The reason for this is generally scale dependent. The thousands of landslides triggered by medium or strong earthquakes can occur over an area of hundreds to thousands km^2 depending on the length and characteristics of the fault rapture, and the magnitude of the earthquake. However, mapping of all these landslides requires a long time, which constitutes the main difficulty to study in detail such large areas. For this reason, each of the landslide events is generally considered as a single point which makes it difficult to classify them according to size or typology. As a result, the reliability and accuracy of landslide susceptibility and hazard studies are negatively affected by the difficulty of understanding pre- and post-earthquake landslide distribution. For instance, Khazai and Sitar (2003) studied the complete inventories of three earthquakes (Loma Prieta (1989), Northridge (1994) and Chi-Chi (1999)) and concluded that the landslides induced after Chi-Chi earthquake concentrated in the areas with slope higher than 60^o, while the landslides after Northridge were concentrated in the areas with a slope range between 20^o and 40^o. Interestingly, they also noted that in both earthquakes the highest landslide concentration values for all slope angles coincided with a dominant mean PGA of 0.4–0.5g both Chi-Chi and Northridge earthquake. Furthermore, landslides were distributed more in some lithological formations at Chi-Chi (Taiwan) earthquake area and most landslides occurred 40-50 km away from the fault rupture and epicenter of earthquake. These anomalies might be related with local morphologic and topographic conditions of the area, but it is not easy to discover those anomalies by regional approaches. The Chiu-fen-erh-shan (Wang et al., 2003) and Tsaoling landslides (Chigira et al., 2003), which are triggered by 1999 Chi-Chi earthquake, illustrated that local geologic and geomorphologic conditions are very important to understand the distribution and causative relations of landslides. The authors studying both landslide events have pointed out that the areas of the earthquake induced landslides, show some geo-environmental precursors before the event and detailed studies are needed to understand these geo-environmental indicators. Therefore, it is important to analyze the relationship between seismic parameters and local geologic and geomorphologic predisposing factors in detail to improve existing earthquake induced landslide susceptibility and hazard maps. Nevertheless, regional assessment of seismic landslide hazards is a complex, multiphase process that requires knowing both the spatial and temporal likelihood of occurrence (Wasowski et al., 2000). Besides this, the inability to temporally predict earthquakes makes it impossible to predict the timing of triggered landslides. After a big earthquake a lot of landslides are triggered and these landslides continue their activity in a specific time period. Preparing pre-earthquake landslide susceptibility and hazard maps is a difficult task since the location and the magnitude of the earthquake cannot be known beforehand. Additionally, landslides occurring after an earthquake increase the landslide hazard susceptibility in the region through creating new weak zones. There are few post-earthquake landslide hazard studies utilizing an approach which consider both the processes prior to the earthquake and the information from landslides which are occurred immediately after the earthquake. In this regard, the most important question to answer is how to reveal the temporal change of landslide activity in a region after an earthquake and then how to utilize the information that will be gained from the characteristics and distribution of landslides induced by the earthquake in the region to identify post-earthquake susceptibility and hazard.

After an earthquake, there are two important phenomenon in terms of landslide hazard. First, after a large earthquake many landslides occurred and these landslides keep their activity in the region for some time. The second issue is related to the hillslopes where no coseismic landslides have developed but which are still prone to landslide after intense rainfall periods following the earthquake. Determining these potentially susceptible hillslopes brings another challenge to tackle. The changes in the landslide triggering threshold values after an event (earthquake, hurricane, etc) affect the temporal probability and spatial persistence of landslides. To be able to explain these well, there is need for good landslide historical records and monitoring of the parameters and landslides after the event continuously.
The detailed information that will be obtained from the distribution and characteristics of the landslides occurring after a big earthquake and from the hillslopes which have not slided directly but which show signs of instability helps to predict the development of landslides after another potential earthquake. In this respect, it wouldn't be sufficient to study the landslides for a comprehensive understanding only taking into account the triggering earthquake parameters or the lithological and topographical conditions formed after the occurrence of earthquake. Therefore it would be necessary first to reveal the pre-earthquake situation and the processes and then, to analyze the landslides triggered after the earthquake and the changing threshold values in the region after the earthquake and finally, to carry out the post-earthquake landslide hazard evaluation on top of these information. As a result, it is important to evaluate together the analyses related with pre- and post-earthquake processes.

Sichuan Province (China) is one of the most affected areas by strong earthquakes and earthquake-induced landslides in historical times. Last year on May 12, 2008, an earthquake having magnitude of 7.9 ruptured the Longmen Shan margin of the eastern Tibetan plateau in Sichuan. The M_w 7.9 Sichuan earthquake occurred at a depth of about 12 km on the NNE-striking Yingxiu-Beichuan fault. This is one of the three west-dipping, active reverse fault zones in the easternmost Longmen Shan thrust belt in western Sichuan; the other two are the Jiangyu-Dujiangyan fault zone (also known as the Anxian-Guanxian fault) to the southeast and the Wenchuan-Qingchuan fault system to the northwest. The epicentre of the May 12 2008 (M_w 7.9) Sichuan Earthquake (Figure 1) seems to be near the junction between two main faults, the Wenchuan fault to the north-northwest and the Beichuan fault to the east. The rupture mainly propagated along the Beichuan fault over more than 270 km, with thrusting toward the East in the southern part becoming more dextral slip in the northern part. The structures of this area result from a polyphased evolution dating back from Triassic (Yong et al., 2003: Densmore et al., 2007: Burchfiel et al., 2008). Particularly, intense deformation is concentrated around the Wenchuan shear zone, and was reactivated during Cenozoic as a far effect of the Indian Asia collision (Yong et al., 2003: Densmore et al., 2007).

This earthquake triggered more than 11,000 mass movements such as landslides, rockfalls, rock avalanches, and debris slides in the area. One third of estimated 88000 casualties of the earthquake were considered to be caused by landslides. Especially Wenchuan and Beichuan cities are most affected in the province. For these places affected by the earthquake, the most urgent point the agenda is the rehabilitation of Wenchuan city and Beichuan County particularly, and site selection for the reconstruction works. There is clear need for the production of landslide hazard maps for Wenchuan county and Beichuan city. The detailed analyses of the landslides that were triggered before and after the earthquake are especially important for such hazard maps. The detailed studies of the sampling areas will serve for understanding the landslide processes in the region and will be useful to contribute the rebuilt works of Wenchuan city and Beichuan county. In addition, five different sites will also be studied in detail in terms of geology and geomorphology for better understanding of the distribution of the landslides triggered by the earthquake.

2.2. Research Objectives

2.2.1. Main Objectives

The main objectives of this study are:

1. The first objective of this study is to improve existing earthquake induced landslide susceptibility and hazard assessment methods based on casual relationships between landslides geo-environmental and triggering factors during Wenchuan earthquake.

2. The second objective of this study is to develop a method for post-earthquake hazard assessment to make use in the reconstruction-planning and rebuilding of Wenchuan county and Beichuan city in Sichuan Province.

2.2.2. Research Sub-objectives and research questions

The specific objectives and the related research questions are as follows:

1.1. To produce different type of landslide inventory maps and analyze distribution, type and characteristics of earthquake induced landslides using pre- and post-event detailed image interpretation and DEM derivatives.

- What kind of detailed information can be obtained from high resolution images for event based landslide inventories, structural geologic and geomorphologic mapping?
- Can we effectively utilize multi-temporal DEM analyze for quantitative estimation of earthquake-induced landslides?
- Which type of landslides has most destructively changed the morphology in the area? What are their volumes, sizes and magnitudes?
- Which geomorphologic mapping techniques are most effective and suitable to understand the landslide morphodynamics of the area?

1.2. To investigate the relation of landslides with structural geologic settings, topographic factors, geomorphologic and seismic parameters.

- Which pre-earthquake topographic predisposing factors control landslide distribution and density most?
- What is the main relationship among epicenter, fault rupture, fault typology and landslides typologies and distribution for the Sichuan earthquake?
- Is there any correlation between the earthquake fault's slip rate and landslide distributions and their densities?
- Are there any differences between landslide distribution and density on the foot wall and hanging wall areas of the fault rupture?
- Are there any prevalent differences with regard to extent and typology of landslides getting either further away or closer to the fault and epicenter in the areas where the geomorphology and lithology are assumed homogenous?

1.3. To characterize terrain indicators using actual geomorphological conditions (old landslides, tension cracks, linear depressions and etc.) before and after the earthquake to understand post-earthquake susceptible areas.

- Which type of lithology is more sensitive in terms of earthquake induced landslides? Is there any relationship between structural geologic settings and earthquake induced landslide distributions and their densities? What is the role of geological discontinuities such as joint sets, cleavage systems bedding planes and active and inactive faults on landslide distributions?
- Which geomorphologic units are the most important with regard to producing landslide? What is their response after the earthquake in point of landslide occurrences and distributions? Is there any relationship between morphologic characteristics such as morphologic roughness, mountain-hill shapes, ridge orientations and earthquake induced landslide distributions?
- Considering the morphological conditions prior to the earthquake, which geomorphologic and geologic parameters can be used as indicator for landslide susceptibility before the earthquake (such as old landslides, linear convex slope breaks, cracks, drainage density and a linear depression)?

1.4. To evaluate rock slope stability based on the analysis of geometry, fabric and kinematics of rock slopes with using Rock Slope Stability GIS (RSS-GIS) software package.

- How can we produce geometry, fabric and kinematics of rock slopes factors for to analyze in RSS-GIS software and how can a structural geologic data base be prepared for the area?
- What is the optimal sampling method for rock slope properties measurement?

1.6. To produce landslide susceptibility and hazard maps using the existing methods and improve these models to the region considering the landslide processes that exist in the area and for the needs of chosen sampling areas.

- How can we produce existing earthquake induced landslide susceptibility map to predict the landslides which are triggered by the Wenchuan Earthquake?
- How can existing earthquake induced landslide susceptibility and hazard methods be improved?

1.7. To compare traditional susceptibility maps, which do not consider the triggering (earthquake) factors, and existing earthquake induced landslide susceptibility maps in terms of significance levels and conceptual differences.

- If a traditional susceptibility map would have been used, how wrong would it be and why?

2.1. To investigate the diminishing landslide activity through time after an earthquake using multi-temporal satellite images and periodic fieldwork.

- How does landslide activity diminish through time after an earthquake?
- Which areas that are destabilized during the earthquake and will continue produced landslides and how is the re-activity trend of landslides after the earthquake?

2.2. To assess changes the rainfall threshold as a consequence of the earthquake.

- How do rainfall thresholds change as result of the earthquake?
- What is the minimum rainfall necessary to cause landslides after the earthquake in the study areas?

2.4. To develop reliable post-earthquake landslide hazard maps applicable to Sichuan Province.

- What should be the requirements to develop reliable and effective post earthquake landslide susceptibility and hazard maps applicable to selected areas in Sichuan Province?
- Which method or approach for landslide hazard assessment (direct, semi-indirect or indirect) is more convenient in the conditions of Sichuan Province?
- What is the distribution of hazard in the study area in terms of specific landslide types and total landslide hazard?

3. Study Areas

3.1. General Introduction

The study area is located in the eastern margin of the Tibetan plateau in Sichuan, China (Figure 1). In Sichuan Province, the climates are remarkably different from the east to the west. It is a typical humid sub-tropical monsoonal climate, mild winters, hot summers, a long frost-free period, plentiful rainfall and mist and fewer sunny days (Di et al., 2008). The average temperature in July, the hottest month, is 25-29°C; while in January, the coldest month, 3-8°C. The Western Sichuan Plateau has lower temperature and less rainfall than the rest of the area. Both the temperature and the rainfall are different in the southern and northern sections of the plateau (Di et al., 2008). The average annual rainfall in Sichuan Province is 1,000 mm and the average annual temperature is 16.5°C.
The plate tectonics movement in China is very active, due to the intense plate collision between Indian Ocean Plate and Eurasian Plate, and continued uplifting of Qinghai-Tibet plateau (Yong, et al., 2003; Burchfiel et al., 2008; Runqiu, 2009;). Strong earthquakes are also frequent in this area, which raise the occurrence of large-scale landslides.
On May 12, 2008, an earthquake having a magnitude of 7.9 (M_w) occurred at the eastern margin of the Tibetan plateau in Sichuan, China (Figure 1).

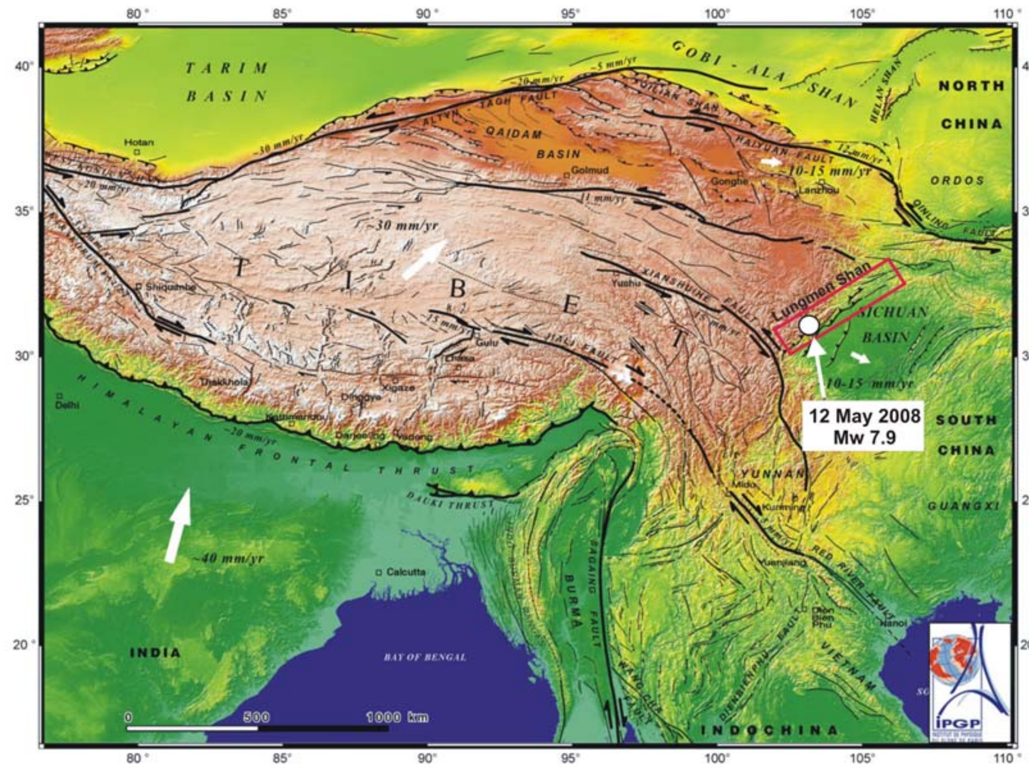

Figure 1: General tectonic map of the China (Source: CIT, Tectonics Observatory Division); white point indicates the epicenter of the May 12 2008 Sichuan earthquake and red frame is the general border of the earthquake induced landslides abundance zone.

Estimated magnitude of the earthquake according to the Chinese Earthquake Administration was 8.0 (M_s), 8.3 (M_w) and according to the USGS earthquake magnitude was 7.9 (M_w). The earthquake epicenter was located at latitude 31.02° N and longitude 103.36° E in the Sichuan Province and the focal depth was ~14 km. Rupture occurred over a length of ~270 km along a north-northeast–striking, west-dipping to steep fault beneath and parallel to the northeast-striking the Longmen Shan thrust belt (Burchfiel et al., 2008). The earthquake affected six provinces, and autonomous regions including Sichuan, Gansu, Shaanxi, Yunnan, Ningxia and Chongqing (Special Report on Engineering Damage of Wenchuan Earthquake, 2008).

3.2. General characteristics of the earthquake-induced landslides

Official statistics list 69,197 confirmed death, including 68,636 in Sichuan Province, 374,176 reported injured, and 18,340 listed as missing (Wang et al., 2009). The Sichuan earthquake is the deadliest and the strongest earthquake to hit China since the 1976 Tangshan earthquake, which killed at least 240,000 people (Wang et al., 2009). After the main earthquake, many aftershocks occurred in the area along the Longmen Shan active fault system. On May 25, a major aftershock of 6.0 (Mw) occurred northeast of the original earthquake's epicenter, in Qingchuan County, causing 8 deaths, 1,000 injuries, and destroying thousands more buildings and on May 27, two more major aftershocks, 5.2 (M_w) in Qingchuan County and 5.7 (M_w) in Ningqiang County in Shaanxi Province (Wang et al., 2009). This earthquake sequences triggered more than 11,000 landslides in different typology at the region. Most of them were extremely rapid and this caused many casualties because evacuation was almost impossible during the unexpected, rapid and massive movement of the sliding masses.

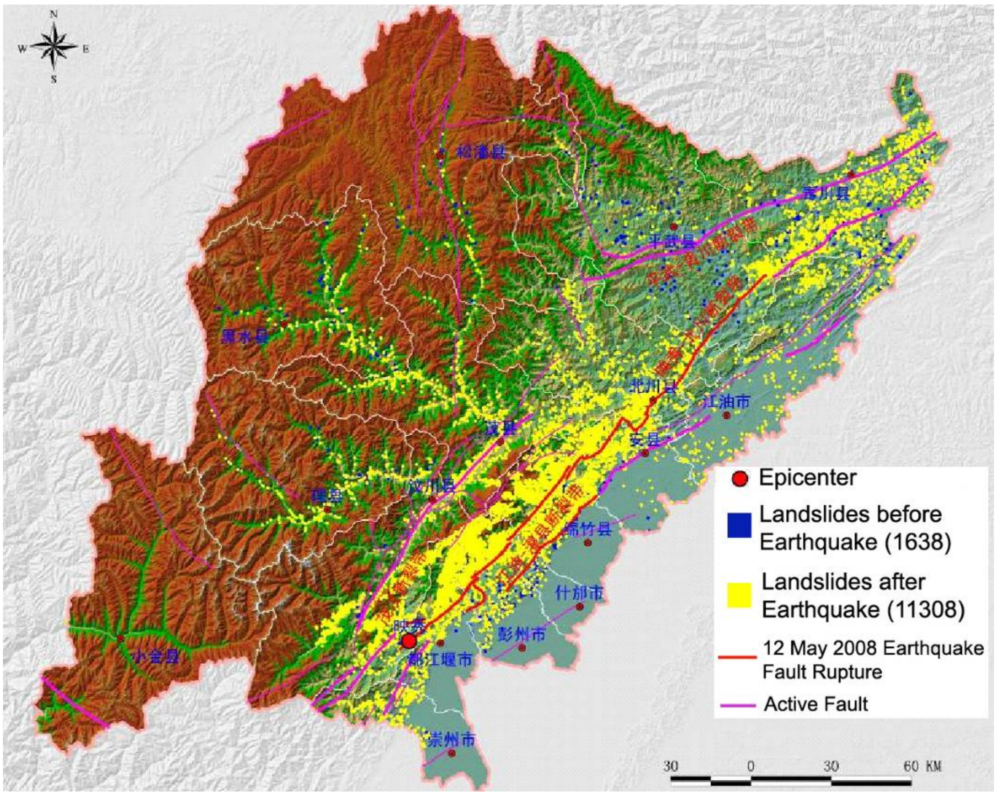

Figure 2: Landslide distributions of before and after earthquake (Source: State Key Laboratory for Geo-hazard Prevention, Chengdu University of Technology)

The field investigation which was made by the State Key Laboratory, for Geohazard Prevention, Chengdu University of Technology's researchers, showed that the distribution of landslides is closely related with fault rupture of earthquake, more landslides occurred at the hanging wall rather than the foot wall of the fault.

Nevertheless, the foot wall area mainly represents a plain characteristic which is known as the Sichuan Basin. The majority of landslides were distributed along the Longmen Shan Fault Zone and banks of major rivers (Figure 2). From the map it can be observed that the landslides are concentrated at 100 km north of the epicenter, and 20 km west and east of the fault rapture. Moreover, it is observed that the landslides are distributed in the hillslopes of the rivers representing a linear morphology and along the main fault zones. In this regard, the distribution of landslides refers to two main density zone: One was the area along the fault that generated this earthquake, and another was along the steep slopes of inner valleys along the Minjian Rivers. Relatively shallow landslides were induced on the slopes in the valley of the Mingjian River from Yinghsiuwa through Wengchan to maoxian (Chigira et al., 2009). The distribution of landslides was wider around the middle and southwest parts of the surface rupture and became narrower to the northeast. The directions of landslides were controlled by the fault: Landslides moving normal to the fault ruptures were most prevailing probably due to the directivity of the seismic wave (Chigira et al., 2009). Looking at the north-south direction distribution, it is observed that the landslides are generally concentrated in the middle parts of the fault rupture. The landslides accumulated around the north of Beichuan city. While in the east west direction, the density of landslides decreases in the eastern part of the fault towards the Sichuan Basin due to the flattening of the morphology. In the western side of the fault, the density of the landslides continues along 30 km distance from the fault, and then it decreases in the mountainous areas except for the patchy landslides observed in the side slopes of mountain valleys. Another interesting finding from the distribution map is that, on the contrary to the south part of the fault rapture where the landslides are densely observed, there is no landslides observed in a certain region of the northern side while the landslides start to get denser again at an unruptured zone (shown with purple color on the distribution map) towards the further northern direction. This finding can be considered as an indicator for that there are some other factors controlling the distribution of landslides in the region besides the epicenter of the earthquake and fault rupture. The important point in this part of the study is to understand the underlying process. To understand this process, it is necessary to answer the questions of "why the earthquake induced landslides occurred and distributed particularly in these areas?", and "which factors mainly affected the landslide processes in these areas?". The understanding of the landslide process will enable to reveal the landslide susceptibility in an effective and reliable manner.

3.3. Specific Study areas

In this regard, five different sampling areas have been selected in the Sichuan Province to clarify the earthquake induced landslide densities and distributions in detailed analyses with regard to their geomorphological, geological and seismic dissimilar characteristics (Figure 3). The main reason of selection of the different sampling areas is to achieve detailed analyses of predisposing factors which governing the earthquake induced landslide distribution and density. In this respect, the sampling areas were selected considering they have different morphological character, located in similar and/or different lithological formations, in different parts of fault-rupture (in terms of hanging wall or foot wall area) and at different distances from the epicenter (Table 1). The selection objective details of the sampling areas and available datasets are given in Table 2. For producing the post-earthquake landslide susceptibility and hazard maps the knowledge of the five different sampling areas, which are selected based on their differences in terms of lithological, geomorphological and tectonic characters and their distances to the epicenter and fault rupture of the earthquake will be used in order to understand landslide processes and future movements in detail. Finally, the results that will be obtained from the sampling areas then will be implemented in Wenchuan County and Beichuan County areas for producing the post-earthquake landslide hazard maps.

Table 1: General characteristics of the study areas.

No	Name	Geomorphologic Characteristic	Dominant Lithology	Fault Rupture Relation (H.wall or F.wall)	Max Distance from Fault (km)	Min Distance From Epicenter (km)	Elevation (m) (Min/Max/Mean)	Slope Deg. (Min/Max/Mean)
1	Wenchuan	Intra-Mountain Valley	Magmatic Rocks	Hanging wall	20	26	1093/5202/2456	0/63/32
2	Mianzhu	Structural Hills	Sandstone and Limestone	Hanging wall (Between two hanging wall)	7	73	689/2472/1320	0/59/25
3	Beichuan	Mountains with Structural Ridges	Limestone, Sandstone and Shale	Hanging wall & Foot wall	13	124	541/2339/1141	0/57/25
4	Wudu	Structural Dissected Plateau	Limestone and Sandstone	Foot wall	19	168	557/2340/1310	0/66/25
5	Nanba	Struc./ Denudational Mountains&Hills with Linear Valleys	Conglomerate and Mudstone	Hanging wall & Foot wall	15	168	627/3023/1323	0/59/24

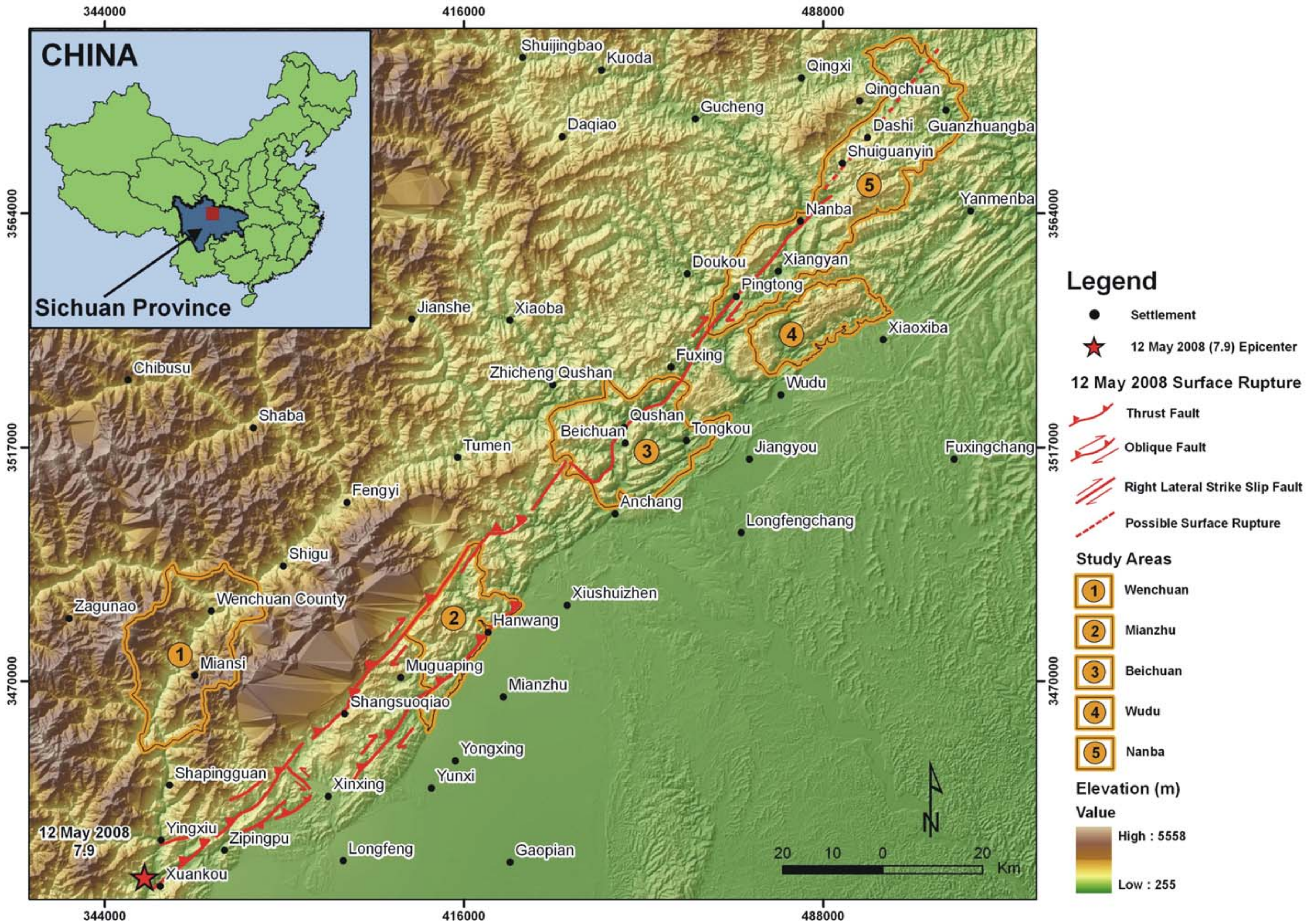

Figure 3 : Location map of the study areas.

Table 2: Selection objective of the sampling areas and available data set.

No	Name	Area (km^2)	Selection Objective	Available Data	
				Before the Earthquake	After the Earthquake
1	Wenchuan	600	To investigate the response of the Intra-Mountain valleys in terms of occurrence of earthquake induced landslides and their distribution characteristics.	ASTER, IKONOS, SPOT 5, and DEM	ASTER, IKONOS, AP
2	Mianzhu	326	To understand the response of the compressional zone which constitutes mainly structural hills in terms of occurrence of earthquake induced landslides and their distribution characteristics	SPOT 5, AP and DEM	AP and DEM
3	Beichuan	546	To examine the response of the mountainous and hilly topography with structural ridges and hanging-foot wall areas of the fault rupture in terms of earthquake induced landslide distribution characteristics	SPOT 5, CARTOSAT-1, AP, and DEM	IKONOS, FORMOSAT-2, CARTOSAT-1, AP, and DEM
4	Wudu	164	To examine the response of the structural dissected plateau with foot slopes, which is located in the foot wall area of the fault rupture, in terms of occurrence of earthquake induced landslides and their distribution characteristics.	ASTER, SPOT 5, IKONOS, AP and DEM	ASTER, AP, and DEM
5	Nanba	1240	To examine the response of the structural and denudational mountains and hills with linear valleys, which are located in the hanging-foot wall areas of the fault rupture, in terms of occurrence of earthquake induced landslides and their distribution characteristics.	ASTER, SPOT 5, AP, and DEM	ASTER, AP, and DEM

AP: Aerial Photographs, DEM: Digital Elevation Model. Topographic (1/25,000) and geologic (1/50,000) sheets are available for all sampling areas.

4. Approach and Methods

The methodology and research framework of this study will be discussed in this chapter. This chapter primarily has five main components to accomplish the research objectives. First stage of this chapter is comprised by data preparation and production (Figure 4). Unlike other stages of this chapter, the first stage is not considered as an analysis step. Second stage is comprised by analyzing the distribution of landslides. In this step, landslide characteristics and their relationship between predetermined predisposing factors will be evaluated. In this regard, the second stage of this chapter can be named as improvement of knowledge. The third stage and second step of the method is constituted by landslide susceptibility and hazard mapping with using existing methods. In the fourth stage, the results of landslide susceptibility and hazard maps that are produced with the method given in the previous stage will be compared and the differences of the results will be evaluated to improve the existing methodology. In this regard, the second and third steps of the flow chart are related with the first objective of the study. In the fourth step and last stage of this chapter, post-earthquake landslide hazard assessment will be carried out. This stage covers the second main objective of this study.

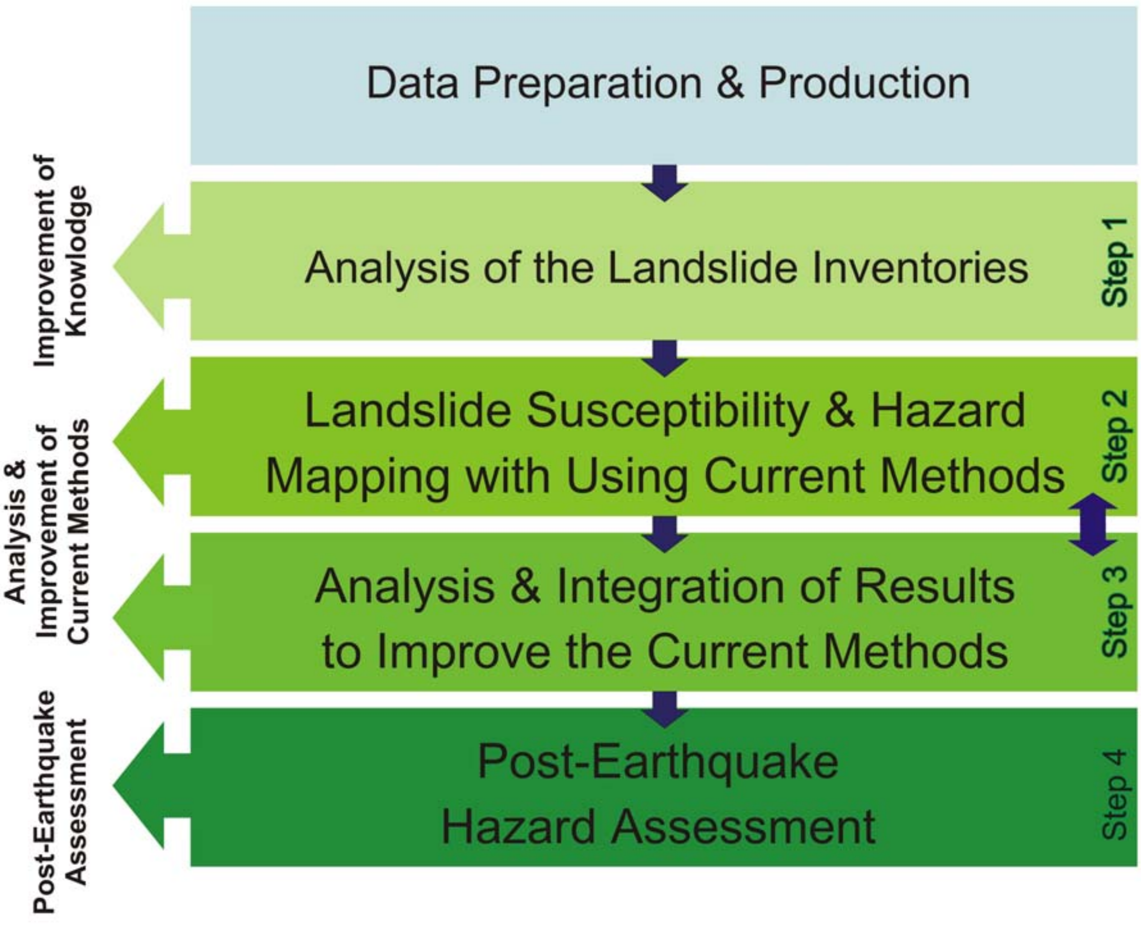

Figure 4: General flowchart of the approach and methods.

4.1. Data Preparation and Production

In this stage five different main data sets will be used for the preparation of the thematic layers which are essentials in point of analysis steps. In this regard, remote sensing products (satellite imagery and aerial photographs), pre- and post-earthquake digital elevation models, existing geological maps, field investigation based data sets and existing instrumental records (seismic and meteorological) and related archive documents will be used in the study.

The thematic layers will be prepared in different scales in accordance with the purpose of the study. For this purpose, two types of scale were determined. The first one will be medium scale (1:25.000 - 1:100.000).The analyses in this scale will be applied to all of the sampling areas. The distribution and characteristics of the landslides and the relations between predisposing factors and landslides will be elaborated with the analyses in this scale. The aim of the medium scale analysis is to reveal the controlling factors, morphodynamics and spatial persistence of landslides occurred in the region and the reasons behind why landslides are distributed in these specific areas. The results of such a study will support enhancing knowledge about the landslide processes in the region. At the same time, this study will make significant support to reveal and understand the landslide susceptibility and hazard.

The second type of scale chosen for detailed analyses in this study is the large scale (1:10,000). Wenchuan and Beichuan Counties in the south and central parts of the region will be evaluated in the context of large scale detailed analyses. In this respect, the detailed analyses included in the second, third and fourth steps of the study will be applied to these two sampling areas. The details of the thematic layers that will be produced for these areas are given in Table 3. As given in Table 3, pre and post earthquake DEMs will be produced using the high resolution images (IKONOS, CARTOSAT-1 and ALOS PRISM) for these areas. Then, these DEMs will be used to produce thematic layers for pre and post earthquake periods and also for the volumetric calculations. Also, detailed geomorphological maps belonging to pre and post earthquake periods will be produced to support the understanding of the landslides processes in the region.

The thematic layers that will be produced in this chapter are summarized below:

Table 3: List of Themes and Thematic data to be produced for the study

Themes	Map	Source of Information and Methods Used for Pre-Earthquake	Source of Information and Methods Used for Post-Earthquake	Apply Which Steps				Study Area Coverage				
				S1	S2	S3	S4	A1	A2	A3	A4	A5
Landslide Inventory	Event Inventory Map	Aerial Photo (API) and High Resolution Satellite Image Interpretation (SPOT and IKONOS), Analysis of Available Documents	Aerial Photo (API) and High Resolution Satellite Images (IKONOS,CARTOSAT-1) Interpretation, Field Survey, Analysis of Available Documents	•	•	•	•	•	•	•	•	•
	Archive Inventory Map			•	•	•	•	•	•	•	•	•
	Detailed Geomorphological Event Inventory Map			•	•	•	•	•	-	•	-	-
Topography	Altitude Map	DEM which produced from digital topographic contour lines (1:25,000)	DEM will produced from IKONOS, CARTOSAT-1 Satellite Images and Stereo Aerial Photographs (1:10,000)	•	•	•	•	•	•	•	•	•
	Slope Gradient Map			•	•	•	•					
	Topographic Curvature Maps			•	•	•	•					
	Sediment Transport Capacity Index Map			•	•	•	•					
	Stream Power Index Map			•	•	•	•					
	Topographic Wetness Index Map			•	•	•	•					
	Topographic Convergence Index Map			•	•	•	•					
	Topographic Solar Radiation Map			•	•	•	•					
	Topographic Roughness Map			•	•	•	•					
	Relief Ratio Map			•	-	-	-					
	Relief Shape Ratio Map			•	-	-	-					
	Orientation Map of Ridges, Hills and Mountains			•	•	•	•					
	Altitude Above Channel Network Map			•	-	-	-					
	Channel Network Base Level Map			•	-	-	-					
Geology	Lithological Map	-	Analysis of Geology Map, Aerial Photo (API), Field Survey	•	•	•	•	•	•	•	•	•
	Surficial Formation Map											
	Weathering Degree Map											
	Bedding Attitude Map											
	3D Geology, Structural Geologic Fabric Map	-	3D Structural Geology will be produced based on Arc-View RSS-GIS and FABRICMAP extension Suite (Günther, 2003)	-	•	•	•	•	-	•	-	-
Geomorphology	***General Geomorphology Map***	Aerial Photo (API) and High Resolution Satellite Images (SPOT and IKONOS) Interpretation, Analysis of DEM which produced from digital topographic contour lines (1:25,000)	Aerial Photo (API) and High Resolution Satellite Images (IKONOS,CARTOSAT-1) Interpretation, Field Survey, Analysis of DEM which will be produced from IKONOS,CARTOSAT-1 Images (1:10,000)	•	-	-	-	***General Geomorphology Map***				
	Morphological Units							•	•	•	•	•
	Lithology/Age											
	Processes											
	Main Structural Geology											
	Detailed Geomorphology Map			•	-	-	-	***Detailed Geomorphology Map***				
	Genetic Class							•	-	•	-	-
	Litho-morphological Units											
	Surfical Geology											
	Detail Structural Geology											
	Relief Class											
	Relief Shape											
	Morpho-structural Zones											
	Morphometry / Morphography											
	Detailed Geomorphological Landslide Units											
	Landslide Indicators											
	Processes											
Seismic	Earthquake Epicenter and After Shock's Distribution Map	Strong Motion Records, Reports, Available Archive Documents and Published Articles	Strong Motion Records, Reports, Available Archive Documents and Published Articles	•	•	-	•	•	•	•	•	•
	Earthquake Fault Rupture Map			•	•	-	•					
	Earthquake Fault Deformation Rate Map			•	•							
	Arias Intensity			•	•	•	•	•	-	•	-	-
	Shaking Intensity			•	•	•	•					
	Peak Ground Acceleration (PGA)			•	•	•	•					
Rainfall	Daily Rainfall Data	Meteorological Records and Available Documents	Meteorological Records and Available Documents	•	-	-	•	•	•	•	•	•
	Antecedent Rainfall Data											

4.1.1. Landslide Inventory

The landslide inventory is by far the most important, as it should give insight into the location of landslide phenomena, the types, failure mechanisms, causal factors, frequency of occurrence, volumes and the damage that has been caused (Van Westen et al., 2008). They can be prepared by collecting historical information on landslide events or from the analysis of aerial photographs coupled with field surveys. Many of the researcher deal with conventional landslide interpretation methods with using mirror stereoscope are very faster and applicable for the large areas rather than the new mapping techniques like LIDAR. However, landslide interpretation and its reliability highly depend on the experiences of the researcher. In this respect, the limitations of landslide inventories refer to their subjectivity and to the difficulty of measuring their reliability. The reliability of archive inventories depends largely on the quality and abundance of information sources and also their quality is very important in terms of producing high reliable landslide susceptibility and hazard maps (Reichenbach et al., 1998: Glade, 1998: Cruden, 1997: Ibsen and Brunsden 1996: Guzzetti, et al.,1994). Thus, a comprehensive landslide inventory plays an important role in quantifying both landslide hazard and risk.

Inventories can be prepared by different methods depending on scope, available resources, and scale of the study (Soeters, and Van Westen, 1996: Guzzetti et al., 2000). In this study, the medium and large-scale will be selected to generate the landslide inventories. Additionally, archive, event and geomorphological based inventory types will be selected for producing and analyzing of the landslide distributions. The flowchart of inventory producing steps (Figure 5) and general instruction of the inventories is summarized below.

4.1.1.1. Archive Inventories

Archive inventories are a form of landslide database (WP/WLI, 1990), and report the location of sites or areas were landslides are known to have occurred. Archive inventories are compiled from data captured from the literature, through inquires to public organizations and private consultants or by searching chronicles, journals, technical and scientific reports, and by interviewing local peoples or landslide experts (Guzzetti et al., 2000). Generally their quality and reliability are limited and they are highly depends on the sources of data. Nevertheless, they provide much information about dates, magnitudes, and locations of landslides. In this study the archive inventories of pre- and post-earthquake, especially for landslides which are triggered by aftershocks or post-earthquake rainfall events will be compiled from public organizations, technical and scientific reports, and by interviewing local peoples or authorities.

4.1.1.2. Event Inventories

According to Guzzetti (2005); an event landslide inventory map must be shows all the slope failures triggered by a single event, such as an earthquake (e.g., Govi and Sorzana, 1977; Harp et al., 1981; Agnesi et al., 1983; Harp and Jibson, 1995; Antonini et al., 2002), rainstorm or prolonged rainfall period (e.g., Govi, 1976; Baumm et al., 1999; Bucknam et al., 2001; Guzzetti et al., 2004; Sorriso-Valvo et al., 2004; Cardinali et al., 2006), or rapid snowmelt event (Cardinali et al., 2000). Event inventories are commonly prepared by interpreting large to medium scale aerial photographs taken shortly after the triggering event, supplemented by field surveys, often very extensive. Good quality event inventories should be reasonably complete, at least in the areas for which aerial photographs were available and where it was possible to perform fieldwork. In this study the event inventories of pre-earthquake landslides will be produced by using pre-event aerial photos and high resolution satellite images and also for determinations of past events dates the advantage of archive inventories will be used. On the other hand, field work studies and the aerial photographs, IKONOS and CARTOSAT-1 satellite images, which are taken shortly after the event, will be used to produce the post-earthquake event inventories. In addition to this, future events will be monitored annually by satellite images and extensive field works.

4.1.1.3. Detailed Geomorphological Inventories

A geomorphological inventory map shows the sum of many landslide events over a period of some, tens, hundreds or even many thousands of years (Guzzetti et al., 2000; Guzzetti, 2005). Geomorphological inventories are typically prepared thought the systematic interpretation of one or two sets of aerial photographs, at print scales ranging from 1:10,000 to 1:70,000, aided by field checks. Geomorphological inventory maps cover areas ranging from few tens to few thousands square kilometers, at mapping scales ranging from 1:10,000 to 1:100,000 (which usually corresponds to publication scales raging from 1:50,000 to 1:500,000) depending on the extent of the study area, the availability, scale and number of the aerial photographs, the complexity of the study area, and the time and resources available to complete the study (Guzzetti, 2005).

Typically, a single map is used to portray all different types of landslides (Guzzetti et al., 2000; Guzzetti, 2005; Van Westen et al., 2008; Gorum et al., 2008). Alternatively, a set of maps can be prepared, each map showing a different type of failure, i.e. deep-seated slides, shallow failures, debris flows, rock falls, etc. (Cardinali et al., 1990).

In this study the detailed geomorphological inventories will be prepared for pre- and post earthquake landslides which will include the different type of failures and also detailed landslide features such as prone area, main body, scarp, depletion and accumulation zone, etc.

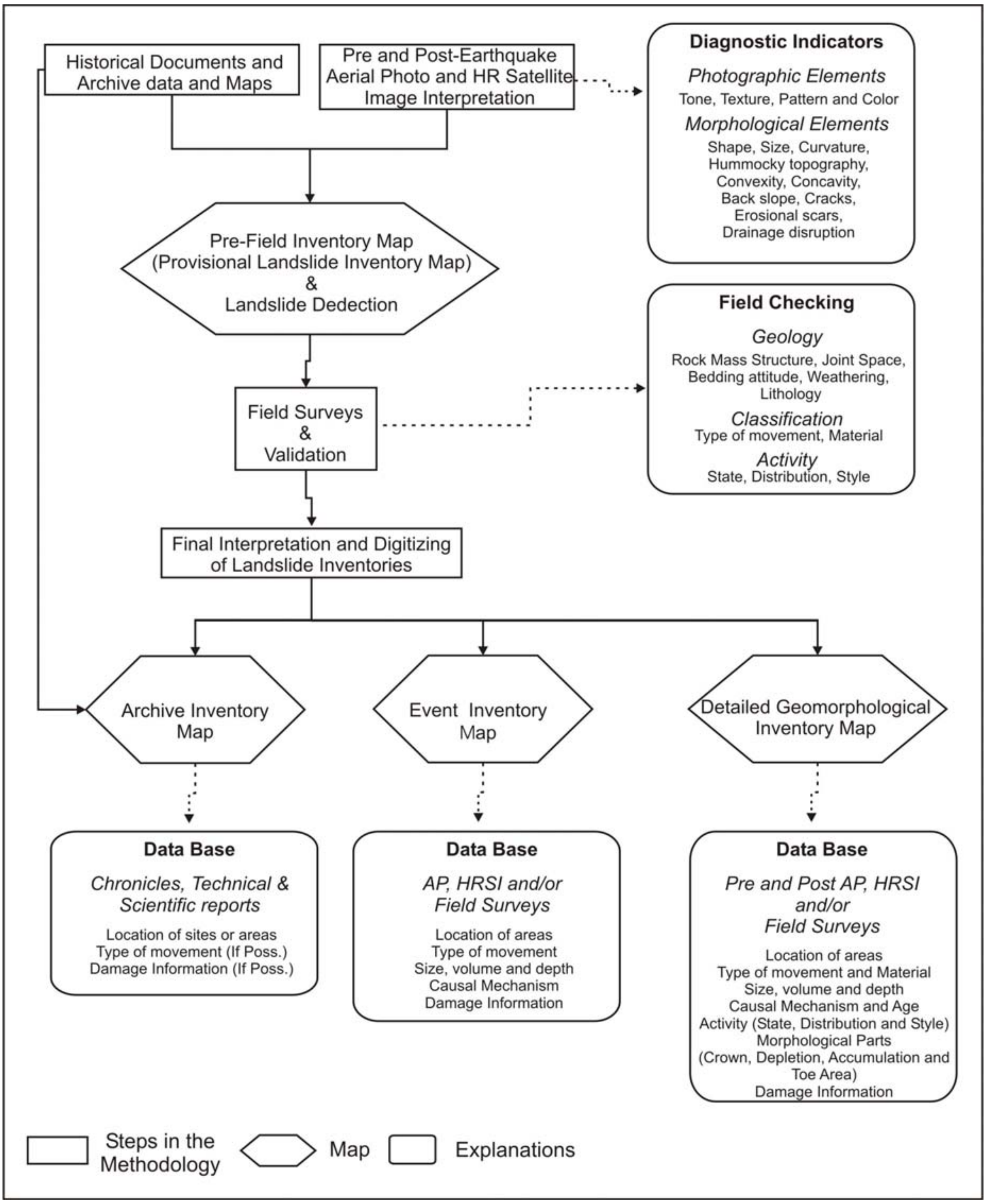

Figure 5: Flowchart of the different landslide inventory mapping types.

4.1.2. Topography

New concepts, data, and methods, emergent in geographic information science in recent years have presented scientists with new opportunities to gain fresh insights into the study of landscape (Pike, 1995; Pike, 2000; Saura and Martinez, 2001). The numerical representation of ground-surface relief and pattern has become integral to geography, geomorphology, geohazards mapping, geophysics and exploration of the earth's sea-floor and the planets (Pike, 2006). Combining earth and computer science with mathematics and engineering (geo)morphometry treats both specific landforms and continuous landscapes (Pike, 2006). The discipline is known variously as terrain analysis or quantitative geomorphology, although the newer term geo-morphometry increasingly seems preferred (Korup, 2004; Crevenna, 2005; Rapisarda, 2008; Hattanji and Moriwaki, 2009).

The influence of topography on mass movements has been well known for decades or even centuries. Accordingly, many works today focus simply on generalizing this idea by trying to correlate individual landscape attributes and the processes of slope failures. Speight (1980) sorted out around 16 primary topographic attributes that can be used to describe landforms and thence examine other processes that are linked to them. Among these attributes, the most significant for the study of landslides are probably altitude, slope gradient, slope aspect, slope length and slope curvatures as pointed out by Moore et al. (1991). On the other hand, there is no agreement in literature on which conditioning factors have to be used in landslide susceptibility analyses (Gokceoglu and Ercanoglu, 2001). While in some areas, topographical parameters are found as significant; in other areas additional factors such as geological or landuse attributes have been evaluated as crucial.

The topographic or in other terms the geomorphometric factors to be produced in this stage of the study are given in Table XX. These factors are commonly used in many landslide susceptibility and hazard studies. However, the significance of each factor for the sampling area will be determined through the landslide inventory analyses. As a result, the factors which are phsically significant in terms of landslide distribution and occurance will be used in this study. These topographic factors will be produced form the pre- and post-earthquake DEMs. While, the derivatives of DEM will be produced using the existing modules of System for Automated Geoscientific Analyses (SAGA), ILWIS and ArcGIS softwares. The details and significance of the DEM derivatives are summarized in Table XX.

Table 4: Primary and secondary topographic derivatives (topographic thematic layers) that can be computed from DEM (Source: adapted from Moore et al., 1993; Wilson and Gallant, 2000)

Attribute	**Definition**		**Significance**
Altitude	Elevation	Height above mean sea level or local reference	Climate, vegetation, potential energy determination, material volumes, vegetation and soil patterns
Slope	$\left(\frac{\partial_z}{\partial_x}\right) = \frac{z_6 - z_4}{2\partial_x}$	Gradient	Overland and subsurface flow velocity and runoff rate, precipitation, vegetation, geomorphology, soil water content, land capability class
Topographic Roughness Indices	$R = \sqrt{\left(\sum x_i\right)^2 + \left(\sum y_i\right)^2 + \left(\sum z_i\right)^2}$	Undulation of the topographic surface	The function measures the dispersion of the vector perpendicular to the surface
Profile curvature	$\left(\frac{\partial_z^2}{\partial_{x^2}}\right) = \frac{z_6 - 2z_5 + z_4}{\partial_x^2}$	Slope profile curvature	Flow acceleration, erosion/deposition rate, geomorphology
Plan curvature	$\left(\frac{\partial_z^2}{\partial_{y^2}}\right) = \frac{z_2 - 2z_5 + z_8}{\partial_y^2}$	Contour curvature	Converging/diverging flow, soilwater content, soil characteristics
Topographic Wetness Indices (TWI)	$TWI = \ln\left(\frac{A_s}{\tan\beta}\right)$	Index of moisture retention	This equation assumes steady-state conditions and describes the spatial distribution wetness indices and extent of zones of saturation (i.e., variable source areas) for runoff generation as a function of upslope contributing area, soil transmissivity, and slope gradient.
Stream-power Indices (SPI)	$SPI = A_s \times \tan\beta$	Index of erosive power	Measure of erosive power of flowing water based on assumption that discharge (*q*) isindices proportional to specific catchment area (*A*s). Predicts net erosion in areas of profile convexity and tangential concavity (flow acceleration and convergence zones) and net deposition in areas of profile concavity (zones of decreasing flow velocity).
Sediment Transport Capacity Indices (LS)	$LS = (m+1)\left(\frac{A_s}{22.13}\right)^m \left(\frac{\sin\beta}{0.0896}\right)^n$	Flow acceleration, relative erosion rates, sediment yield	This sediment transport capacity index was derived from unit stream power theory and is equivalent to the length–slope factor in the Revised Universal Soil Loss Equation in certain circumstances. Another form of this equation is sometimes used to predict locations of net erosion and net deposition areas.
Radiation Indices (RI)	$R_t = (R_{th} - R_{dh})\,F + R_{dh}\,\nu + R_{th}\,(1 - \nu)\,\alpha$	Amount of solar energy received per unit area	This equation estimates the total short-wave irradiance incident at the earth's surface for some user-defined period ranging in length from 1 day to 1 year. The three main terms account for direct-beam, diffuse, and reflected irradiance.

4.1.3. Geology

Geological structure and the material or the characteristics of the material composing the natural hillslope directly control the landslide distribution (Crozier, 1986; Cruden, 1988; Selby, 1993; Chigira et al., 2003). Generally, in the geological terms, the landslides are distributed according to the characteristics of weak, sensitive and weathered materials, sheared, jointed, or fissured materials, adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth), and contrast in permeability and/or stiffness of materials. These parameters, which are widely used in landslide susceptibility and hazard studies, are generally determined based on field work and applying certain tests according to the characteristics of the material.

The geological units at a certain area are not independent from the climate and internal processes of that area. As a result, they can show high variability even at short distances. In addition, different types of landslides can develop in these non-homogeneous formations. For this reason, each landslide susceptibility map should be prepared for only one type of landslide and the geological conditions should be evaluated in accordance with the purpose of the study.

In this study, the geological factors given in Table 3 will be first evaluated from the available maps and then the obtained information will be detailed through field work. The conventional geological mapping procedure will be applied in the collection geological data, and the bedding-dipping and discontinuity systems belonging to these units will be measured and the weathering classification will be formed. The geological mapping will be done for the whole region in 1: 100.000 and 1: 50.000 scales, while the maps belonging to Wenchuan and Beichuan Counties will be studied in large scale 1:10.000-1:20.000. Aerial maps and existing geological maps will be used additionally to support fieldwork and also producing the final maps. Also, the information regarding the friction angle, strength and cohesion belonging to geotechnical parameters will be collected from the existing scientific reports. The remaining missing information related with these parameters will be completed with the support of the laboratory experts in State Key Laboratory for Geo-hazard Prevention, Chengdu University of Technology. Finally in the context of large scale study, the 3D geology and structural fabric map of the study area will be produced using the ArcView RSS-GIS Slope Map-Extension developed by Günther (2003). As a result, each of the produced maps will be used as an input parameter in the landslide distribution analyses and also landslide susceptibility and hazard maps.

4.1.4. Geomorphology

A geomorphological map is not only a presentation of data, but also a method of research important for the understanding of individual landforms, and whole landscapes, their development and processes acting upon them. Geomorphological maps can be classified based on their content, representation, acquirement, application or scale.
Generally, for the purpose of landslide studies, geomorphology maps are prepared taking into account the hillslope processes and other related processes. Because each country has

its own mapping approach, there is no consensus globally on preparing the geomorphology maps.

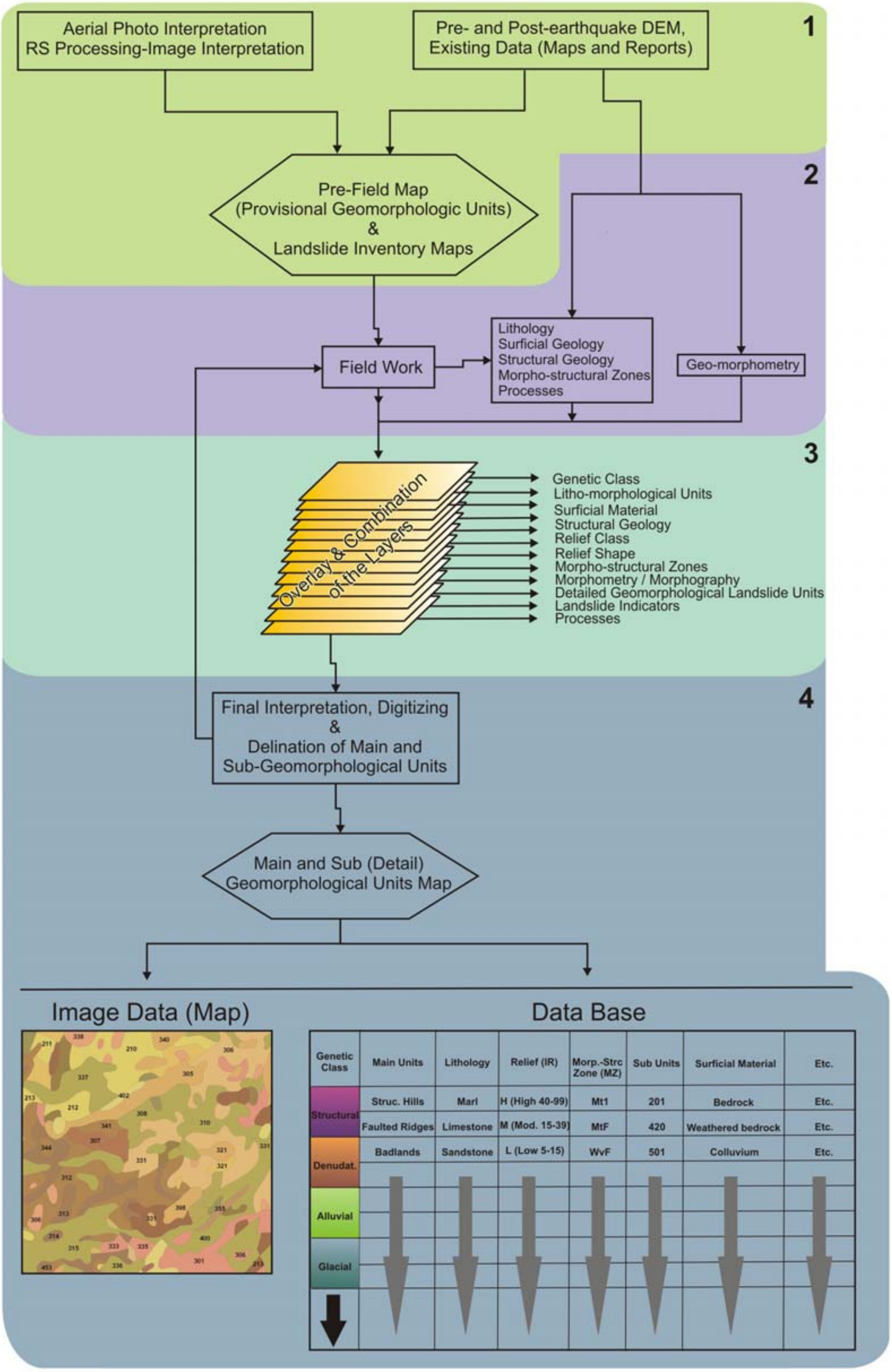

Figure 6: Flowchart of Geomorphological Mapping Procedure (Adapted from: Verstappen and Zuidam, 1975; Meijerink, 1998). (1) : Pre-field mapping step, (2) Field mapping and verification step, (3) Combination and Integration step, (4) Final interpretation and creation of the image (map) and the data base.

On the other hand, the development in the GIS technology over the last 20 years has speeded up the transition from map hatching to polygon based mapping. The production and analysis of geomorphology maps that based on analysis of many layers became easier thanks to multi layer analysis capabilities of GIS.

In this study, pre- and post earthquake geomorphologic will be produced for each period. Terrain mapping units defined by Meijerink, 1998, will be used as the mapping method. After the definition of the terrain units, geomorphology maps will be produced applying the geomorphological mapping approach developed by ITC (Verstappen and Van Zuidam, 1968). The final map will be produced using the geo-morphometric factors that will be extracted from the aerial photo based main and sub-geomorphologic units, field work and pre- and post-earthquake DEM. Then, based on these maps, General Geomorphology Maps will be produced for five sampling areas. Among these sampling areas, Detail Geomorphological Map will be prepared for Wenchuan and Beichuan sampling areas. Finally, these maps will be used to determine the hillslope processes and the processes related with the changing topography between pre and post earthquake. Also, possible indicators belonging to each period will be evaluated using detailed geomorphological mapping and the highly susceptible hills to landslide production will be defined. In addition, during Post-earthquake Hazard Analysis stage as the last part of the study, Geomorphic Hazard Maps will be produced based on the expert judgment to reveal the significance of the maps that will be produced using indirect methods. Geomorphological maps of different periods will be the base for the production of these maps. The flowchart showing the production of maps is given in Figure 6.

4.1.5. Seismic and Meteorological Data

The records of the earthquakes as the first seismic thematic layer will be obtained from China Earthquake Administration. The records belonging to the older earthquakes will be provided from the historical catalog. In addition, the surface rupture causing the landslide in the region have already been mapped and published by the same organization. The information regarding the surface rupture - digital fault rupture and slip distributions – will be obtained from Chengdu University of Technology, Structural Geology Research Center. The information about the general slip distribution and deformation rate of the fault has been published by USGS (http://earthquake.usgs.gov) and California Institute of Technology, Tectonics Observatory Division (http://www.tectonics.caltech.edu). These maps are large scale and not suitable for the detailed parts of this study. On the other hand, these data is of sufficient quality for the general evaluations in this study. The studies describing the deformation rate of the fault already exist in the literature. It is the intention to cooperate with the authors of those studies to be able to use the data about the deformation rate. Also, in the context of SAR, Japan Aerospace Exploration Agency (JAXA) has made an assessment and published about the region using ALOS images. The Japanese agency will be contacted to get a support related with this study. The other thematic maps related with the seismic parameters will be produced using the existing strong motion records. Finally, the daily rainfall records will be obtained from the local meteorology stations through Chengdu University of Technology. The records will be updated in the future with the help of the university again.

4.2. Analysis of Landslide Inventories

The first step of landslide susceptibility and hazard analyses is to determine the physical significance of the parameters to be used. To obtain a reliable map, the relation of each factor with the landslide distribution must be evaluated using both correlation and statistical distribution analyses and also based on expert judgment. Especially in studies using statistical approaches like black box analysis method, a result map is obtained anyway whichever of the topographical, lithological and environmental condition parameters are chosen randomly. However, the important thing is the physical meaningfulness of the resultant map produced. Therefore, the relation and significance of each parameter related with the landslide distribution should be evaluated beforehand. In this respect, landslide inventory analysis is an important step to understand the significance of such parameters before passing to produce the landslide susceptibility and hazard maps.

The first step of the landslide inventory analysis is producing the distribution maps based on aerial photo interpretation, ground survey, and/or a data base of historical landslides in an area (Van Westen, 1993; Soeters and Van Westen 1996). Van Westen (1993) was sorted the inventory analysis of landslides in three substances: (i) landslide distribution analysis, (ii) landslide density analysis and (iii) landslide activity analysis. In addition to this, landslide spatial persistence analysis and temporal frequency analysis of landslides will be evaluated in scope of this methodological step.

4.2.1. Landslide distribution analysis

Landslide distribution maps are the essential for most of the other landslide hazard mapping techniques and also they can be used as elementary form of landslide map, because they display where in an area a particular type of slope failure has occurred (Van Westen, 1993). They only give information from a specific time and consequently they don't provide any information in point of temporal changes of landslide distributions. However, the distribution characteristics (zonal/azonal) of the landslides in an area provide some initial information and also give some aspects for the researchers.

4.2.2. Landslide density analysis

Landslide distribution can also be shown in the form of a density map (Van Westen, 1993; Soeters and Van Westen 1996). Landslide density or frequency maps measure the spatial distribution of mass movements (Wright et al., 1974; DeGraff, 1985; DeGraff and Canuti, 1988) and landslide density is the quantity (i.e., frequency, percentage) of landslide area, and is generally computed as:

$$D_L = \frac{A_L}{A_M},\ 0 \le D_L \le 1 \qquad (1)$$

where, A_M is the area of the mapping unit used to compute the density (e.g., grid cell, slope unit, unique condition unit, etc., and A_L is the total landslide area in the mapping unit. In each mapping unit landslide density varies from 0, for landslide free units, to 1, where the entire unit is occupied by landslides.

Density maps (Figure 7) have different applications. Guzzetti (2005) was summurized these applications under six substances: (i) show a synoptic view of landslide distribution for large regions or entire nations, (ii) portray a first-order overview of landslide abundance, (iii) show the magnitude of slope failures triggered by severe events, (iv) evaluate landslide abundance or landslide activity in relation to forest management, agricultural practise, and land use changes, (v) show the spatial distribution of the historical frequency of slope failure events, and (vi) as a week proxy of landslide susceptibility. Landslide density maps are different from inventory maps, which provide information only where landslides were recognized and mapped. Guzzetti (2005) stated that density map does not show were landslides are located, but this loss in resolution is compensated for by improved map readability and reduced cartographic errors and also he added that landslide density is independent of the extent of the study area, which makes comparison between different regions straightforward. Such characteristics make density maps appealing to decision-makers and land developers.

Depending on the type of mapping unit used to compute and portray the density, landslide density maps can be based on statistical or geomorphological criteria (Guzzetti et al., 2000).

Statistical landslide density maps

In statistically-based density maps, the mapping unit is usually an ensemble of grid cells (i.e., pixels), square or nearly circular in shape, with a size generally 10 to 100 times larger than the size of the individual grid cell (Guzzetti et al., 2000). Density is determined by counting the percentage of landslide area within the mapping unit (in this case an artificial “kernel”), which is moved systematically across the territory. This is equivalent to a moving average filtering technique. Additional filtering or weighting techniques can be applied to improve map consistency and readability. By interpolating equal quantity (isopleth) lines, a statisticallybased density map can be portrayed as a contour map (Wright *et al.,* 1974). The latter was the favoured method for showing landslide density (Campbell, 1973, 1975; Wright and Nielsen, 1974; DeGraff, 1985) before GIS technology and raster colour display were largely available.

Geomorphological landslide density maps

For geomorphological density maps, slope units (as defined in Carrara et al., 1991) appear to be particularly suited to the determination of landslide spatial frequency. This subdivision of the terrain partitions the territory into domains bounded by drainage divides and stream lines. To delineate the divide and stream networks, manual techniques or automatic selection criteria can be adopted. The latter is based on the analysis of a digital terrain matrix (DTM) that acts as a computerised representation of topography (Carrara, 1988; Carrara et al.1991). Slope units, therefore, correspond to the actual slopes on which landslides take place. The percentage of landslide area within each slope unit, as counted, is equivalent to the percentage of failed area on each slope (see equation 1). The landslide density in this case, is the proportion or percentage of the slope unit that is occupied by the landslides.

Figure 7: Landslide density map types (Source:Guzzetti et al., 2000; and Guzzetti, 2005)

4.2.3. Landslide activity analysis

Landslide activity analysis are generally prepared based at least two aerial photo period and/or field survey to understand number or percentage of reactivated, dormant, new or stabilized landslides. Depending on the aim of the study different time intervals can be selected. The most appropriate scales are the medium and large scales, for the reason of the required detail of input maps (Soeters and Van Westen 1996). Van Westen (1993) indicated that main problems of the landslide activity method are that it is very time-consuming, and that it is difficult to prevent inconsistencies between interpretations from the various dates. And he was sorted the activity analysis of landslides in three steps: (i) digitized map of recent landslides is used as the basis for the digitizing of maps from earlier dates, (ii) calculation of the differences in activity between two different dates, (iii) calculation of all landslides which were initiated or reactivated in the period between the photo-coverages.

4.2.4. Spatial persistence analysis of landslides

Spatial persistence analysis can be regarded as a part or second step of the activity analysis but in this study it was evaluated separately. Landslide persistence is the degree to which new slope failures occur in the same place as existing landslides (Guzzetti 2005). Establishing landslide persistence has implications for landslide susceptibility and hazard assessment and also provides information about general or specific landslide hazard trend of an area. The spatial persistence of landslides can be determined, and quantified, by comparing geomorphological, event, and multi-temporal inventory maps in GIS frame.

The application of the spatial persistence analysis is based on spatial or geographical intersection and union of the individual landslide layers. In this regard, multi-temporal landslide inventory is essential to perform the landslide persistence analysis. This analysis is basically rely on the principle of comparing the recent landslide distribution produced with the latest aerial photo or field work and the previous landslide distribution obtained from the previous aerial photo or fieldwork. The recent landslide inventory is overlaid with the previous landslide inventory to understand the continuity of the old landslides. As a result, spatial landslide persistence of the area or certain landslides is found. In this study, spatial persistence analysis will be applied to the landslides triggered by the earthquake and the landslides developed after the earthquake. At the same time, the landslides developed after the earthquake will be compared with the landslides that occurred before the earthquake. As a result of these comparisons, long-term and short-term landslide persistence trend and rate will be determined for the sampling areas.

4.2.5. Temporal frequency of landslides

The temporal frequency or the recurrence of landslide events can be produced from archive inventories (Coe et al., 2000; Guzzetti et al., 2003) and from multi-temporal landslide maps (Guzzetti et al., 2005). A probability model for landslides considers the occurrence of landslides during a specified time in a particular area. According to the Crovelli (2000), landslides can be considered as independent random point-events in time. In this regard, the exceedance probability of occurrence of landslide events during time t is:

$$P(N_L) = P\left[N_L(t) \geq 1\right] \tag{2}$$

where *NL(t)* is the number of landslides that occur during time *t* in the investigated area.

Two probability models are generally used to examine the occurrence of naturally occurring random point-events in time: (i) the Poisson model and (ii) the binomial model (Crovelli, 2000; Önöz and Bayazit, 2001). The Poisson model is a continuous time model consisting of random-point events that occur independently in ordinary time, which is considered naturally continuous (Guzzetti, 2005). Adopting a Poisson model for the temporal occurrence of landslides, the probability of experiencing *n* landslides during time *t* is given by

$$P[N_L(t) = n] = e^{(-\lambda t)} \frac{(\lambda t)^n}{n!} \quad n = 0, 1, 2, \ldots \tag{3}$$

where λ is the estimated average rate of occurrence of landslides, which corresponds to 1/μ, with μ the estimated mean recurrence interval between successive failure events. The model parameters λ and μ can be obtained from a historical catalogue of landslide events or from a multi-temporal landslide inventory map (Guzzetti, 2005; Guzzetti et al., 2007). In this regard, probability size distribution of events will be produced from multi-temporal landslide inventory and available historical archive inventories for study area.

4.3. Landslide Susceptibility-Hazard Mapping with Using Current Methods and Analyzing & Integrating of the Results to Improve the Methods

In this section, three approaches from the literature will be compared. The methods suggested in the literature for mapping earthquake induced landslide susceptibility and hazard will be applied to the two sampling areas chosen for Wenchuan earthquake. These methods have been applied to similar earthquake induced landslides in other areas and have been successful to predict incidences in those areas. Here in this study, it is aimed to apply these methods and their predisposing factors to the chosen sampling areas in Wenchuan and to compare the results. In this step, three different methods will be applied considering the environmental conditions before the Wenchuan earthquake. In addition, the parameters of the earthquake that occurred in 12th May 2008 will be used as the triggering mechanism and the capacity of predicting the landslides, which occurred after the earthquake will be compared. As the next step, analysis, comparison and integration of the results will come. In this step, integration of these methods to the region will be obtained using the additional parameters and taking into account the previously explained landslide processes and the geologic-geomorphologic processes in the region. For instance, according to the preliminary analysis, it is understood that the structural geology has an important effect on the distribution of the landslides developed after the earthquake. Similarly, in accordance to the needs of the region, how the predictive capacity of existing methods is influenced by integrating such parameters to the methods will be analyzed.

In this regard the first approach which will be used in this study was published at 2008 by Lee et al. They applied discriminate analysis method for susceptibility assessment to Chi-Chi (Taiwan) earthquake (M_s 7.3) which occurred in 1999. They used event based landslide inventory for susceptibility analysis and they applied methodology to hilly and mountainous area separately.

The working procedure for their landslide susceptibility analysis (LSA) is illustrated in Figure 8. In this approach the first step is data collection, after which an event-based landslide inventory was established by using post-earthquake SPOT (XS and PAN) satellite images. In parallel with this, the causative factors of the landslides were processed and the triggering factors determined. These factors were then statistically tested, and the most effective were selected for susceptibility analysis. Each selected factor was rated, and their weighting analyzed. Lee et al., (2008) mentioned that discriminant analysis allows determining the maximum difference for each factor between the landslide group and the non-landslide group, as well as the apparent weights of the factors. After this, a landslide susceptibility index (LSI) for each grid point was calculated from the linear weighted summation of all factors.

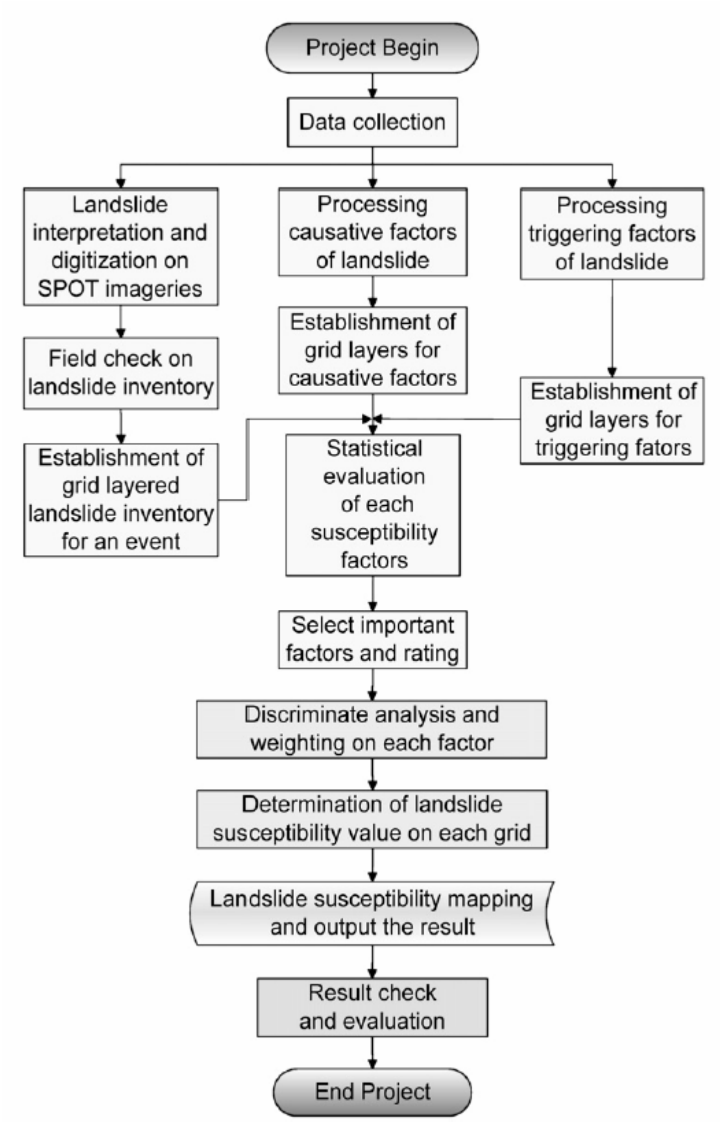

Figure 8: Working procedure for event-based landslide susceptibility analysis (Lee et al., 2008).

The LSIs were then used for landslide susceptibility mapping. Because the landslide inventory was used event based, this LSA was called event-based LSA (EB-LSA). They indicate this procedure must be performed separately for each type of terrain, because of differences in their geomorphic and geologic characteristics. In their study, hilly terrain and mountainous terrain was considered separately. The basic data which they utilized in their study included a 40m x 40m grid digital elevation model (DEM), SPOT images, 1/5000 photo-based contour maps, 1/50,000 geologic maps, and earthquake strong-motion records. They consider the slope, slope aspect, terrain roughness, slope roughness, total topographic curvature and lithology as an independed variable in their studies and also they processed and rated the arias intensity. For calculation of arias intensity they checked each grid point to find the maximum AI among the 7 earthquakes (one main shock and six after shock), and these values were adopted as the intensity that triggered the landslides. They interpolated AI for each grid point by using the ordinary Kriging method and they calculated this interpolation for each earthquake to find maximum AI rate for seven earthquake. They further considered topographic effects in relation to earthquake intensity. They applied empirical formula of Lin and Lee (2003) to making topographic corrections. They indicate the height relative to riverbed (height of the grid point above the riverbed) was founded to be a good factor for making corrections with using the empirical formula proposed by Lin and Lee (2003). After the corrections they found out the correlation between the landslide ratio and the AI parameter becomes clear. Finally they calculated success rate of their analysis 0.91 (AUC) for hilly terrain and 0.77 (AUC) for mountainous terrain with using Receiver Operating Curve (ROC).

The second approach was published by Miles and Keefer at 2009a and 2009b. Miles and Keefer (2008) describe the prototype design of a comprehensive areal model of earthquake-induced landslides and they named this model CAMEL. CAMEL is a knowledge-based model, developed using fuzzy logic systems. To facilitate regional-scale analysis, CAMEL has been integrated with GIS. The prototype model determines the possibility and estimates areal landslide concentration (number of landslides per square kilometer) of six aggregated types of earthquake-induced landslides-three types each for rock and soil. CAMEL was designed specifically for use with the U.S. Geological Survey's ShakeMap system for scenario prediction and near real-time interpolation of ground shaking intensity based on instrumental measurements (Wald et al., 1999). CAMEL affords flexibility in characterizing input conditions. For instance, they mentioned that shear strength data of rock and soil are not required for characterizing slope material conditions and landslide concentration estimates can be made with missing or incomplete data. They applied the CAMEL to model the 1989 M=6.9 Loma Prieta earthquake to understand issues of applying CAMEL, such as collecting and processing spatial data inputs as a case study. The case study application also permits comparison of CAMEL outputs to landslides mapped after the Loma Prieta earthquake (Keefer, 1998). Only evaluation of results with respect to disrupted landslides (Category I, Keefer (1984)) was conducted to date by the authors. The results of the empirical comparison were then judged against a similar evaluation of a popular existing model developed by Jibson et al. (2000) based on Newmark's displacement method (1965) and they mentioned that this serves to put CAMEL's predictive performance in context of the capabilities of models currently used in practice.
The first step in the development CAMEL was eliciting the knowledge to define variables and compose IF-THEN rules. Knowledge elicitation for CAMEL consisted primarily of compiling literature that describes analyses of past landslide-triggering earthquakes and extracting relevant numerical or correlative information. They mentioned that they found two types of knowledge in the literature: knowledge of about the possibility of landsliding and knowledge about the intensity or hazard of landsliding. These types of knowledge are formed the basis of CAMEL's design (Figure 9 and 10).

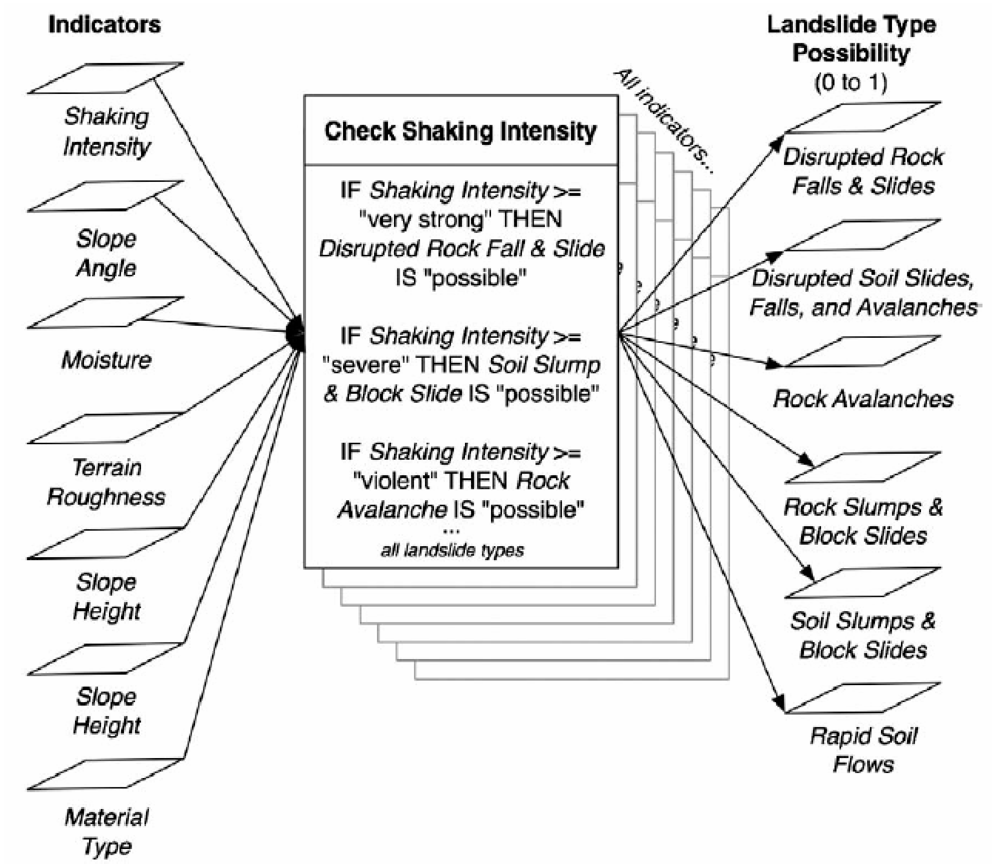

Figure 9: Data flow diagram for the possibility module of CAMEL (Miles and Keefer, 2009a).

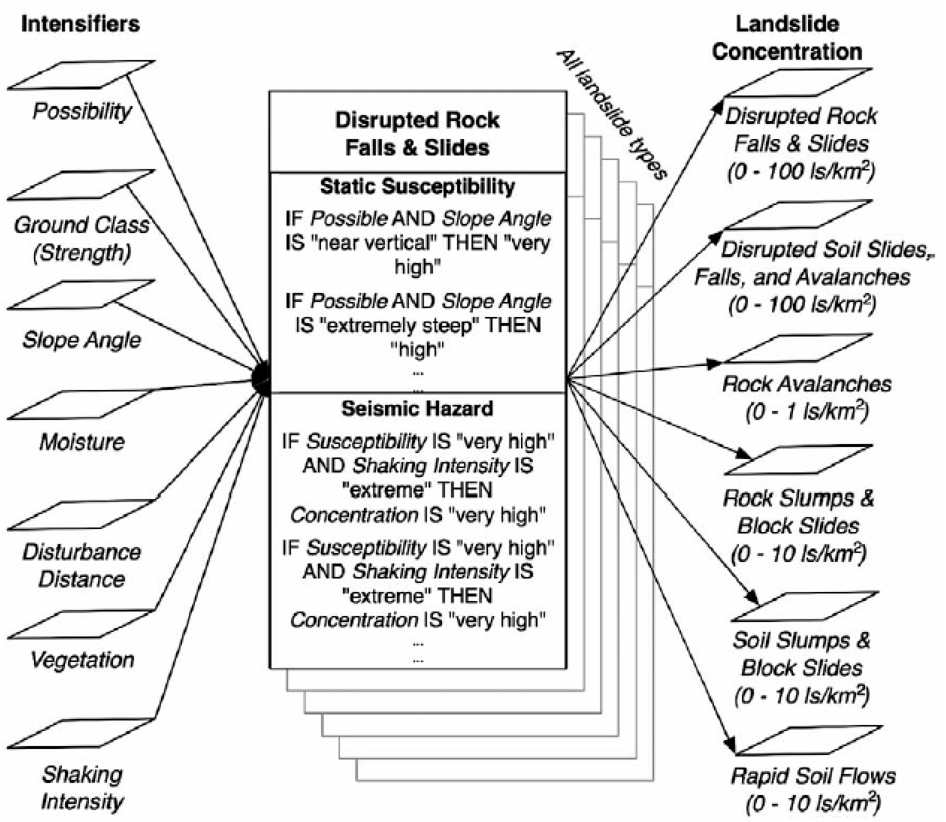

Figure 10: Data flow diagram of CAMEL hazard module (Miles and Keefer, 2009a).

Miles and Keefer (2009a) are summarized their model as follows: *"CAMEL models the hazard associated with the six aggregated landslide types (disrupted rock falls and rock slides, disrupted soil slides/soil falls, rock avalanches, rock slumps and rock block slides, soil slumps and soil block slides, rapid soil flows). CAMEL is comprised of two modules - the possibility and hazard modules - each of which are made up of several fuzzy IF-THEN rule-blocks. The possibility module determines whether the occurrence of each respective landslide type is possible based on data provided for each input. Each rule block in the possibility module contains knowledge-based rules associated with a specific input variable to collectively determine the degree to which, from zero to one, each landslide type is possible. The hazard module determines the relative hazard, expressed as areal landslide concentration (landslides per square kilometer), for each possible landslide type (Figure 9). The hazard module treats each landslide type separately in two sub-modules: static susceptibility and seismic hazard. The susceptibility sub-module of the hazardmodule is comprised of rules about terrain conditions independent of earthquake shaking (i.e., static conditions). The seismic hazard sub-module consists of rules relating earthquake ground-shaking to the static susceptibility computed in the previous sub-module. Importantly, the possible range of concentration values computed by the hazard module, and in turn what would be consider "very high" or "very low" values, is different for each landslide type, as indicated by the maximum output values shown in Figure 10 For the possibility module, an estimate is given of the fuzzy threshold that needs to be exceeded with respect to each variable (considered) for a particular landslide type. (The actual thresholds are represented as fuzzy sets.) For the hazard module, an indication is given for each variable (considered) regarding CAMEL's sensitivity to the variable for a particular landslide type based on extensive sensitivity analysis."*

The variables in CAMEL and their respective roles with respect to the six landslide types were determined and their respective roles are given in Figure 11.

Variable name	Units	Landslide type	Possibility module	Hazard module**
Instrumental intensity	Estimated MMI (floating point; 1 to 10)	Disrupted rock falls and slides	>~7	H
		Rock avalanches	>~9	H
		Disrupted soil slides, falls, and avalanches	>~7	H
		Rock slumps and block slides	>~8	H
		Soil slumps and block slides	>~8	H
		Rapid soil flows	>~8	H
Ground class	Unitless (floating point;1 to 5, 5 is poorest)	Disrupted rock falls and slides		H
		Rock avalanches		H
		Disrupted soil slides, falls, and avalanches		H
		Rock slumps and block slides		M
		Soil slumps and block slides		M
		Rapid soil flows		H
Slope angle	Degrees	Disrupted rock falls and slides	>~35	M
		Rock avalanches	>~25	M
		Disrupted soil slides, falls, and avalanches	>~15	M
		Rock slumps and block slides	>~15	H
		Soil slumps and block slides	>~5	M
		Rapid soil flows	>~5	M
Disturbance distance	Meters	Disrupted rock falls and slides		L
		Rock avalanches		L
		Disrupted soil slides, falls, and avalanches		L
		Rock slumps and block slides		L
		Soil slumps and block slides		L
		Rapid soil flows		L
Vegetation type	Percent	Disrupted rock falls and slides		L
		Rock avalanches		
		Disrupted soil slides, falls, and avalanches		L
		Rock slumps and block slides		L
		Soil slumps and block slides		L
		Rapid soil flows		L
Moisture	Percent	Disrupted rock falls and slides		L
		Rock avalanches		
		Disrupted soil slides, falls, and avalanches		L
		Rock slumps and block slides	>~5	M
		Soil slumps and block slides	>~5	M
		Rapid soil flows	>~75	L
Slope height	Meters	Disrupted rock falls and slides		
		Rock avalanches	>~150	
		Disrupted soil slides, falls, and avalanches		
		Rock slumps and block slides		
		Soil slumps and block slides		
		Rapid soil flows		
Terrain roughness	Slope of slope	Disrupted rock falls and slides	>~15	
		Rock avalanches	>~15	
		Disrupted soil slides, falls, and avalanches		
		Rock slumps and block slides		
		Soil slumps and block slides		
		Rapid soil flows		
Soil depth	Meters	Disrupted rock falls and slides		
		Rock avalanches		
		Disrupted soil slides, falls, and avalanches		
		Rock slumps and block slides		
		Soil slumps and block slides	>~3	
		Rapid soil flows		

*Value indicates fuzzy threshold above which landslide type is possible. No value denotes variable not considered for that landslide type.
**H, M, L indicates high, medium or low sensitivity, respectively, of hazard module to a particular variable. No indication means variable not considered for that particular landslide type.

Figure 11: CAMEL variable definitions, roles, and sensitivity (Miles and Keefer, 2009a).

As mentioned before they applied their model for disrupted rock slides which were triggered by Loma Prieta earthquake and they compared their results probabilistic hazard method which produced by Jibson et al. (2000). They calculated success rate of their analysis and also they compared their success rate results with the other model results. Accordingly, the success rate results were calculated for CAMEL and Jibson’s method, 0.69 % (AUC), 0.66 % (AUC) respectively.

The third approach was published by Jibson et al., (2000). They generate a method to map the spatial distribution of probabilities of seismic slope failure in any set of ground-shaking conditions of interest. They modeled the dynamic performance of slopes using the permanent-displacement analysis developed by Newmark (1965). The Newmark’s method models a landslide as a rigid friction block that slides on an inclined plane (Figure 12). The block has a known critical (or yield) acceleration, a_c, which is simply the threshold base acceleration required to overcome shear resistance and initiate sliding (Jibson et al., 2000).

The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration time history.

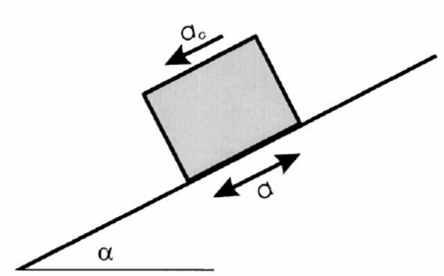

Fig. 12: Sliding-block model used for Newmark analysis. The potential landslide is modeled as a block resting on a plane inclined at an angle (a) from the horizontal. The block has known critical (yield) acceleration (a_c), the base acceleration required to overcome shear resistance and initiate sliding with respect to the base. The block is subjected to a base acceleration (a) representing the earthquake shaking (Source: Jibson et al., 2000).

Their analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration–time history. In the analysis, an acceleration–time history of interest was selected, and the critical acceleration of the slope to be modeled was superimposed (Fig. XXa).

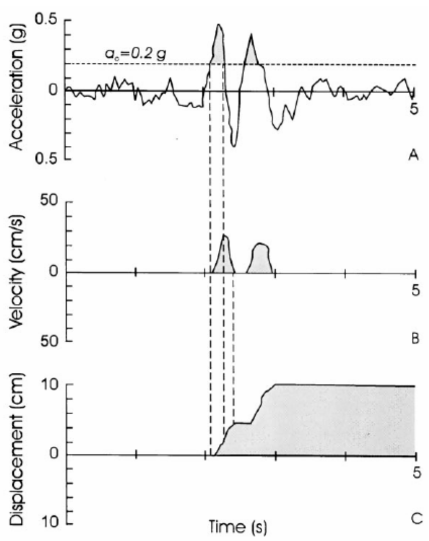

Figure 13: Demonstration of the Newmark-analysis algorithm (adapted from Wilson and Keefer, 1983). (A) Earthquake acceleration–time history with critical acceleration (horizontal dashed line) of 0.20g superimposed. (B) Velocity of landslide block versus time. (C) Displacement of landslide block versus time.

They mentioned that accelerations below this level cause no permanent displacement of the block and those portions of the record that exceed the critical acceleration are integrated once to obtain the velocity profile of the block (Figure 13b); a second integration is performed to obtain the cumulative displacement history of the block (Figure 13c). The user then judges the significance of the displacement. Jibson et al. (2000) emphasized the Newmark's method is based on a fairly simple model of rigid-body displacement, and thus it does not necessarily precisely predict measured landslide displacements in the field and Newmark displacement is a useful index of how a slope is likely to perform during seismic shaking.

Jibson et al., applied their model in Northridge, California earthquake. They used (1) a comprehensive inventory of triggered landslides (Harp and Jibson, 1995, 1996), (2) 200 strong-motion records of the main shock recorded throughout the region of landsliding, (3) detailed (1:24 000-scale) geologic mapping of the region, (4) extensive data on engineering properties of geologic units, and (5) high-resolution digital elevation models of the topography for their hazard assessment. They combined these data sets in a dynamic model based on Newmark's permanent deformation (sliding block) analysis yields estimates of coseismic landslide displacement in each grid cell from the Northridge earthquake. The modeled displacements was then compared with the digital inventory of landslides triggered by the Northridge earthquake to construct a probability curve relating predicted displacement to probability of failure. They represent their model in a flowchart to show the sequential steps involved in the hazard mapping procedure (Figure 14).

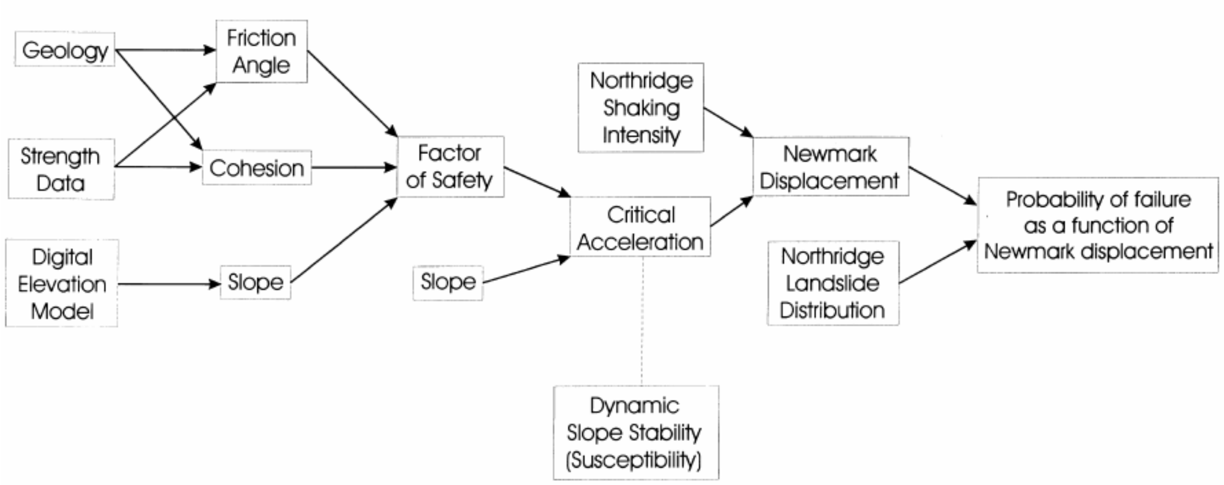

Figure 14: Flow chart showing steps involved in producing a seismic landslide hazard map (Jibson et al., 2000).

Jibson et al., (2000) are summarized their model steps as follows: *1. Compute the static factor of safety (ratio of resisting to driving forces). (a) Using compiled shear-strength data, assign representative shear strengths to each unit on the geologic map, which yields friction (φ') and cohesion (c') grids. (b) Produce a slope map from the digital elevation model (DEM). (c) Combine shear-strength and slope data in a factor of safety equation to estimate static factors of safety in each grid cell.*
2. Compute the critical acceleration by combining the factor-of-safety grid with the slope grid to yield the critical acceleration grid, which represents seismic landslide susceptibility.
3. Estimate Newmark displacements from the Northridge earthquake using an empirical regression equation to combine the critical acceleration grid with the grid containing shaking-intensity values from the Northridge earthquake.
4. Construct a curve to estimate probability of slope failure as a function of Newmark displacement. (a) Compare the map of landslides triggered by the Northridge earthquake to the Newmark-displacement grid. (b) For sequential intervals of Newmark displacement, compute the proportion of cells containing landslides. (c) Plot the proportion of failed slopes in each interval as a function of Newmark displacement, and fit a regression curve.
5. Generate maps showing probability of seismic slope failure in any shaking scenario of interest. (a) Estimate Newmark displacements by combining a ground-shaking grid of interest with the critical acceleration grid, as in step 3. (b) Estimate probabilities of failure using the calibrated regression curve from step 4.
Jibson et al., applied their model in Northridge, California earthquake as mentioned before and they represents their results visually. They added their event inventory map on their result map to reveal their correlation. The visual correlation they made reveals that the Newmark displacement values in the modeled areas match with the landslide initiation zones in good agreement.

4.4. Post-earthquake Hazard Assessment

As mentioned before after an earthquake, there are two important phenomenon in terms of landslide hazard: First, each landslides triggered by the earthquake create a weakness zone and the landslides keep their activity in the region for some time. The second issue is related with the hillslopes where no landslides have been developed but still prone to some risks for landslide. Determining these potentially risky hillslopes brings another challenge to tackle. The changes in the landslides triggering threshold values after an event (earthquake, hurricane, etc) affect the temporal probability and spatial persistence of both phenomenon. To be able to explain these well, there is need for good landslide historical records and monitoring of the parameters after the event continuously.

This part, as the last step of the method, covers the second main objective. It is foreseen a two stage study for the post-earthquake hazard assessment. The main reason for such a two stage study is the change of threshold values (earthquake and rainfall) regarding the post-earthquake triggering mechanisms. In this context, the first post-earthquake hazard assessment will be short term (5-10 year). The limit of this period equals to the time passed until the landslides occurring after the earthquake in the region becomes stabilized. For the determining the upper limit of this period, the experiences obtained from the previous Chi-Chi (Taiwan) and Kashmir (Pakistan) earthquakes and the landslide monitoring studies carried out in these areas (especially in Taiwan) will be utilized. The main limitation will be faced in this stage is the different climate and tectonic conditions existing in these areas. In addition to this, historical records belonging to the earthquake that occurred in 1933 in the study area, China Sichuan region, will be tried to reach and the information collected on the events and landslide activities after the old earthquake will be used as an input to the short term assessment. Besides, the pre-event normal rainfall thresholds will be evaluated obtaining the landslide records induced by rainfall events before the earthquake in the region. Then, the threshold values before the earthquake will be compared with the threshold values of the post-earthquake rainfall triggered landslide events to differentiate the change in the threshold values. In this context, some of the rainfall induced landslides prior to the earthquake have already been recorded by Chengdu Institute of Mountain Hazards and Environment. In the region, more than 100 landslides occurred as a result of the prolonged rain events in July 11th 2003 and August 23rd 2004 (Chen et al., 2004; Ma et al., 2005; Di et al., 2008). The institute has also the records belonging to some landslides developed by the rainfall after the earthquake. The records of these events will be used to determine the pre- and post-earthquake rainfall thresholds. After determining the thresholds, temporal probability of the landslides induced by rainfall in the region will be established.

In the short term post-earthquake hazard assessment (STPEHA) stage of the study, the spatial probability of the landslides will be determined using the predisposing factors and multi-temporal landslide inventory. After this stage, the probability of landslide size will be determined. For this, multi-temporal landslide inventory of the region will be utilized. Then, for the landslides that can be triggered by the rainfall events after the earthquake in the region, empirical thresholds (historical, statistical) based the temporal probability will be determined. In addition, probabilistic earthquake hazard map of the region after the earthquake will be prepared and also using the information from the previous earthquake, the minimum g values to trigger the landslides will be calculated. Colomb stress change analyses carried for the region by Toda et al., (2009) will be the base for the realistic estimation of the probabilities regarding the development period of the earthquakes. For the foreseen earthquake locality scenarios, the zones where the stress is transferred will be taken as the base. The resultant energy and the distribution of this energy will be considered in terms of triggering landslides. Afterwards, short-term post earthquake hazard assessment will be completed integrating the both triggering mechanisms for establishing the temporal probability. As it is stated previously, after the production of the temporal probability values for STPEHA stage covering certain time period (i.e. 10 year), a new temporal probabilistic assessment will be carried out following this date for long-term post-earthquake landslide hazard assessment (LTPEHA). This process will be applied to long-term post-earthquake landslide hazard assessment (LTPEHA) taking into account the older rainfall threshold values that are assumed normal for the region. The scenario earthquakes produced for the evaluation of STPEHA stage will be reproduced for the LTPEHA analyzing for the period starting after the upper time threshold of STPEHA. Figure 15 shows the method proposed for deriving the post-earthquake hazard analysis. This proposed method will be developed further in detail.

The approach can be concised as:

- Estimate probability of landslide size, a proxy for landslide magnitude (from the statistical analysis)
- Generation of landslide spatial probability
- Pre-event empirical rainfall threshold determination
- Post-event empirical rainfall threshold determination
- Differentiate the change in the threshold values
- Temporal probability of the landslides induced by rainfall
- Earthquake scenarios generation and producing of seismic hazard map
- Temporal probability of the landslides induced by earthquakes
- Integration of triggering (earthquake and rainfall) events to finalize the temporal probability of landslide occurrence.
- Multiply of layers (probability of landslide size, spatial and temporal probability) to generate post-earthquake hazard maps

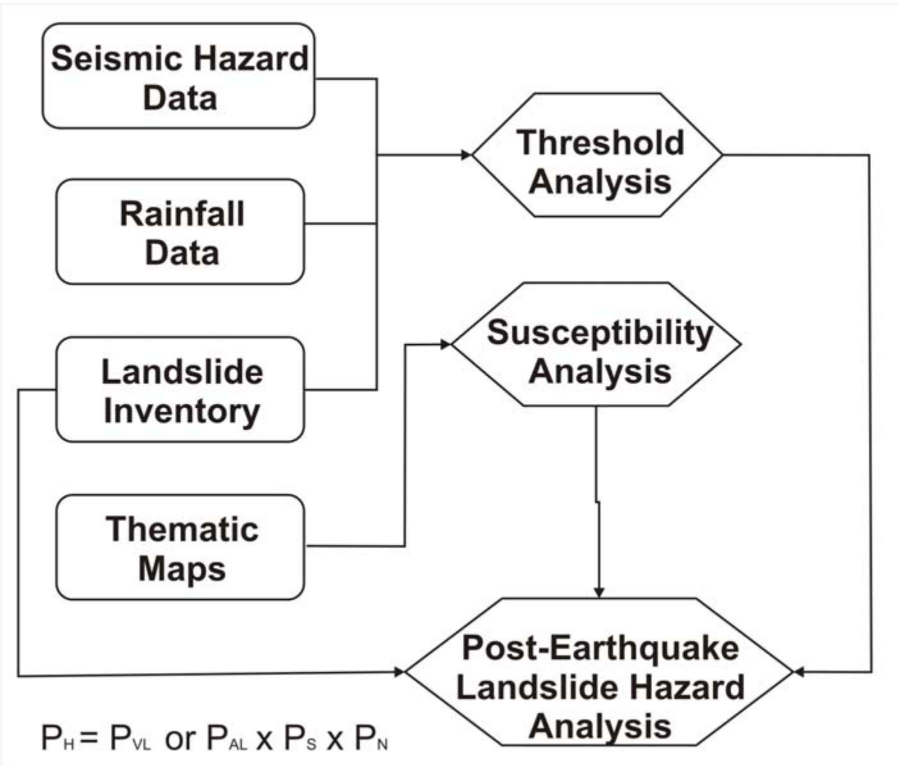

Figure 15: General flowchart of proposed method for post-earthquake hazard analysis. (P_H is hazard probability, P_{VL} and P_{AL} is the probability of landslide volume and area, respectively, P_S is the spatial probability and P_N is the temporal probability).

5. Research Programme

5.1. M.Sc thesis opportunities

The proposed research provides opportunities for some M.Sc thesis works to be carried out. Specific papers that are envisaged may be individual thesis problems for regular M.Sc students at ITC. In this regard, some topics such as 'landslide mapping and assessment of potential landslide source areas', 'visualization of spatio-temporal probabilities of landslides' etc. are issues for geo-engineering and geo-informatics students to address. A maximum of 2 students per year can be guided under the proposed research with a supervisor from ITC.

The following general topics are proposed:

1. Post-event landslide detection based on object-oriented classification approach with using ASTER, IKONOS and CARTOSAT-1 imagery.
2. Geomorphometric analysis of Great Wenchuan earthquake landslides and landslide dams.
3. Extraction of potential rock debris source areas by logistic regression technique.
4. Pre- and Post-earthquake induced landslide susceptibility mapping.

5.2. Training and courses requirements

Required training in the following domains to be able to carry out the research more efficiently. They are:

- Geostatistics and Open-Source Statistical Computing (ITC)
- Multi-Hazard Risk Assessment (ITC)
- Geo-Environmental Engineering (ITC)
- Academic Writing (ITC)
- Advance Academic Writing (TCP Language Centre, Twente University)
- Geomorphometry 2009 Workshop (will be registered) (Automated analysis of elevation data in R+ILWIS/SAGA") University of Zurich, 29 & 30 August 2009
- ICL International Summer School on Rockslides and Related Phenomena in the Kokomeren River Valley (Kyrgyzstan) (will be registered), from July 30 to August 14 2009.

In addition, a short-term (35 days in 2009) internship on landslide image interpretation will be arranged in Istituto di Ricerca per la Protezione Idrogeologica (Geomorphology group at CNR-IRPI in Perugia), Perugia, Italy under the guidance of Dr. Mauro Cardinali. In 2010, it is planned to participate a short training (30 days) on probabilistic seismic hazard mapping and assessment in Middle East Technical University, Ankara, Turkey (under the supervision of Prof. Sebnem). Finally, for post-earthquake hazard assessment, it is aimed to visit DURHAM University as an exchange student (under the supervision of Prof. David Petley).

5.3. Tentative Thesis General Layout

Chapter 1: Introduction
Chapter 2: Earthquake-induced landslide mapping and analysis
Chapter 3: Spatial data preparation and production for earthquake induced landslide susceptibility and hazard assessment.

Chapter 4: Earthquake-induced landslide susceptibility zoning.
Chapter 5: Earthquake-induced landslide hazard assessment.
Chapter 6: Discussion and conclusion

5.4. Provisional Titles for Scientific Paper

The topics to be published or presented in conference are listed below. The final title will be determined at the time of preparation:

- Distribution of earthquake induced landslides in the Sichuan Province, Central China.
- Assessment of Geological and geomorphological characteristics of landslides triggered by the 2008 Great Wenchuan Earthquake in China.
- Geomorphologic and Geomorphometric Analysis of Earthquake Induced Landslides Using Detailed Landslide Distribution Maps: A Comparative Approach to Understand Pre- and Post-Earthquake Circumstances.
- Spatial persistance and hazardaus trends of the Landslides after a big earthquake.
- Assessment of potential landslide source areas extraction by logistic regression and decision tree technique: a case study from Wenchuan and Beichuan Counties, Sichuan Province (China).
- Comparison of traditional susceptibility maps and existing earthquake induced landslide susceptibility maps.
- Earthquake induced landslide susceptibility and hazard assessment methodologies: An overview and possible improvements.
- A method for producing post-earthquake landslide hazard maps.

The papers will be presented to be published in (for example):

- Geomorphology
- Earth Surface Processes and Landforms
- Natural Hazards
- Landslides
- Natural Hazards and Earth System Sciences
- Environmental Geology
- Bulletin of Engineering Geology and Environment

5.5. Time Schedule

The proposed research is schedule to 48 months commencing on 1 November 2008. Duration of the phases and tasks are indicated in Table 5.

Table 5: Schedule phases for the PhD research

Activity: 2008/2009	Nov	Dec	Jan	Feb	March	April	May	June	July	Aug
Proposal review and compilation of existing data										
Fieldwork: GCP collecting for producing DEM, data collecting from CDUT and Landslide Inventory Mapping										
Digital data analysis: Producing of DEM, API for Landslide Inventory Mapping and Digitizing										
Activity: 2009/2010	Sep	Oct	Nov	Dec	Jan	Feb	March	April	May	June
API for Landslide Inventory Mapping, Structural Geological Interpretations AP-RSI and Provisional Geomorphological Mapping from AP and RSI										
Producing&Quantifying geo-environmental variables: Producing of Topographic, Geomorphologic and Seismic Thematic Layers										
Fieldwork: Validation of Landslide Inventories and Finalization of Geomorphological Units. Geological mapping (Lithological, Surficial formation, Weathering degree and Bedding Attitude Map)										
3D Geology, Structural Geologic Fabric Map										
Activity: 2010/2011	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	March	April
Task 1 and 2: Earthquake-induced landslide inventory and spatial data analysis: Writing the paper for chapter 2 and 3										
Task 3: Earthquake-induced landslide susceptibility analysis and zoning: Writing the paper for chapter 4										
Fieldwork: Final validations, Field checking for new landslides and Finalization of Geomorphic Hazard Map										
Seismic Hazard Mapping										
Activity: 2011/2012	May	June	July	Aug	Sep	Oct				
Task 4: Earthquake-induced landslide hazard assessment: Writing the paper for chapter 5										
Thesis Compilation and submission										
PhD defense										

Legend:

Time at ITC	Fieldwork	Time at CNR-IRPI	Time at Durham Univ.	Time at METU

5.6. Local coordination and support

Some part of the PhD research will be done together with State Key Laboratory for Geo-hazard Prevention, Chengdu University of Technology. This institute will support some of the laboratory tests and provide certain pre-and post-earthquake aerial photographs and high resolution satellite images of the study area. Fieldwork expenses will also be covered partly by the institute.

Moreover, one of the sandwich PhD student of ITC, Ms. Xuanmei Fan, has also been working on the same study area on the topic of "Understanding the causes and effect of earthquake triggered landslide dams". In this regard, both PhD studies will be carried out in coordination for the necessary cooperation.

5.7. Research budget

According to the PhD current regulations there is 5,000 EUR research budget per year. The budget planned for the research is given in Table 6.

Table 6: Planning budget for the research.

	Year 1	Year 2	Year 3	Year 4	Total
Conference	1,000	1,000	2,000	500	4,500
Travel to China	1,000	1,000	1,000	0	3,000
Fieldwork	1,000	2,500	1,000	0	4,500
Data collection	2,000	1,000	0	0	3,000
Total	5,000	5,500	4,000	500	15,000

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