DEVELOPMENT OF A RAPID EVALUATION METHOD FOR MULTI-HAZARD ASSESSMENT ALONG ROADS:

A CASE STUDY FROM CHINA

AO SUN

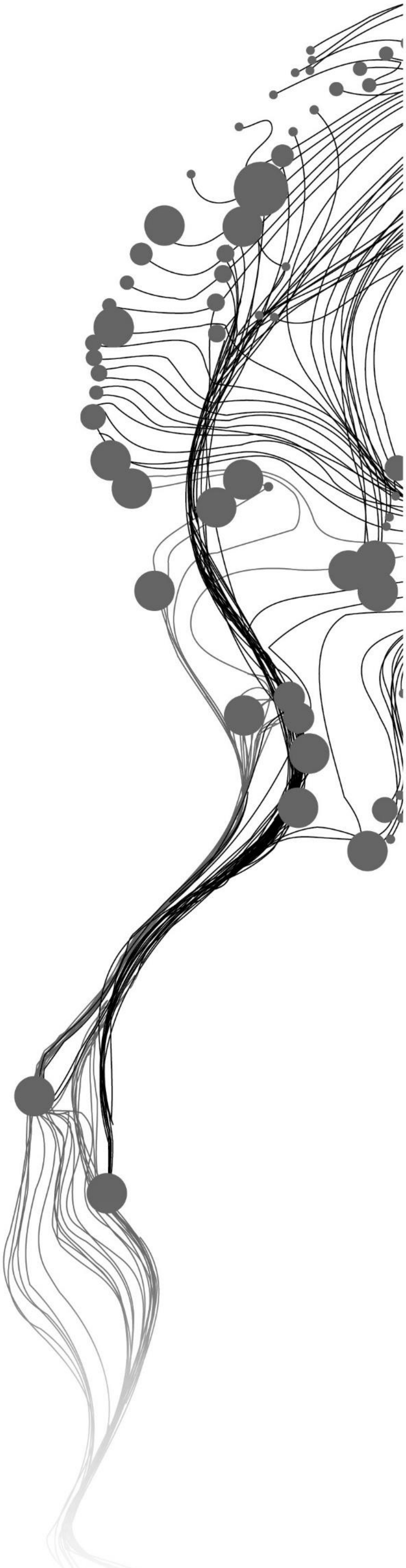
March, 2018

SUPERVISORS:

Dr. Cees. J. Van Westen

Drs. Nanette. C. Kingma

Dr. Olga. C. Mavrouli



DEVELOPMENT OF A RAPID EVALUATION METHOD FOR MULTI-HAZARD ASSESSMENT ALONG ROADS:

A CASE STUDY FROM CHINA

AO SUN
Enschede, The Netherlands, March, 2018

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialization: Applied Earth Sciences: Natural Hazards, Risk and Engineering

SUPERVISORS:
Dr. Cees. J. Van Westen
Drs. Nanette. C. Kingma
Dr. Olga. C. Mavrouli

THESIS ASSESSMENT BOARD:
Prof. Dr. V.G. Jetten (Chair)
Dr. A.C. Seijmonsbergen (External Examiner)

DISCLAIMER

ABSTRACT

In order to prioritise budget allocation for implementing or repairing remedial measures along roads, there is a need to pinpoint the most critical locations. And hazard assessment methods can aid the procedures to identify critical assets. For example, after the 2008 Wenchuan earthquake in China, rock falls, landslides and debris flows were very common hazards in the epicentre region, which caused substantial damage to roads as well. Due to the widespread occurrences of co-seismic landslides, many remedial works were constructed along roads in the earthquake affected area, but a large number of them have been destroyed already. Moreover, during the field work, it was found that there were no mitigation measures conducted in some locations which are susceptible to landslides.

Direct and rapid evaluation methods for multi-hazard assessment along roads are relatively limited, and most landslide hazard assessment approaches largely depend on landslide inventories. This research aimed to develop a simple, rapid but effective qualitative evaluation method for multi-hazard assessment along road networks which can be used by people who are not experts but have a basic knowledge and awareness about natural hazards, such as local technical persons. This method is designed primarily for areas without sufficient historical or detailed thematic data.

This hazard assessment method starts with the identification of homogenous road sections. Six input parameters, which can be identified from field observation were used to subdivide the road into homogenous sections. A specific code will be given to each homogenous section, to reveal the road cross-sectional attributes. The hazard assessment approach incorporates a decision tree method to assess the hazard activity, to judge whether it has favourable conditions to produce hazard and to evaluate the efficiency of the installed protection works. Then according to the evaluation results of hazard activity and the favourable conditions, a hazard matrix method is used to determine the hazard class (high, moderate and low). Finally, the efficiency of protection work should be taken into consideration to obtain the final prioritization class for implementing or repairing remedial works.

This method was applied in the Yingxiu area which was affected by the Wenchuan earthquake in 2008, to evaluate the landslide hazard and the efficiency of the conducted protection work along several roads. It was also tested in the area with very limited natural hazard problems in Duyun city, Guizhou province, China. The reproducibility of the method was tested both in the field and in the office, using Google Earth image and dashboard camera videos

Keywords: landslide, rockfall, debris flow, hazard assessment, homogenous road section

ACKNOWLEDGEMENTS

I would like to express my heartfelt thanks of gratitude to my first supervisor Dr. Cees J. van Westen for his amazing ideas, insightful suggestions. I am particularly grateful to my other supervisors Nanette. C. Kingma and Dr. Olga Christina Mavrouli for their patient guiding and encouragement throughout the entire MSc period. I feel very proud to conduct this study under their supervision.

Many thanks to my friends, classmates and staff in ESA department who help me a lot in my study. Special thanks to Dr. Jianqiang Zhang and Chenxiao Tang, from whom I got much useful advice, and Bart Korl who readily replies to any questions I had in study or in life.

And I am pleased to thank all the participants involved in the tests of my study method for their valuable comments.

Last but not the least, I would like to express my eternal gratitude to my parents for their sacrifice and continuous encouragement and support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

Landslides are considered as a common type of natural hazards, and is defined as "the movement of a mass of rock, earth or debris down a slope" (Cruden, 1991). They can be induced by the external factors (e.g. persistent rainfall, earthquake) which cause a decrease in slope stability (Dai et al., 2002). Landslides are usually isolated processes that may not be very large in size individually, but can frequently occur in a region (van Westen et al., 2006).

With the increase of the flow of travellers and goods due to the convenient traffic facilities, the degree of exposure to natural hazard along traffic routes has risen sharply. While the road system is fundamental for the social and economic functioning of a society, it also acts as a life-line system for rescuing people as well as for restoring other disrupted infrastructure systems (Mattsson & Jenelius, 2015). Once landslides occur along the transport lines, they may cause many serious problems, not only including death and or injuries of passengers but also causing traffic interruption and high repair costs to the transport infrastructure (Martinović, 2017). In mountainous area, road transport networks are continuously exposed to a number of natural hazards (Jaroszweski et al., 2010), including slow or fast moving landslides, rock falls, and debris flows. Therefore, an assessment is needed to identify the location of critical network segments (e.g. those with heavy traffic, those which are vital for access to essential facilities) and to support landslide risk management (Wang et al., 2017).

Landslide hazard refers to the probability of occurrence of a landslide of a given magnitude within a specific period in a given area (Varnes 1984). The hazard assessment approaches have been classified into three groups, as qualitative, semi-quantitative and quantitative. One of the significant limitations of the quantitative hazard assessment approaches along transport networks is that they have high requirements for the quality of input data, such as more accurate geological and geomechanical data, high-quality DEMs. Assessment of frequency, as well as intensity or magnitude (volume) of the hazardous events, requires detailed datasets (Fell et al., 2008) Usually, landslide inventories are important and required in landslide hazard assessment (Dai et al., 2002). However, they are often not complete. The potential data may be provided by the relevant traffic administration authorities (Hungr et al., 1999), while reliable maintenance records are scarcely kept and seldom available. So some alternative approach could be used to assess the frequency and magnitude of the hazard events, such as extracting data from high resolution remote sensing images (DEMs) (Santana et al., 2012), or using multi-temporal DEMs obtained by Terrestrial Laser Scanners or Digital Photogrammetry (Abellán et al., 2009) . It is worth mentioning that physically-based modelling methods which are used to model the slope failure. The combination of the probability of the occurrence of the landslides triggering factors and the response of landslide to it is also used to estimate the temporal probability of landslide. Furthermore, most quantitative risk assessment methods which have been developed are case-specific (Hadmoko et al., 2010).

Qualitative approaches are done by direct and direct methods and often involve expert judgment. These methods describe the landslide likelihood in qualitative terms and classify the hazard using terms such as "low," "moderate" and "high" (Castellanos Abella & Van Westen, 2008a). Analysing hazard qualitatively is often carried out using the hazard matrixes, hazard indices tables or using Spatial Multi-Criteria Evaluation. In general, qualitative hazard assessment may be more applicable to a large area where the quality and quantity of available data are too meager for quantitative analysis (Dai et al., 2002). Qualitative analysis is perhaps the most widely used approach, as it is quick and straightforward to carry out

(Modarres, 2006). However, it depends on the experience and skills of the expert, and may, therefore, differ when carried out by different persons.

Semi-quantitative risk approaches are a transition between quantitative and qualitative methods. They often include certain components which are carried out using quantitative methods (e.g. probabilistic slope stability calculations using physically-based modelling), and other components are obtained through expert judgment. But based on stochastic methods, semi-quantitative methods could provide an overall view of the possible future damages. This method is frequently applied on transport lines for some scoring systems are used to determine relative risk for cut and fill slopes (Martinović, 2017).

In the past decades, many advances in landslide related studies have been made, but relatively few researchers have been carried out on the analysis on the landslide hazard and risk along roads. Mostly because of the unavailability of a sufficiently detailed landslide inventory and the lack of sufficient historical data on landslide damages, frequency and landslide magnitude. Still, some researchers tried to use quantitative and qualitative methods to estimate direct and indirect landslide hazard along transportation networks (e.g. Zêzere et al., 2007; Jaiswal et al., 2010). Some researchers also have used the event tree method to estimate the landslide hazard along motorways (e.g. Budetta, 2002; Bunce et al., 1997). In the event tree approach, the probability of an occurrence is assigned to each event sequentially, which could cause a landslide disaster (Jaiswal et al., 2010). In other research, the annual probability of landslide hazard and their related consequences have been used to evaluate the landslide risk along the roads (e.g. Zêzere et al., 2007; Remondo et al., 2008). Actually, these methods are not direct estimations but indirect assessments.

However, for small-scale landslide risk analysis along large sections of the transport lines, a simple and direct method is required which can be used by many people at the local level. On the whole, direct methods are based on certain visible indicators of dangerous phenomena and the geological and geomorphological setting, through observing the factors in the field, and experts could estimate the risk directly (Rana, 2017). Then a qualitative approach could be a good choice.(Jaiswal & van Westen, 2013)

1.2. Problem statement

On 12 May 2008, a large earthquake occurred in the Wenchuan region is Sichuan province in China. China Transport Ministry (2008) reported that the Wenchuan earthquake damaged a total of 24 highways, 161 national and provincial trunk roads, 8618 country roads, 6140 bridges and 156 tunnels. Preliminary estimates indicate the earthquake directly caused an enormous number of secondary events, mainly in the form of landslides, debris flows and rock fall. It caused more than 10,000 locations where potential geohazards might occur in later years, especially for rock fall (Yin et al., 2009).

Yingxiu area is located in north-western Sichuan province of southwest China, near the epicenter and is one of the worst hit areas of the 2008 Wenchuan earthquake. Almost all the old national road (G213) which lies on the route to Wenchuan county was heavily destroyed or buried by the co-seismic landslides during the earthquake(Gu, 2015). And in the years following the earthquake, reactivations of landslides in the form of rock fall and debris flows have occurred, up to now. Although many mitigation measures were already constructed in this area, but a large number of them have been destroyed again.

In China, there is no single agency that has the responsibility for collecting historical hazardous events data, which makes it difficult to acquire a complete record of the past occurrences of landslides in many cases. Without sufficient historical data, the application of data-driven, statistical methods are difficult and time-consuming, as it requires to generate the landslide inventories at first. Physically-based modelling is not an appropriate method for the whole area, as it requires a mass of parameters, for which data is not always available in large areas. However, landslide inventories and thematic data are not always complete or available in most cases. So a method designed for the area without sufficient historical inventories, especially for the area after large events (e.g. earthquake) is needed. Moreover, in small scale landslide hazard analysis along the transport lines is required a simple and direct method as well which can be used by many people who have the basic knowledge of landslides, such as engineering geologists or local infrastructure managers, to get a quick assessment of the multi-hazards, rather than only rely on expert judgements. Therefore, in this study, we proposed a qualitative rapid evaluation approach to estimate the landslide hazard along roads directly, and also could provide suggestions for prioritizing the construction of mitigation measures along roads.

1.3. Research objective and questions

1.3.1. Objectives

The general objective is to develop a rapid qualitative evaluation approach for the prioritization of the most hazard prone sections of a road network, which should be protected by mitigation measures or where damaged protection works should be repaired, and to apply it for several road alignments in southwest China.

Sub-objectives:

1. To subdivide road networks into homogenous sections, based on certain features of the road and the slopes along the roads, such as infrastructure type, slope angle, landuse etc.
2. To develop a simple and rapid hazard assessment method to characterize the hazard per road section, based on a decision tree approach.
3. To develop a qualitative method for prioritizing the implementation or repair of remedial works along roads.
4. To evaluate the efficiency and the reproducibility of this method, both in the field as well as in the office.

1.3.2. Research Questions

1. Which attributes and factors can be used to subdivide the road sections into homogenous sections and what are the scale effects?
2. Which spatial data (derived from UAV, satellite images, Google Street View or dashboard cameras') can be used for the generation of homogeneous units, and can this procedure be automated?
3. How to estimate the landslides activities along the road network without sufficient historical data?
4. How to evaluate the favourable conditions for producing different types of hazards along roads, using a generally applicable method?
5. How to combine the information to prioritise the road sections for construction or repair of remedial works?
6. How reproducible is this evaluation method?

The research conceptual framework which contains the major stages of this research related to the sub-objectives is shown in Figure.1.1

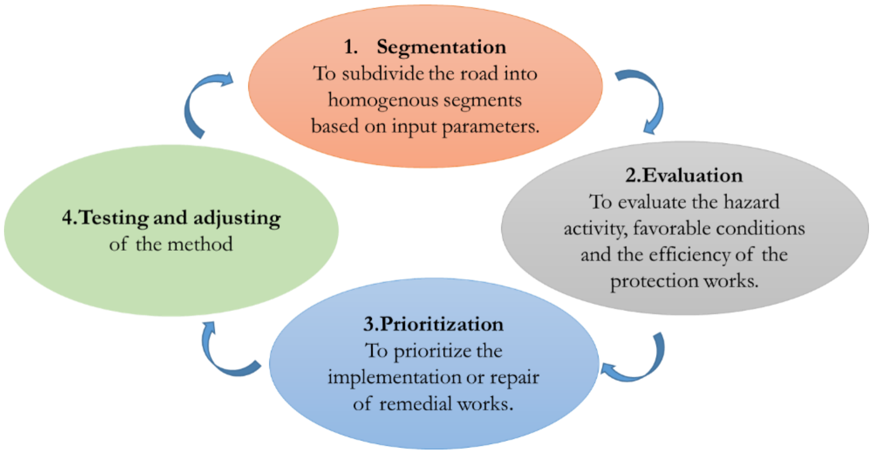


Figure 1.1 Conceptual framework

1.4. Thesis structure

The research is structured as follow:

Chapter 1: The background chapter contains the susceptibility and hazard assessment approaches of different types of hazards, the research problem is addressed, the research objectives and the corresponding questions and the overall research method.

Chapter 2: A relatively detailed literature review on the methods for susceptibility and or hazard assessment of different types of hazard along the roadways is included in this chapter.

Chapter 3: This chapter provides the general information of the study areas, the data have been obtained from the field or other resources.

Chapter 4: This chapter deals with the development of a rapid method for multi-hazard assessment., including the progress of data processing, the development of the rapid evaluation method.

Chapter 5: This chapter contains the results from the application of the improved rapid evaluation method in study areas.

Chapter 6: Testing the methods. To test the outcomes from the method in the field by a group of Chinese students and the results from testing the method in the office by both the students and teachers from ITC.

Chapter 7: Ends with conclusions and recommendations.

2. LITERATURE REVIEW

This chapter presents a summary of the literature related to the topic.

2.1. Introduction to method for hazard assessment along roads

- Quantitative methods

In quantitative methods, the hazard in terms of probability of an event of a given magnitude requires extensive data on the frequency as well as intensity (velocity, energy) or magnitude (volume) of the events (Fell et al., 2008; Jaiswal et al. 2010). Bunce et al. (1997) were amongst the first to use the roadway damage to assess the rockfall frequency. And Hungr et al. (1999) quantified the rockfall hazard along the road at the British Columbia, after deriving magnitude-cumulative frequency curves. Jaiswal et al. (2010) used a quantitative method to assess landslide hazard along transportation lines using historical records. In this research, a quantitative landslide hazard model is presented for transportation lines of the Nilgiri Hills in southern India. For the hazard calculation, they assumed that the probability of landslide occurrence can be calculated directly from the landslide inventory by analysing the number of expected landslides per kilometre of roadways for different triggering events. They used the Gumbel method for frequency–magnitude analysis in which the magnitude is regarded as the number of landslides per kilometre. The volume of expected landslides was analysed separately using the volume–frequency analysis.

One of the major limitations for the quantitative hazard assessment in roadways is the great data demand that it requires. Most commonly, landslide inventories are required (Dai et al., 2002), nevertheless these are often scarce. Highway and traffic administration authorities are potential data providers (Hungr et al., 1999), however complete and reliable maintenance records are rarely kept and made publicly available. Alternatively, for the assessment of frequency and magnitude of data, high resolution remote sensing digital elevation models DEM can be used (Santana et al., 2012; Domènech et al., 2017) or multi-temporal DEM (Abellán et al., 2009 ; Roýan, Abellán, & Vilaplana, 2015), obtained by Terrestial Laser Scanners or Digital Photogrammetry. Physically-based modelling coupling the probability of occurrence of the landslide triggering factor and the response of the landslide to it has also been used to estimate the temporal probability of landslides. Still these works have been mostly developed at site specific scale and their application to an entire road network has not yet been applied.

- Qualitative approach

Qualitative approach (knowledge driven approach) for landslides hazard assessment can be done direct and indirect methods and often involve judgements from an expert. The main idea of knowledge based method is to understand the relationship between landslides susceptibility and the cause factors for certain areas directly from field observation by expert geomorphologists(Rana, 2017). These methods often describe the landslide likelihood in qualitative terms, and classify the hazard using terms such as “low”, “moderate” and “high” (Castellanos Abella & Van Westen, 2008). For the direct method, experts could interpret the susceptibility directly from field according to observations of the terrain characteristics, geological and geomorphological setting. There is no extensive GIS modelling used in this direct method. GIS modelling is only used as a tool to prepare final map (Corominas et al., 2014). In the indirect method, knowledge based approach is used for assessing landslides hazard map by considering the factor maps with different weights using GIS tools. Spatial Multi-Criteria Evaluation (SMCE), Fuzzy logic, Multiclass overlay are commonly used indirect knowledge based approaches.

A qualitative hazard assessment method based on clear definitions and a weighting approach has been developed and tried on a total of 23 sites within the Greater Wollongong Area and along the Unanderra to Moss Vale Railway Line (Ko Ko et al., 2004).This method is based on detailed visual site inspection and may be described as a systematic qualitative approach by an expert in the absence of comprehensive sub-surface investigation. Comprehensive procedures and guidelines using numerical ratings for various influencing factors can greatly improve a qualitative assessment method in terms of consistency and repeatability.

Analysing hazard qualitatively is often carried out using the hazard matrixes, hazard indices tables. And qualitative hazard assessment may be more applicable for a large area where the quality and quantity of available data are tooscarce for quantitative analysis (Dai et al., 2002). Qualitative analysis is perhaps the most widely used approach, as it is simple and quick to carry out (Modarres, 2006). However, qualitative analysis highly depends on the experience and skills of the expert and may therefore differ when carried out by different persons.

- Semi-quantitative approaches

Semi-quantitative approaches are a transition between quantitative and qualitative methods, here by semi-quantitative is referred to methodologies that assess the hazard in terms of numerical scores instead of probability of occurrence. Instead, the pure quantitative hazard assessment consists in the hazard assessment in terms of probability of failure/occurrence of an event of a given magnitude (Fell et al. 2005), which is not treated by semi-quantitative methods. Several qualitative and semi-quantitative methods was reviewed in highway slope instability risk assessment systems which is provided by Pantelidis (2011). A well-known example of semi-quantitative methods is the Rockfall Hazard Rating System (RHRS) (Pierson & Van Vickle, 1993) recommended by the FHWA, which is a process that allows agencies to manage the rock slopes along the roadway systems and provides reasonable approaches for managers to make informed decisions on where and how to spend construction funds. RHRS was later adapted by Budetta (2004), specifically for rockfall risk along roads. Moreover, Losasso et al. (2017)used the modified RHRS 2.0 method to analysis landslide risk along strategic touristic roads in Basilicata southern Italy.

2.2. Homogenous segmentation mapping

There are many methods used to do terrain or geomorphological homogenous unit mapping. And Das et al. (2011) proposed to replace terrain mapping units with more logical parameter, such as HSU for calculating hazard. However, seldom papers illustrate the method used in the homogenous road segmentation which are taken the roadside hazards into account.

- Homogenous susceptible units mapping

Das et al. (2011) assessed the landslide hazard based on homogenous susceptibility units (HSU) along a national highway corridor in the northern Himalayas . HSU were developed from a grid-based landslide susceptibility map which combined geo-environmental factors and landslide occurrences. To divided the landslide susceptibility map into homogenous susceptibility unit map, an automatic segmentation way was used. A region-growing segmentation algorithm which results in segments with statistically independent spatial probability values was applied in this study. This methodology was tested along a national highway in Bhagirathi river basin of north Himalaya, India. They proposed that homogenous susceptibility units could replace the terrain mapping units for combining three probabilities (spatial, temporal and landslide size probabilities) for calculating landslide hazard.

However, HSU is derived from susceptibility map, that is to say, a susceptibility map is needed to be developed in advance. To obtain the susceptibility map, many thematic variables need to be analyzed, including lithological parameters and morphological factors. Normally, the collection of these parameters used in generating susceptibility map is time consuming, this data-driven method is not suitable for the simple and direct hazard assessment method.

- Homogenous road segmentation

For roadway design or maintenance projects, it is necessary to divide a long road into several homogenous road sections according to certain criteria (Misra & Das, 2003). As the focus is on the exposed elements (road infrastructure) in this study, here specific reviewed two methods related to this topic used to make homogenous road sections.

(1) Infrastructure Risk Rating (IRR) is a specialized methodology prepared for the New Zealand Transport Agency. It used to assess road safety risk automatically by coding road. In IIR manual, eight key roadside features: road stereotype, alignment, carriageway width, roadside hazards, land use, intersection density, access density and traffic volume, are put in the model, used to diagnose the effect on road safety and are categorized appropriately. A guidance of the identification for the road section by coding is provided. Assessing the IRR features and coding each feature by assigning them a value based on the categories. In order to simplify and expedite coding, selecting homogenous sections is prior to coding. The homogenous section in IRR is referred as the road section with little difference in IRR features. Making the section breaks where the feature changes. The roadside hazard coding should be consistent in one road sections, and if the roadside hazards change, the road section should be broken.

In IRR, it is recommended that to identify different features assisting with maps and aerial photography before coding and a street level view could be used to define the section boundaries. Google Street View could provide panoramic images that allowing users to visually walk down the street from the web service. It has potential to reduce the resources required to complete large-scale street characterization(Griew et al., 2013). While the new service named Maplliary has the same function as Google Street View. It provides different angles of view on streets at different locations. These two tools could help user to get vivid views in the office rather than go to the field.

(2) An manual approach of homogenous road sections was provided by Rana (2017). In this method, first, an automated method was used to do terrain unit mapping (TMU). For each terrain unit, it has the information of the topographic factors, such as the slope gradient, land cover as well as possible hazard runout path. Then in order to digitize the homogeneous road section, TMU was combined with the information on road drainage, road cuts and historical events within Google Earth. The homogenous road sections were classified into six types: normal segment, drainage path segment, active landslides zone, debris slide segment, rockfall zone and road cut segment, and every type has unique characteristics. After digitizing, each homogenous road section has a unique ID as well as attributes information.

2.3. Landslide conditioning factors used in susceptibility/ hazard analysis

The occurrence of landslides due to numerous conditioning factors, such as geology, meteorology, hydrology, geomorphological factors. Understanding the conditioning factors of landslides is important for hazard susceptibility assessment and its mapping is significant for implementing mitigation strategies (Ray et al., 2010). However, it is impossible to cover all these factors in a landslide susceptibility assessment (Moreiras, 2005). Domínguez-Cuesta et al. (2007) pointed out that these conditioning factors can be classified into two general categories. One group refers to topographic factors which contains the quantitative variables of altitude, curvature, etc. Another group contains the qualitative variables related to geology and vegetation.

Some researchers tried to assess the impact of conditional factors and determine the most significant factors. According to Donati & Turrini (2002) they tried to identify the most influential factors for the occurrence of landslides in southeast Umbria and ranked them according to the importance. They found that the factors have significant impacts on landslides in theory, but in reality, they showed different effects. Only some of the conditioning factors they identified, such as lithology, showed the effect of the prediction. And Moreiras (2005)stated that lithology and slope are the most influential factors in landslide mapping in the study area of Rio Mendoza Valle, Argentina. Glennet al. (2006) evaluated the efficiency of LiDAR deriver terrain factors in characterizing landslide activity and morphology. They pointed out that topographic factors are most influential parameters in landslide researches.

2.4. Methods used for estimating landslide activity

Many methods were used to estimate the landslide activity. Some phenomenon can indicate the activity of mass movement, such as the tilted trees on sloping land which indicates that the trees are affected by mass movement (Braam et al., 1987). And a dendro-geomorphological analysis of landslides was carried out by Jiménez et al. (2017)to determine their activity. The date on the occurrence of landslides will be indicated by tree growth anomaly, such as a new compression wood ring. For historical inventory, Niculiţă et al. (2016) studied landslide activity in a lowland area using nine geomorphological inventories for nine archaeological sites. To prepare inventories, a LiDAR survey was used to produce landslide inventories via images (slope maps, shaded relief map, etc.) derived from a digital terrain model. Then a contour map was used to map landslide. Last, the landslide and the age were decided based a classification proposed before. This historical inventory method can be extended spatially and temporally. And based on the data collected from field investigation, local government reports, and multi-temporal aerial photographs, Zhuang et.al (2017) calculated landslide activity.

2.5. Evaluation of remedial measures along roads

Remedial measures can be carried out before an instability may cause by excessive deformation or after a landslide event (Popescu, 2001). The design of remedial measures need an assessment of instability causing factors, a landslide geometry prediction, and a relevant soil properties estimation (Neves, Cavaleiro, & Pinto, 2016). A brief list of landslide remedial measures was prepared by IUGS WG/L Commission on Landslide Remediation (Popescu, 2001) (see Table 2.1). The remedial measures has arranged in four groups, that is, modification of slope geometry, drainage, retaining structures and internal slope reinforcement.

To evaluate the most appropriate remedial measures, Neves, Cavaleiro, & Pinto, (2016) used six selected models to quantify the merits of each remediation techniques for several conditions, using both Finite element approaches and limit equilibrium methods. To achieve the evaluation results, the structural elements, include soil nails, gabion wall and sheet piles, were analysed for each model. Others, Zhang, Xu, Shao, Zou, & Sun, (2013) compared two different remedial measures, to investigate the improvement of stability. To achieve the evaluation results, a multistage excavation was used to execute a 3D non-linear numerical analysis. However, the method for evaluating remedial measures along roads is still lack of systematic study and the relevant research is superficial and lack of specific condition analysis.

Table 2.1 A brief list of landslide remedial measures

1. Modification of slope geometry	1.1 Removing material from area driving the landslide (with possible substitution by lightweight fill) 1.2 Adding material to area maintaining stability (counterweight berm or fill) 1.3 Reducing general slope angle
2. Drainage	2.1 Surface drains to divert water from flowing onto slide area (collecting ditches and pipes) 2.2 Shallow or deep trench drains filled with free-draining geomaterials (coarse granular fills and geosynthetics) 2.3 Buttress counterforts of coarse-grained materials (hydrological effect) 2.4 Vertical (small-diameter) boreholes, pumped or self draining 2.5 Vertical (large-diameter) wells with gravity draining 2.6 Sub-horizontal or sub-vertical boreholes 2.7 Drainage tunnels, galleries or adits 2.8 Vacuum dewatering 2.9 Drainage by siphoning 2.10 Electro-osmotic dewatering 2.11 Vegetation planting (hydrological effect)
3. Retaining structures	3.1 Gravity-retaining walls 3.2 Crib-block walls 3.3 Gabion walls 3.4 Passive piles, piers and caissons 3.5 Cast-in-situ reinforced concrete walls 3.6 Reinforced earth-retaining structures with strip/sheet- polymer/ metallic-reinforcement elements 3.7 Buttress counterforts of coarse-grained material (mechanical effect) 3.8 Retention nets for rock slope faces 3.9 Rock fall attenuation or stopping systems (rock trap ditches, benches, fences and walls) 3.10 Protective rock/concrete blocks against erosion
4. Internal slope reinforcement	4.1 Rock bolts 4.2 Micro piles 4.3 Soil nailing 4.4 Anchors (pre-stressed or not) 4.5 Grouting 4.6 Stone or lime/cement columns 4.7 Heat treatment 4.8 Freezing 4.9 Electro-osmotic anchors 4.10 Vegetation planting (root strength mechanical effect)

3. STUDY AREAS AND DATASETS

As the proposed method is a generic method for data-scare region, it will be tested in areas without sufficient historical data, and therefore two totally different study areas were selected for the application of the method. One is located in the zone affected by the Wenchuan earthquake in the north-western Sichuan province in south-western China, an active multi-hazard area with many hazardous problems. The other is located in the southeast of Guizhou province, hilly terrain with a limited amount of landslide problems. This chapter gives the background information on the two study areas. It includes the geographic locations, geology and geomorphology situations and other relevant aspects. Moreover, the existing data and the data collected from fieldwork are described here as well.

3.1. Yingxiu area

3.1.1. Location and general description

The study area is located in the north-western Sichuan province of Southwest China, around Yingxiu town and Longchi town (Figure 3.1). The Wenchuan earthquake with measured magnitude of Ms8.0 occurred on May 12, 2008. The epicentre was located at 31°N, 103.4°E, which is close to the study area.

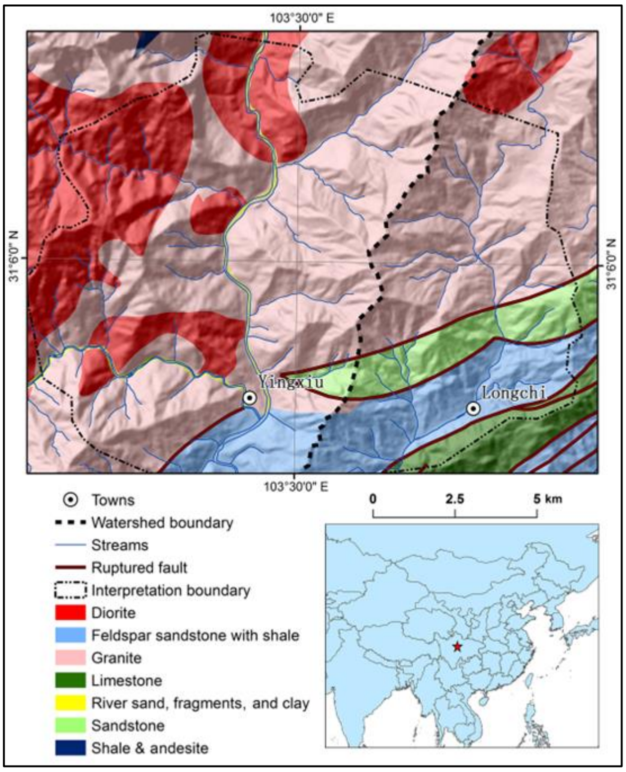


Figure 3.1 Map of the study area. Source: Tang et al. (2016)

It is located in the eastern of the Qinghai–Tibetan Plateau and is settled on Quaternary deposits. It is a tectonically active area, as the Yingxiu–Beichuan fault which is the main fault rupture of the Wenchuan earthquake passes through the area, running southwest to northeast (Tang et al., 2016). The main topographic characteristics of this area are high mountains and deep-cut rivers (Liu et al., 2016). The elevation of the study area ranges from 767 meters to 3950 meters, with an average elevation of 1736 meters. The dominant lithology exposed in this area are Diorite, granite, feldspar sandstone with shale.

Yingxiu features a subtropical monsoon climate, and the weather is relatively moderate with an annual average temperature of 13℃.

During the earthquake, there was a large number of landslide events and related casualties, mainly due to the changes of geological structure which cause slope stability decreased (Liu et al., 2016). Although it has been several years since the occurrence of the earthquake, there are still regular landslide occurrences. Rock falls and debris flows were very common in the epicentre region which caused heavy damage to roadways or disruption of the below the slopes properties (Dai et al., 2011). That is to say; this area is still under the potential long-term threat of various types of natural hazards (Koi et al., 2008).

3.1.2. Dynamic change of transportation infrastructure

Yingxiu Town is the part of a crucial transportation corridor to Siguniang tourism, Wolongzhen and the Jiuzhaigou. The road networks in Yingxiu area can be roughly divided into four types: highways, national roads, provincial roads and county roads.

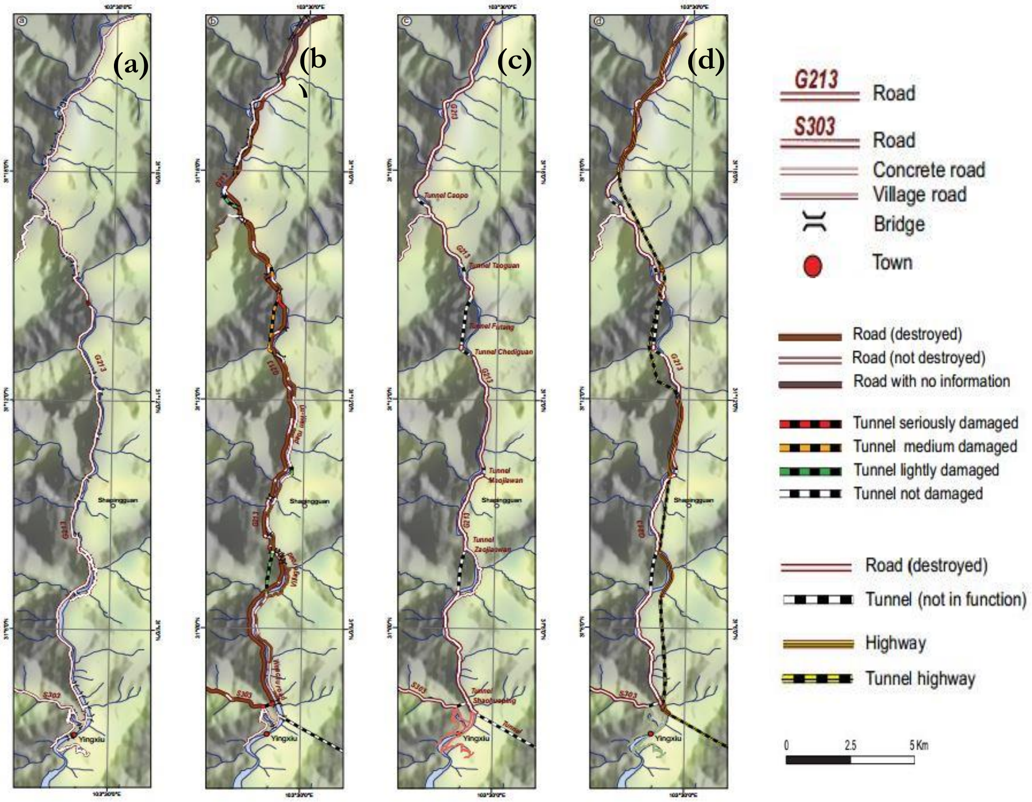


Figure 3.2 Dynamic change of transportation infrastructure. (a) Roads 2005. (b) Roads 2008. (c) Road 2009/2010. (d) Current roads and tunnels 2016/2017.

The dynamic changes of transportation infrastructure in this area betwwen 2005 with 2017 were shown in Figure 3.2. In 2005(Figure 3.2 a), the old national road (G213) was located along the Min River, connected Yingxiu town and Wenchuan county. Since the geological setting in this area was very complex, it was regarded very susceptible to some types of geohazards (e.g. rockfalls, landslides and debris flows). Then a new national road was constructed and was completed in 2008 before the earthquake. It can be seen from Figure 3.2b that some road infrastructures, such as tunnels and bridges were constructed along the new national road which was named Duwen Road. Nevertheless, because of the occurrence of 2008 Wenchuan earthquake, many parts of the old G213 national road was buried by co-seismic landslides or severely damaged by the earthquake. The post-earthquake road status in the study area is shown in Figure

3.2b. The reconstruction of the new G213 road was started from 2009 and was completed in 2010. The segments of the new road contain some parts of the old G213 road and some parts of the Duwen Road which were not severely destroyed during the earthquake. And a new highway was constructed started from 2010 and was completed in 2012. The large components of the highway are tunnels and viaducts. The current status (2016/2017) of roads and tunnels are shown in Figure 3.2d.

3.1.3. Datasets

3.1.4. Existing data

There are three main types of existing dataset, DEMs, secondary data (lithology map, landslide inventories) and satellite images (Table 3.1).

Table 3.1 List of existing data

Type	Source	Date	Resolution/Scale
DEM	Government, academic institute	2014 2014	1m 25m
Lithology	Office geology map, geological survey	-	-
Landslide inventory map	C. Tang et al., (2016)	2008 2015	Polygon
Satellite images	Worldview 2	2011	1m
Google Earth images		Many dates	
DSM	UAV	2017	1m
UAV image	UAV	2017	1m

- Satellite images

The multi-temporal satellite images could be checked from Google Earth, which contained high resolution images from the following years: 2006, 2010, 2011, 2014, 2015, 2016 and 2017. Also, a relatively high-resolution satellite image from Worldview 2 was collected for the study area from 2011 and a UAV image is cover a small part of the study roads was provided by Chengdu University of Technology. In this study, satellite images are important data, as they will be used to identify the road, roadside features, vegetation cover and so on.

- Digital Elevation Model

Topographic characteristics are considered as a critical factor to the occurrence of landslides. Usually, the steeper slopes are more prone to occur landslides. A Digital Elevation Model (DEM) is a representation of the condition of terrain surface created from elevation data. Some topographic information could be provided by DEM. Its derivative, such as slope gradient map, slope aspect map, slope curvature and hillshade map can be used to analyse the topographic factors. In this study, an available 1m×1m DEM from 2015 as well as a latest UAV based DSM from 2017 with resolution 1m×1m were collected from State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP).

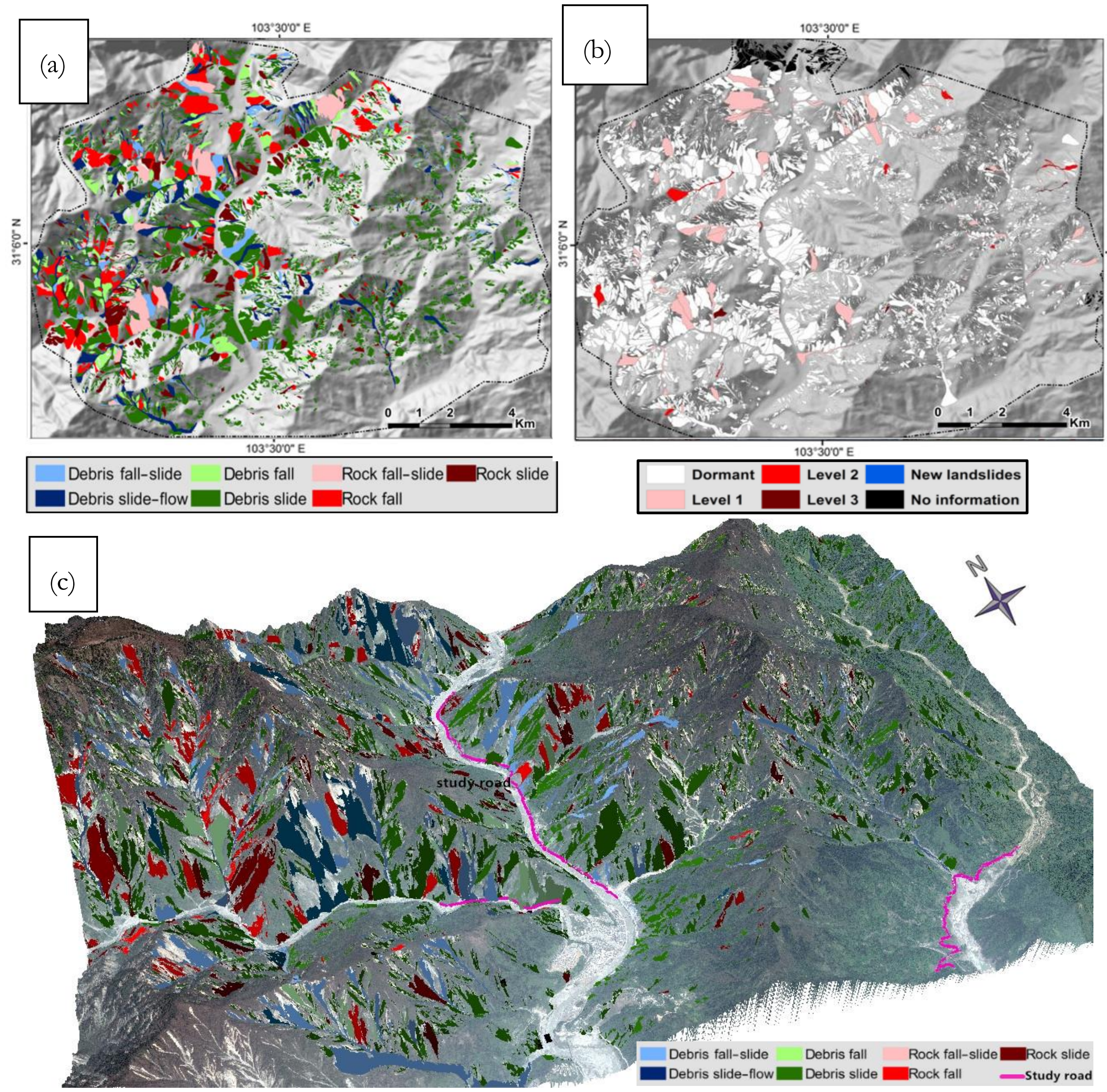


Figure 3.3 (a)Co-seismic landslide inventory. The background image was hillshade map with spatial resolution 25m. (b)Landslide inventory map reflecting the state of activity after the rainy seasons of 2013 and 2014. (c)3D-viewing of co-seismic landslide distribution

- Landslide inventories

Landslide inventory is the most important record demonstrating the attribute and distribution of historical landslides. It represents a basic knowledge of landslide, is a useful tool that helps the local authorities in decision making for land planning or prioritizing the mitigation work(Colombo et al., 2005).

Two landslide inventories were provided by Phd. student Cheniao Tang from ITC. One was prepared to show the distribution of the co-seismic landslides, using aerial photographs taken shortly after the earthquake and two satellite images from Spot 5: one taken from 2005 and the other taken shortly after the 2008 Wenchuan earthquake. There are 6727 landslides with a total area of 54.6 km^2 contained in the co-seismic landslide inventory map. The majority of the earthquake-triggered landslides in the eastern part of the study area are in small or medium size. Their average area is 3780 m^2. As the terrain is steeper in the western part and it is closer to the epicentre, most of the large size of landslides occurred in the west part with the average area of 10000m^2. And because of the topographic amplification that causes the failure of weathering soil layers, the most common co-seismic landslide type was debris slides in study area. The co-seismic landslide inventory map is presented in Figure 3.3a and 3.3b. The categories of landslides in the inventories follow the system proposed by British Geological Survey (BGS). The inventories contain these attributes, as a material component of the landslides (rock or debris), mass movement type (fall, slide, and flow), landslide activity level, vegetation cover level, the area of the landslide, the major lithology, aspect and max slope angle. For this study, the information is adequate to be applied in the rapid evaluation method to assess the hazard.

Another landslide inventory map was made using the high spatial resolution Spot 6 image dated in April 2015 (Figure 3.3b). It shows the activities of the landslides after the earthquake. In the image, 66 active landslides were identified, and among them, only two newly occurred. In summary, the landslide activity decreased significantly during the period from 2008 to April 2015.

3.1.5. Video images data collected from field work

It is not enough to identify the features along the road only based on satellite images, a street-level view is required. Although the resolution of the satellite images or the images from UAV could be high, it is difficult to see the protection work, for example, rock fall nets, established on the slope surface.

A dash cam is a video camera that installs on the windshield of the car. Users can film the entire car ride with it. In this study, a dashboard camera was used for registering the condition of three study roads. The video images collected from the field providing real conditions of the road which can be used to refine the road segmentation after coming back from the field, and as an essential data for other people to do the test in the office as well rather than going to the field. However, this dashboard camera is not linked with GPS, so another new service for sharing geotagged photos worldwide named Mapilliary was used to capture 3D street-level images, uploaded images with mobile phones and visualised them on the map which could show the location.

3.2. Duyun City

3.2.1. Background of the study area in Duyun City

Duyun City is located in the eastern part of southern Guizhou Province. It features a subtropical humid monsoon climate. The average coldest temperature in winter is 5.6 °C, the average hottest temperature in summer is 24.8 °C. Rainfall is abundant there, with an average annual rainfall of 1431.1 mm. The northern part of Duyun city is the hilly terrain while central and southern part is the valley basin. It is the karst landform area.

Guizhou-Guangxi railway, New Guizhou highway, Xia Rong Expressway, 320 and 321 National Roads, 207 National Highway and the Guizhou-Guangzhou high-speed railway across this city. The road networks in Duyun City can be roughly divided into four types: national roadways, country roads and county roads (Figure 3.4a).

The study area is called Shaobaobao administrative region, located in the north part of Duyun City which covers around 45 km². A landslide inventory was provided by State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP). It includes the hazard location there is very limited amount of landslide problems as thirty-five landslides and two rockfall hazards were recorded. Most slopes are gentle with vegetation covered well in the study area. This method was only tested in a short part of the study road.

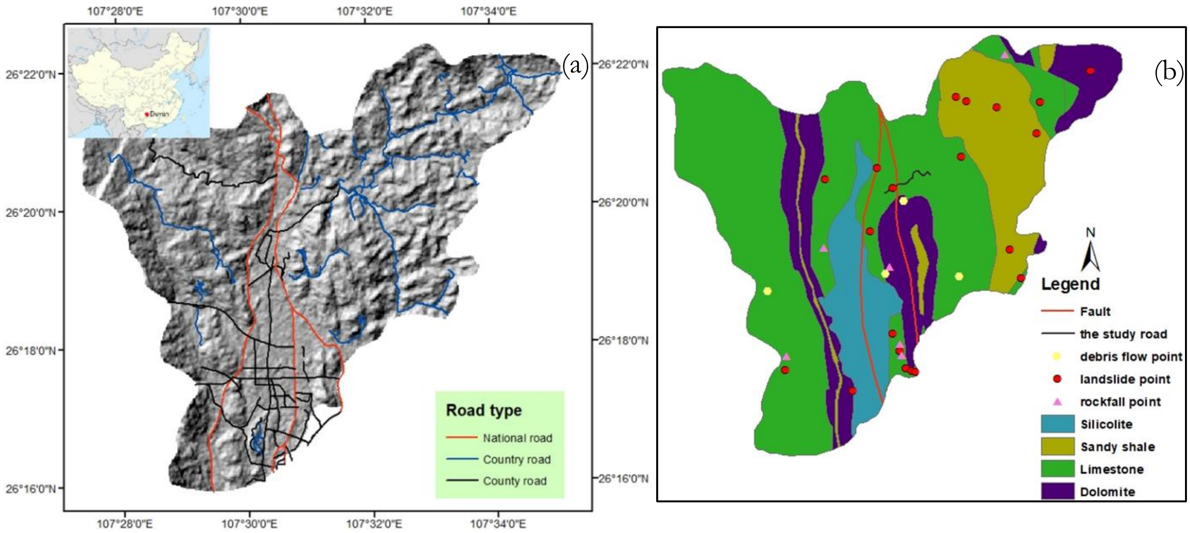


Figure 3.4 (a) Map of the Duyun area that shows the three types of roads on top of the Digital elevation model. (b) Geological map.

3.2.2. Datasets

The available data from different sources in Duyun study area are listed in Table 3.2. The satellite image was collected from Worldview 2 dated in 2015 to prepare homogenous road segmentation before going to the field. And DEM, geological map and historical record were ancillary to make it.

Table 3.2 List of existing data of Duyun area

Type	Source	Date	Resolution/Scale
DEM	Open source	-	30m
Geological map	Geological Environment Monitoring Institute of Guizhou & field survey	-	-
Historical record	SKLGP	2000-2017	point
Satellite image	Worldview 2	2015	5m

Geological information is provided by Geological Environment Monitoring Institute of Guizhou province. The lithology shown on the map is very general (Figure 3.4b). A historical record was provided by SKLGP, which was digitized in point format and added the relevant information of each hazard point in attribute table. Checking from the geological map, there are very limited landslide problems in this study area, as only 19 landslide points, six rockfall points and four debris flow point shown on the geological map.

During the fieldwork, some basic information about the previous hazards were enquired from local people also added in the historical record. Also, the dashboard camera was used to record the condition of both sides of the study road.

4. DEVELOPMENT OF A RAPID METHOD FOR MULTI-HAZARD ASSESSMENT

The method proposed in this chapter is a rapid qualitative hazard assessment approach, which is not only focusing on susceptibility but also tries to assess frequency in qualitative terms. It was designed for the prioritization of the most hazard-prone sections along a road network based on homogenous road section. It includes three parts: (1) to subdivide the road into homogenous sections; (2) to assess the hazard level per road section based on hazard activity and favourable conditions for producing hazards; (3) to evaluate the prioritization class for implementing mitigation works per road section.

4.1. Subdividing roads into homogenous segments manually

Different road sections may be susceptible to different types of hazards and have different levels of susceptibility or hazard to landslide process. Reasonable subdivision methods should try to ensure the maximum similarity of intrinsic properties of each section, and the obvious different properties between adjacent segments. However, subdividing a road into sections with absolute homogeneity is almost impossible in real circumstances(Das et al., 2011). For this study, a homogenous road section does not mean that the materials on each section have the same properties at every point. Instead, it means the section has a homogenous hazard occurrence potential.

In this study, the focus is on the exposed elements (road infrastructure). In order to evaluate possible hazards occurring from the slope above the road or from the slope below the road, automatic road segmentation methods require more detailed information and higher quality data, while the manual way could be an approach to solve it in data scarce situations. Manual road segmentation is a process to manually subdivide the road into different sections based on available information and knowledge judgement. The topographic information of the exposed element and its surrounding physical condition are required to identify the sections.

4.1.1. Input parameters used to identify homogenous road sections

In general, most roads in the study areas are built in mountainous or hilly areas with heterogeneous terrain conditions. As it was previously stated, a homogenous road section is supposed to be susceptible to the same types of hazards in an equal manner. Based on field survey, six most visually obvious vital factors (Figure 4.1) have been used to determine the homogeneity of a road section. So, each homogenous road section will have similar terrain characteristics, surrounding land use or land cover types and the type of protection works.

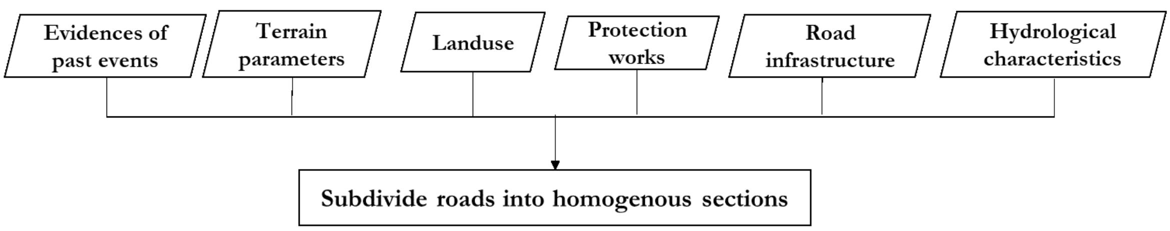


Figure 4.1 The six types of parameters used to subdivide the homogenous sections

A combination of different data sources, such as Google Earth images, Google Street View, dashboard video camera images, UAV images, digital elevation models (DEMs), lithology maps, land use/cover maps, landslide inventories, road maintenance records and field surveys, were used to describe each of the six categories used for dividing the road into homogenous sections (Table 4.1). Since the focus of this research is on road infrastructure, the most obvious thing is to observe the type of road infrastructure. In the study area, some road sections are presented in the form of viaducts or bridges, because usually they are built to avoid certain types hazards. Five common types of artificial work conducted in the study area are: bridge, viaduct, tunnel, gallery and road. To determine the terrain parameters, the slope is classified into two categories: natural slope and engineered slope. Natural slopes refer to slopes without anthropogenic disturbances, while engineered slopes have been intervened by anthropogenic activities. The slope material composition is divided into three categories: rock, soil and mixture of soil and rock. Topographic characteristics of slopes include the height of the slope and slope angle. The common types of land use or land cover in the study area are houses, farmland, forest and bare land.

Detailed description of the definition of the input parameters, as well as the corresponding data source are shown in Table 4.1.

Table 4.1 Detailed description of six input parameters used to identify homogenous road sections

Parameters categories		Description	Data sources
Road infrastructure		The structure that allows people or vehicles to pass. E.g. bridge, viaduct, tunnel, embankment	a. Google Earth, satellite images b. Google street view/ Mapillary c. Dashboard camera video images d. UAV images e. Field survey f. DEMs g. Thematic data • Lithology map • Landuse map • Landslide inventories • Road maintenance records
Terrain parameters	Slope type (up & down slope)	They are classified into two main types, natural slope and engineered slope	
	Topographic characteristics of slopes	In this study, only taking the height of the slope and slope angle into consideration	
	Materials type	The material composition of slopes. E.g., rock, soil or the combination of rock and soil	
	Drainage channel	A channel along which drained water flows away. The most common one is the gully in the study area.	
Land use		Land use involves the management and modification of natural environment into built environment. E.g., houses, farmland.	
Evidence of past events		Some evidences show the occurrences of past events, e.g. the rock fall deposits.	
Protection works		Some remedial measures are taken to increase the stability of slopes, e.g. retaining structure.	
Hydrological characteristics		In this study, only taking whether there is a river at the foot of the slope into consideration	

In this research, four types of hazards are taken into consideration: rockfall, debris flow, landslide, and the failure of the embankment. The protection work types only list the most common remedial work seen in the field (see in table 4.2 and Appendix 1).

Table 4.2 The common protection measures in the field

Hazard type	Rock fall	Landslide	Debris flow	Embankment failure
Protection work	Nets	Soil nailing/ Anchors	Gallery/ tunnel	Concrete walls
	Fences	Retaining wall	Artificial drainage	Gabion
		Grouting	Check Dam	

4.1.2. Road coding method

To identify the six parameters used to subdivide the homogenous sections, we allocated attribute codes(Table 4.3) for each road segment. The definition of the section boundaries is based on this code and each section has a different code compared with neighbour sections. When the elements of the section change, the coding of the section will change as well.

The coding has two purposes: (1) the coding explains the characteristics of the sections; (2) the coding also may indicate the possible hazards that are relevant for this section; (3) Road sections that have the same parameters will have the same coding and could be grouped together to assess hazard class.

Table 4.3 The road section codes

		Code	Definition
1. Road infrastructure		R1	Road
		R2	Bridge
		R3	Gallery
		R4	Tunnel
		R5	Viaduct
2. Terrain parameters	Slope type	N	Natural Slope
		C	Cut slope
		E	Embankment
	Drainage channel	G	Gully
	Steepness	V	Vertical
		S	Steep (>35 degrees)
		M	Moderate steep (5-35 degrees)
		F	Flat (<5 degrees)
3. Land use		L1	Buildings
		L2	Farmland
		L3	Terraces
		L4	Bare land
		L5	Forest
4. Protection works		P1	Rockfall nets
		P2	Rockfall fences
		P3	Artificial drainage
		P4	Concrete walls
		P5	Grouting
		P6	Retaining wall
		P7	Check Dam
		P8	Gallery
		P9	Other protection works
5. Evidence of past events	Deposit type	Er	Rockfall deposit
		Ed	Debris flow deposit
		El	Landslide deposit
6. Hydrological characteristic		W	River

4.1.3. The process of segmentation

The process for the homogenous road segmentation is not a standard method because the six input parameters can be obtained in different ways. The first step contains two options (standard and improved options shown in the Figure 4.2), it depends on which data is available. The standard option is only based on free software and data (mainly focusing on Google Earth data) to identify the six input parameters. The improved option indicates there are more available data can be used to observe the parameters. It is worth mentioning that these optional procedures are not independent, they can be combined with each other based on existing data. The standard option and the improved option are determined manually. Moreover, there are opportunities to automate it. These possible automatic or semi-automatic procedures were discussed more in the last chapter.

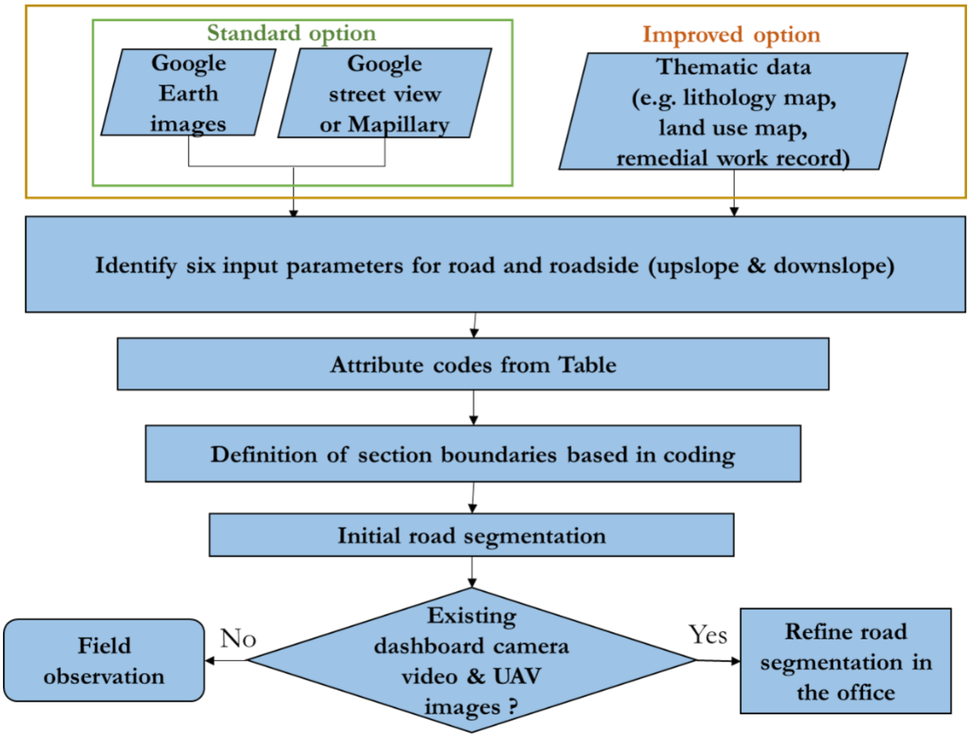


Figure 4.2. The flowchart shows the process of road segmentation

Step 1: Identifying input parameters

The first step is to collect the six input parameters from roads and roadsides (up slopes and down slopes), based on existing data. There are two choices:

- Using the standard option to identify input parameters

The standard procedure is applied in the situation when there is little data available, that is to say, doing the initial segmentations in the office only based on Google Earth and Google Street View or Mapilliary (if it is available in study area). Mapillary has the same function as Google Street View. It provides 3D representation of the earth and 3D street-level view which allows the users to check the study area from various angles and get a deeper understanding of the condition of the study area.

- Using the improved option to identify input parameters

The improved option is used in the situation when more thematic data is available, such as lithology data, land use or land cover maps, landslide inventories or detailed information on remedial works. Combined with the standard option, the road segmentation could be more detailed.

Step 2: Coding according to the attributes of the road section

Acquire the attributes along roads, roadsides (upslopes and downslopes or left slope and right slope) by visual interpretation, and allocate a code based on Table 4.3.

Step 3: Definition of homogenous section boundaries

When one or more of the six parameters change, the code will also change, and a boundary can be drawn to divide the road into homogenous sections. So compared with the neighbor sections, each section has a different code.

After these three steps, initial segmentation will be done. It might be a coarse segmentation because of the limitation of the available data, some parameters cannot be seen only using open source data and there is a need for the modified process.

Step 4: The refined procedure

After making the initial segmentation, there are two options to improve this segmentation. This can be done with additional data, such as dashboard camera video as well as UAV images, which can be done in the office. If there are no additional detailed data available, the initial road segmentation can be refined during the field survey.

4.1.4. An example of how to attribute the codes

In order to show how to code a road section, an example was illustrated as follows.

Example 1:

Location: A part of the S303 road in Yingxiuzhen, Sichuan Province, China

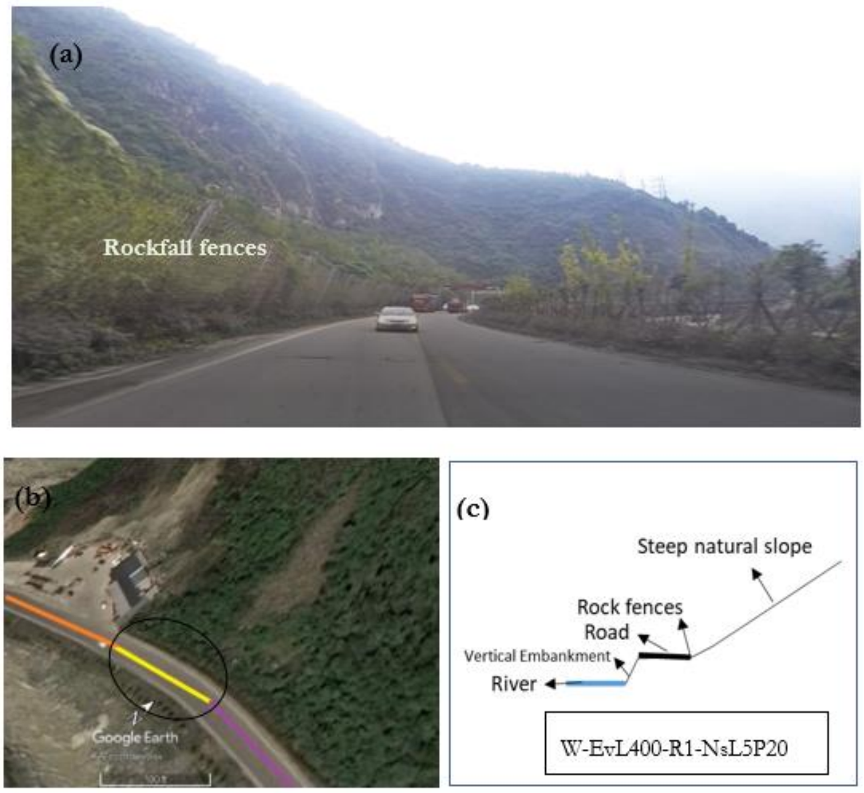


Figure 4.3(a) Dashboard camera image was taken on October 2017 during the field work (b) Google earth image dated 5/1/2017 (c) the cross sectional profile

Figure 4.3 shows an example of attributing the codes for the section. Firstly, to identify the six input parameters in this section, draw a cross-sectional profile (Figure 4.3 c) from below the road to above the road. In the downslope part, there is a river (hydrological characteristics), and a nearly vertical embankment (terrain parameter) with no vegetation (Land use parameter) on it. And rock fall fences (Protection work parameter) were conducted at the bottom of the upslope, the steepness of natural upslope is steep (terrain parameter) and there is more vegetation (Land use parameter) on the slope surface in this section. However, no evidences show the occurrences of past events in this section, hence, the evidence parameter was replaced in the code with 0. Based the codes proposed in Table 4.3, from the bottom to the top, the road section can be coded as W-EvL400-R1-NsL5P20.

4.2. The method for qualitative hazard assessment

In this method, a hazard matrix was developed to assess the hazard level based on the evaluation results of the hazard activity and favorable conditions for producing a hazard. The entire procedure for the prioritization of implementing the remedial works is shown in Figure 4.4.

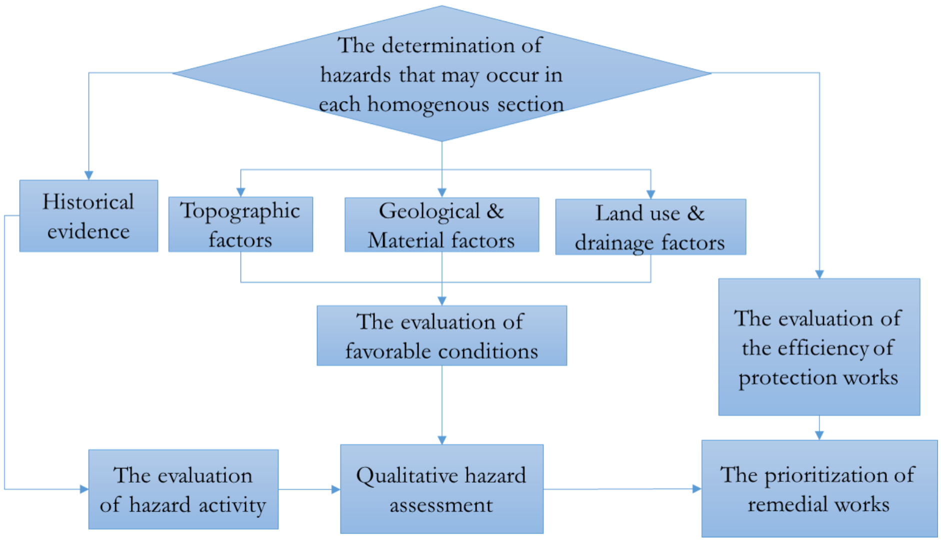


Figure 4.4 The flowchart describing the prioritization process

4.2.1. The determination of the hazard type

After finishing the segmentation, the types of hazards that may occur in each homogenous section need to be determined. In principle, the type of hazard is determined based on the evidence of past events or according to the secondary data, such landslide inventories, road maintenance records. Moreover, in the Yingxiu study area, many mitigation works were implemented, and based on these mitigation works, the type of hazard also can also be determined by the corresponding prevention measures. Some common evidence regarding the specific events in the study area are listed in Appendix 2. If there is no evidence or landslide inventories of historical events, the hazard type can be determined by certain topographic characteristics. The typical topographic characteristics related to the hazard are listed in the form of questions on the favorable condition decision tree (Appendix 4). In other words, the hazard type can be determined using the so-called "favorable conditions" decision tree.

4.2.2. Using decision tree method to evaluate the activity

To evaluate the activity of the events in the study area, a simple activity decision tree was designed (shown in Figure 4.5 and Appendix 3). The decision tree method uses a flow-chart-like and top-down classification strategy based on certain criteria and their possible consequences. It is a decision support method performed in the Excel sheet, which guides the users by answering some questions to obtain the evaluation results. If the answer is yes, the user should move on to the question on the right, vice versa, if the answer is no the user should continue to the question below.

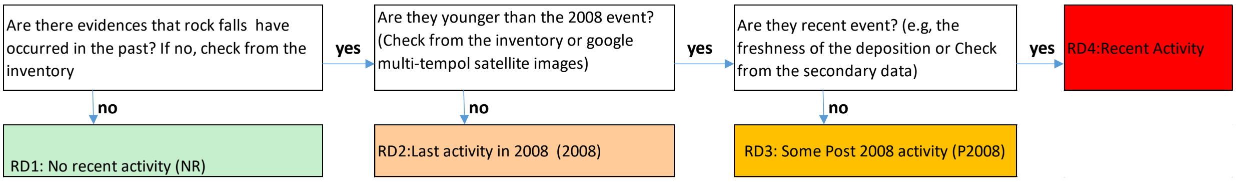


Figure 4.5 A part of the "activity decision tree" to evaluation rockfall activity

Due to the specificities of the different regions, according to the historical records, some modifications of hazard activities class are required for different study areas. As there was a destructive earthquake which occurred in 2008 in Yingxiu area, the status of the hazard activity in this area is classified into four classes which are "no recent activity", "last activity in 2008", "some Post 2008 activity (2008-2015)" and "recent activity". However, there were very limited landslide problems that occurred in the Duyun area, and accoding to the historical data which recorded the landslides from 1990 to 2017, the status of the hazard activity in the Duyun area are classified into three classes: "recent activities (2015-2017)", "some post 1990 activity" and "no recent activity".

- Based on evidence of past events

Evidence plays a very important role in this evaluation method, it is the most direct way to judge whether a hazard event has occurred or not. The evaluation method is carried out by looking at the evidence of the historical events in the field. Since different phenomena indicate the occurrence of different hazard events, such as the rock blocks on the road indicates the occurrence of rockfall and the landslide deposits on or below the road indicates the occurrence of landslide. It is attempted to associate the evidence with the temporal occurrence of the events. For example, rockfall activity can be assessed based on the freshness of the rockfall deposits. Some questions regarding the evidence of the certain type of hazards have been listed in the Excel sheet (see in appendix 2).

- Based on secondary data

If there are no clear evidence along the roads during the field survey, or the deposits were cleaned by the road maintenance workers, the activity assessment could be determined using secondary data only, such as landslide inventories, historical records, inquiring with nearby residents or the administration authorities if they know any event has occurred before.

4.2.3. Using decision tree method to evaluate the favourable conditions for the triggering of hazards

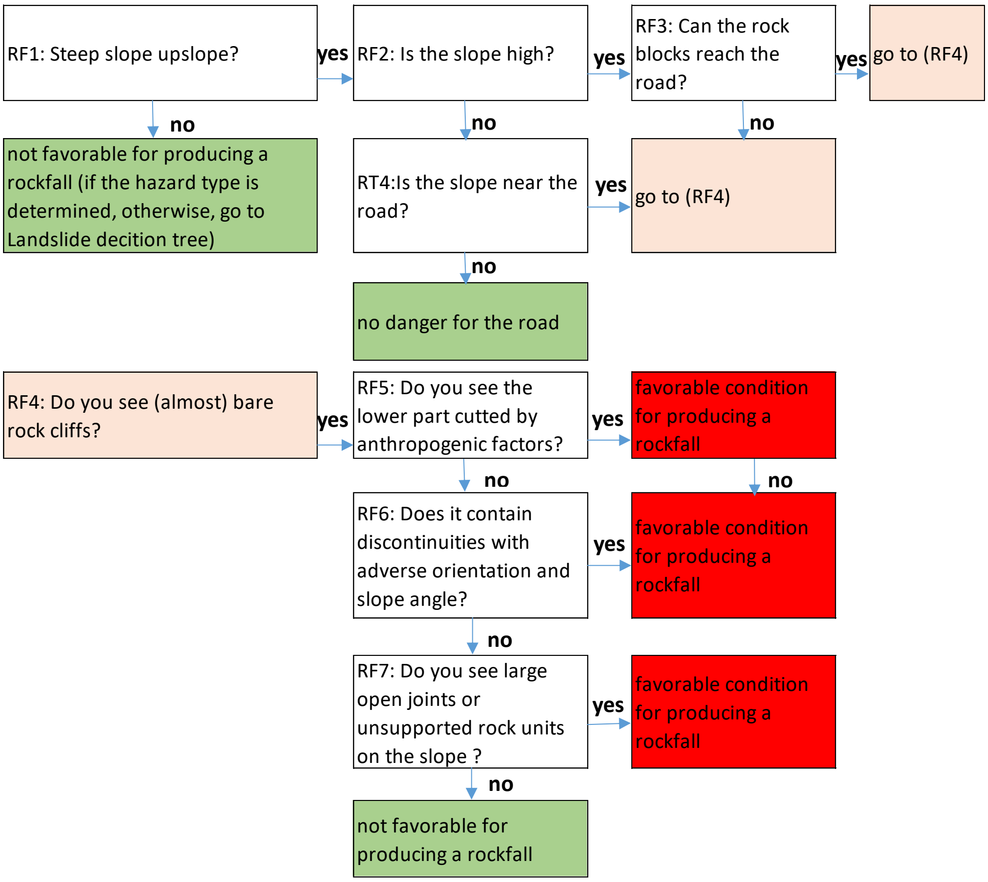


Figure 4.6 "Rockfall favorable conditions" decision tree

To assist with assessing whether the conditions are favourable to lead to mass movement, the decision tree was developed (overall decision tree methods were shown in Appendix 4). The decision tree was developed in an Excel sheet which guides the users by answering some questions. If the answer is yes, the user should move on to the question on the right, vice versa, if the answer is no the user should continue to the question below. By answering these questions, the user will be able to determine if the section is favourable for the occurrence of landslides, rockfalls, debris flows, or embankment failures.

The decision tree method has been developed by taking into account five major potential factors causing slope failure: topography, geological, slope materials, landuse and drainage, and contains the most relevant questions regarding the four factors in a systematic way. For example, if the user is in the field and wants to determine if a homogenous road section is susceptible to rock falls, the user should use the rock fall decision tree (Figure 4.6, Appendix 4.1). Firstly, to assess if the conditions are favourable for rock fall, the user looks at topographic factors. Three topographic conditions are considered: slopes angle, the height of the slopes and the distance between the slopes and the roads. If the slope is not near vertical, then the condition of this section is considered as not favourable. Then the material characteristics of the slopes are assessed, such as the feature of the joints (continuity and orientation). Land use and drainage factors are taken into account at last.

4.2.4. Hazard matrix

A hazard matrix method (shown in Tables 4.4 and 4.5) was used to determine the hazard level. It is based on the results of the hazard activity and favorable conditions. Table 4.4 shows the matrix for Yingxiu area and Table 4.5 for Duyun area.

Table 4.4 Hazard matrix for Yingxiu area

Activity / Favorable condition	Recent Activity (2015-2017) (Very high activity)	Post 2008 (High activity)	2008 (Moderate)	No recent activity (Low activity)
Favorable	Very high	High	Moderate	Moderate
Not favorable	High	Moderate	Low	Low

Table 4.5 Hazard matrix for Duyun city

Activity / Favorable condition	Recent Activity (2015-2017) (High)	Post 2000 (Moderate)	No recent activity (Low)
Favorable	High	Moderate	Moderate
Not favorable	Moderate	Low	Low

In the Yingxiu area, the hazard levels are classified into four classes in qualitative terms: *very high, high, moderate* and *low*; in Duyun city, the hazard levels are classified into three classes: *high, moderate* and *low.*

4.3. The evaluation of the prioritization class for implementing mitigation works

Many protection works were constructed in the study area, and a large diversity of mitigation measures were taken to increase the slope stability. Some of them were built on the edge of the roads; and others were built on the slope. However, because of the occurrence of post-earthquake mass movement and floods, many protection works were damaged. Therefore, it is also important to evaluate the efficiency of the protection work after assessing the hazard level.

4.3.1. The protection efficiency decision tree

To assist with the evaluation of the efficiency of the protection work, a decision tree was designed (Figure 4.7 and Appendix 5). If the answer is *Yes*, it will go right, if the answers is *No*, it will go downwards, to answer another question. Besides, if the protection works are damaged, some information of the hazard frequency could be obtained, in this case, the activity might be classified in recent activity class. In this study, the efficiency of protection work are classified into four classes: “P1: sufficient protection”, “P2: insufficient protection”, “P3: destroyed protection, “P4: no protection”.

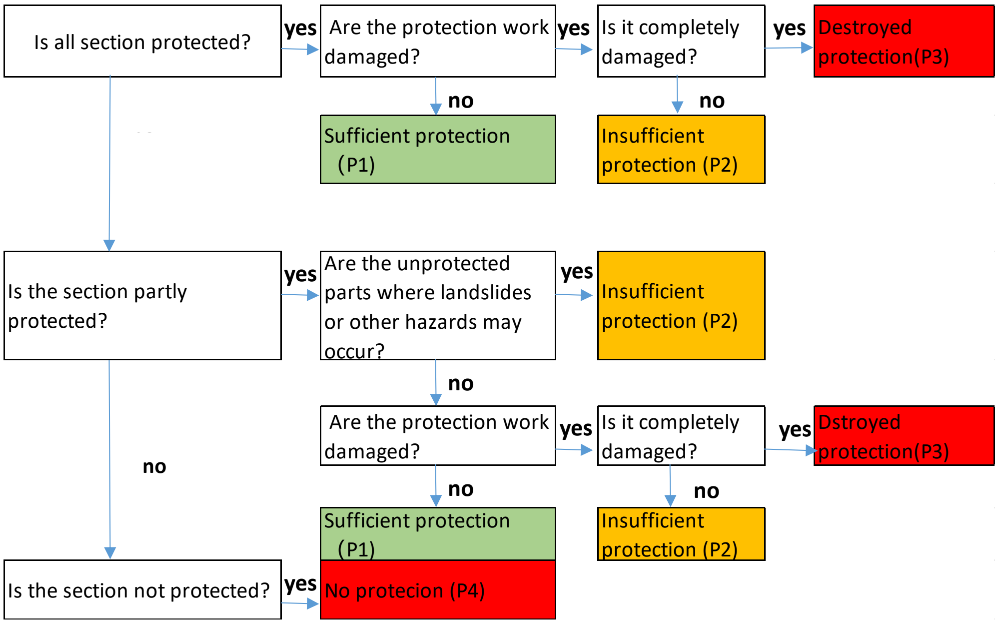


Figure 4.7 The protection efficiency decision tree.

4.3.2. The prioritization method

In order to determine the prioritization of the most multi-hazard prone sections along the roadways which need to take necessary mitigate measures or the mitigation works need to be repaired, the results from activity, favorable condition and the efficiency of protection work need to be combined together.

Table 4.6 The prioritization class

Activity	Favorable conditions	Efficiency of protection works	Prioritization class
Recent Activity	Yes	No/Destroyed protection	1
Recent Activity	Yes	Insufficient protection	2
Recent Activity	Yes	Sufficient protection	4
Recent Activity	No	No/Destroyed protection	2
Recent Activity	No	Insufficient protection	3
Recent Activity	No	Sufficient protection	4
Post 2008	Yes	No/Destroyed protection	1
Post 2008	Yes	Insufficient protection	2
Post 2008	Yes	Sufficient protection	4
Post 2008	No	No/Destroyed protection	3
Post 2008	No	Insufficient protection	3
Post 2008	No	Sufficient protection	4

2008	Yes	No/Destroyed protection	2
2008	Yes	Insufficient protection	3
2008	Yes	Sufficient protection	4
2008	No	No/Destroyed protection	4
2008	No	Insufficient protection	4
2008	No	Sufficient protection	4
No recent activity	Yes	No/Destroyed protection	3
No recent activity	Yes	Insufficient protection	3
Not recent activity	Yes	Sufficient protection	4
No recent activity	No	No/Destroyed protection	4
No recent activity	No	Insufficient protection	4
No recent activity	No	Sufficient protection	4

The prioritization classes have the following meaning:

1 = Highest priority, remedial works are required to be conducted or repaired in the section.

2 = Second highest priority, remedial works are required to be conducted or repaired in the section

3 = Urgent study needed to decide if mitigation works are needed.

4 = No need for mitigation works. Lowest priority.

4.3.3. The rapid evaluation questionnaire used to do prioritization

A qualitative multi-hazards evaluation questionnaire (Figure 4.8) was designed for the convenience of filling the available information in each section, then to derive the prioritization class. In this questionnaire, four types of natural hazards (rockfall, debris flow, landslide and embankment failure) are considered to do the prioritization.

Section No.	code of section	To which hazards could it be susceptible?	Are there evidences of past events? (Check from evidence sheet)	Are there protection works? Write the type	Evaluate the activity	Evaluate the favorable conditions	Evaluate the efficiency of the protection work	Prioritization class

Figure 4.8 The evaluation questionnaire

In the questionnaire, the users need to check all the sheets provided in the Excel file and fill the corresponding question codes in the questionnaire. Firstly, each section will be given a unique section number. Then a code is assigned based on attributes from below the road to above the road using the standard format. The next step is to find the evidence of past events in this section and write down the question codes in the questionnaire. Then the three decision trees are used to evaluate the activity, favourable condition and the efficiency of the protection work. Finally, the evaluation results were combined to determine the prioritization class.

5. RESULTS

This chapter contains two parts, illustrating the results for the application of the rapid evaluation method in the two study areas: the Duyun area and the Yingxiu area, respectively. Each part consists of 3 aspects: the subdivision of the roads into homogeneous sections, the hazard assessment for each road section, as well as the evaluation of the prioritization class for implementing mitigation works per homogenous section.

5.1. The application in Duyun area

In Duyun study area (Figure 3.4a), only one county road in the northeast part, which is circled by a yellow ellipsoid in Figure. 5.1, was selected to perform the qualitative method due to the limited time to do fieldwork.

To enter the available road information (both in the left and right sides of the road) into a geospatial dataset, a high resolution satellite image from Worldview 2, a relative coarse DEM with the resolution is 30m by 30m, a historical hazard record provided by State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP) as well as the video images collected during field work were used.

5.1.1. The result of homogenous road segmentation

The road which was surveyed in this study is around 3 kilometres long. Based on the six parameters used for road segmentation and the road information obtained during the field survey, the study roadway was subdivided into 20 homogenous sections (Figure 5.1).

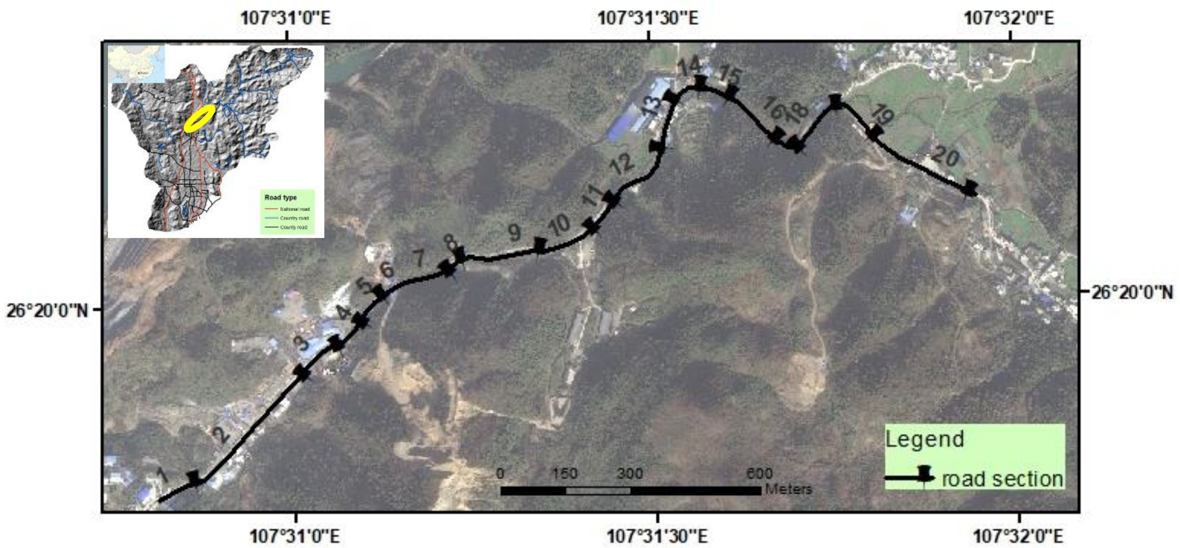


Figure 5.1 The result of homogenous road segmentation. Circled in yellow is the study road The numbers indicate the section numbers.

The length of these road sections ranges from tens of meters to hundreds of meters. The shortest section is around 35 meters while the longest one is 360 meters. As the road was digitized on a shapefile in ArcMap using the high-resolution(1m) image from Worldview 2 date in 2015 as a reference, the available information of each section was entered in the attribute table. Moreover, the detailed information of each road section incorporated with the evaluation results was shown in the Appendix 6..

5.1.2. The result of hazard assessment per section

The results of the evaluation of the hazard activity, the favourable conditions and the hazard class are described in this part.

The hazard type was determined before applying this rapid evaluation method in these 20 homogenous road section. To present the evaluation results of each road section on both sides, the buffer map along the road was digitized, that is to say, the buffer distance does not mean the average roadsides unit height. The definition of the left and right sides of the road follow the order from section 1 to 20.

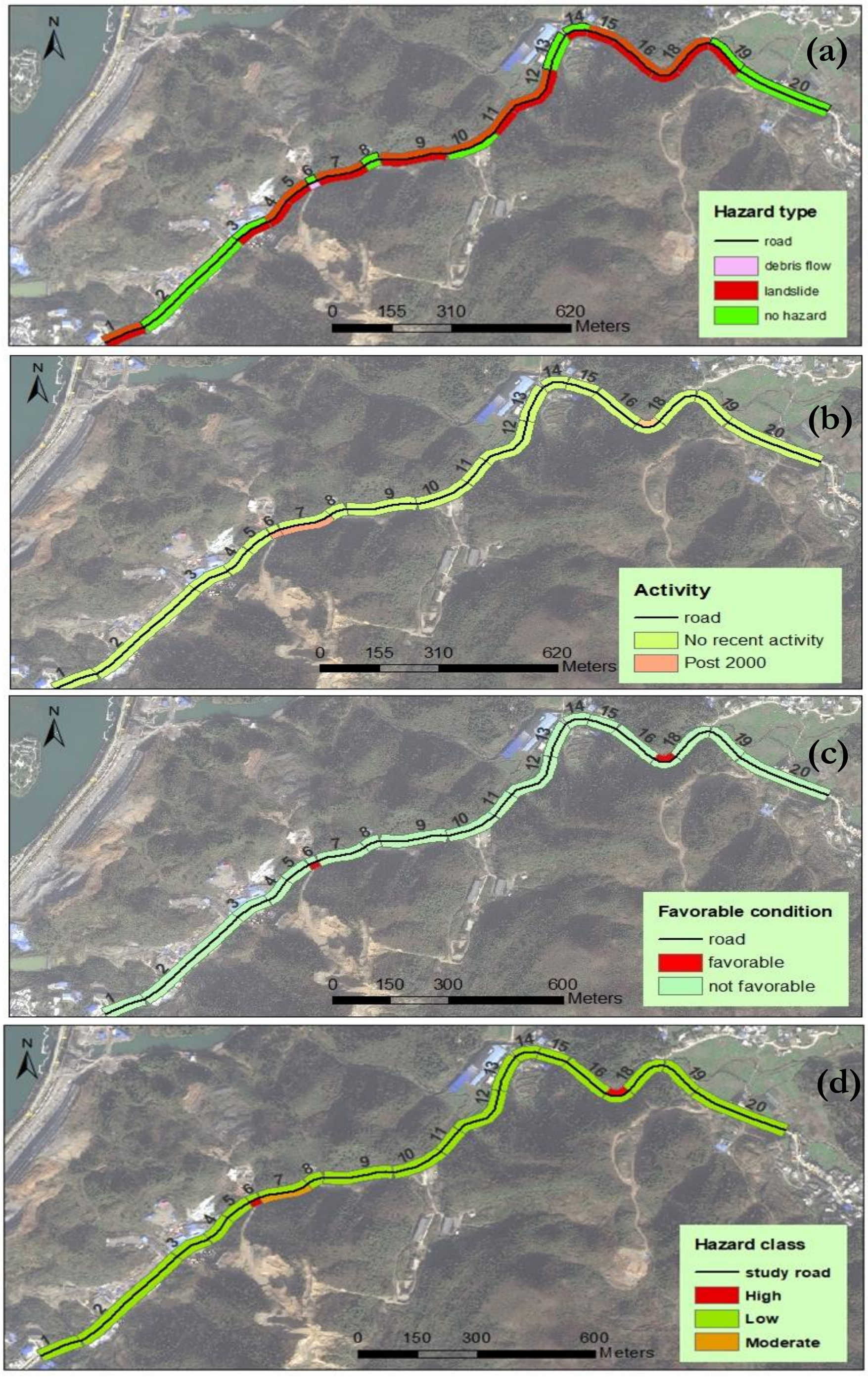


Figure 5.2 The result of hazard assessment per section. (a) The hazard type of each section on both sides (b) The evaluation results of hazard activity (c) The evaluation results of favourable conditions for producing hazard in each section (d) The hazard class of each section on both sides

Figure 5.2 (a) shows the possible hazard types may occur in each section on both sides. It is evident that landslide (in red color) is the most common hazard along this road while many road sections will not be threatened by natural hazards. Regarding debris flow (in purple color) hazard, only the right sides of section 6 is susceptible to it. However, there is no rockfall hazard along this road.

The hazard activity of each section is presented in Figure 5.2 (b). Based on the historical records and field observation, the rockfall activity on the right side of section 6, landslide activity on the right side of section 7 and the landslide activity on the left side of section 17 are determined as post-2000 activity while the rest sections are no recent activities.

Figure 5.2 (c) displays the determination of whether the condition is favourable for producing hazard per section. There is the favourable conditions for producing debris flow hazard in section 6 right side and the favourable conditions for producing landslide in section 17 left side. Figure 5.2 (d) shows the different hazard levels (high. Moderate and low) of the 20 road sections. The hazard classes in section 17 right side and section 6 left side are high and in section 7 right side) is moderate, the remainders are all in low level.

5.1.3. The result for the prioritization class for implementing mitigation works

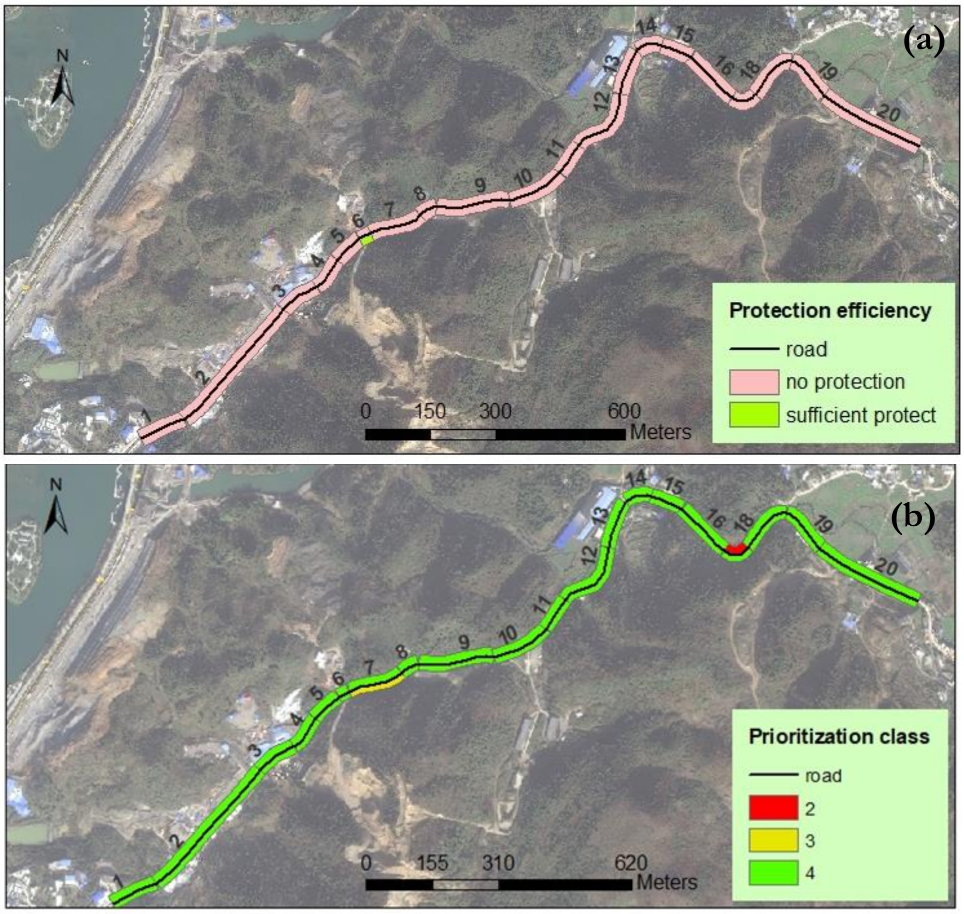


Figure 5.3 (a) shows the state of protection work along this road. A debris flow check dam was conducted on the right side of section 6, which also provides sufficient protection. Figure 5.3 (b) presents the final prioritisation class for each road section. It is evident that the prioritization class in most sections are 4, which means no need to implement mitigation work in these sections. But the prioritization class in section 7, the right side is 2, that is to say the detailed survey is needed to determine whether there is a

need to implement mitigation measures. As the prioritization class in the left side of section 17 is 2, it is suggesting that some mitigation measures should be implemented in the left part of this road section.

The evaluation questionnaire was used to record the detailed information for each section. The details of these 20 road sections are shown in Appendix 6.

5.2. The application in the Yingxiu area

Three roads (Figure 5.4) near Yingxiu Town were chosen to applicate the method.

5.2.1. The result of homogenous road segmentation

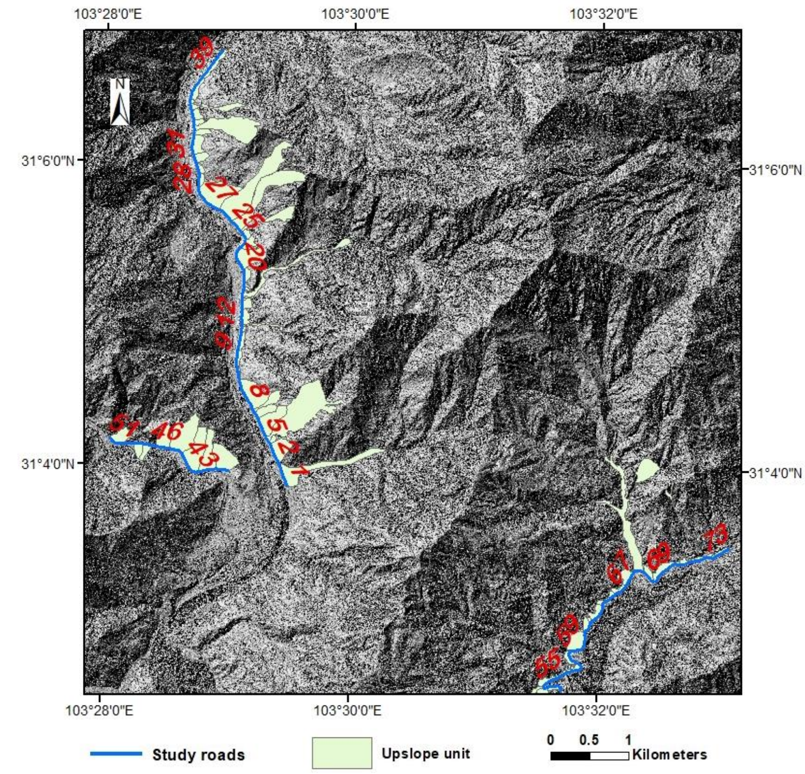


Figure 5.4 The result of homogenous road segmentation. Different numbers indicate different sections.

Three roads near Yingxiu Town were chosen to conduct the field survey: 2km of the old provincial road S303 from Yingxiu to Wolong before a long tunnel starts (the left road in Figure 5.4), 7km of the old national road G213 from Yingxiu to Wenchuan and 4.5km of the county road in Longchi Town (the right road in Figure 5.4). As seen in Figure 5.4, these three roads were subdivided into 73 different homogenous sections in total. Among them, the G213 sector was subdivided into 39 sections, S303 sector was subdivided into 12 sections, and the county road of 4.5 km was subdivided into 22 road sections. Compared with upslope parts, the downslope areas are small, as the roads were close to the river, only the upslope units were digitised. And all the available information, such as the code of each section, the length of each section, lithology, etc. was entered in the road shapefile attribute table in ArcMap. A part of road section attribute table was shown in Figure 5.5.

Figure 5.5 part of road section attribute table

Id	type	length	lithology	hazard_up	upslope angle	Activity_up	favora_up	protect_up
4	W-Nv000-R3-Nm00P7	67	Granite	landslide	41.28	P2008	not favorable	no protection
5	W-EsL400-R1-Ns000	245	Granite	landslide	41.21	2008	not favorable	no protection
6	W-EsL400-R1-Ns000	75	Granite	rockfall	40.85	2008	not favorable	sufficient
7	W-EsL400-R1-Gs000	60	Granite	debris flow	43.78	2008	not favorable	no protection
8	W-EsL400-R1-Ns000	409	Granite	landslide	41.51	P2008	not favorable	no protection
9	W-EsL400-R1-NsL10Ed	586	Graniteriver sand, fragments and clay	landslide	31.51	2008	not favorable	no protection
10	W-NvL500-R1-NsL100	66	Granite	rockfall	36.38	no recent activity	not favorable	no protection
11	W-NsL10Ed-R1-Gs0P70	43	Granite	debris flow	42.99	2008	not favorable	no protection
12	W-NsL400-R1-NsL100	201	Granite	landslide	30.45	no recent activity	not favorable	no protection
13	W-NsL400-R1-Ns000	110	Granite	rockfall	44.41	2008	not favorable	no protection
14	W-Nm000-R-Cv000-NmL500	23	Granite	rockfall	44.73	2008	not favorable	no protection
15	W-EsL400-R3-Gs000	140	Granite	debris flow	29.31	P2008	favorable	sufficient
16	W-C(V)-R-E(V)-R-C(V)-N(M)	19	Granite	landslide	44.19	2008	not favorable	no protection

5.2.2. The result of hazard assessment per section of the three roads

Figure 5.6 shows the possible hazard types that may occur in each section on the upslope and downslope sides. For upslope parts, three types of hazards (rockfall, debris flow and landslide) were taken into consideration while for downslope parts, only landslide and embankment failure were taken into consideration. Because the downslopes are very small and close to the river, there is no judgment on the potential downslope potential hazard types along the county road in Longchi Town. From this figure, landslide is the most common hazard type in the road sections upslope parts.

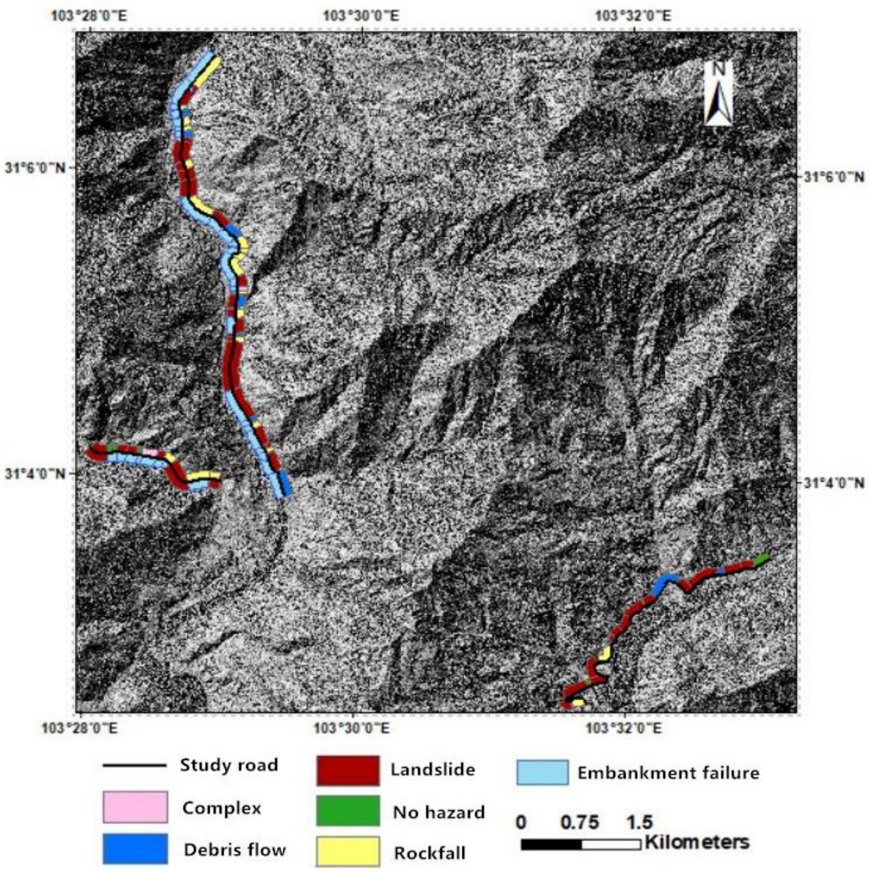


Figure 5.6 Hazard type that may occur in each section

To show the results clearly, the evaluation results of each road were displayed separately.

- **S303 and G213 roads**

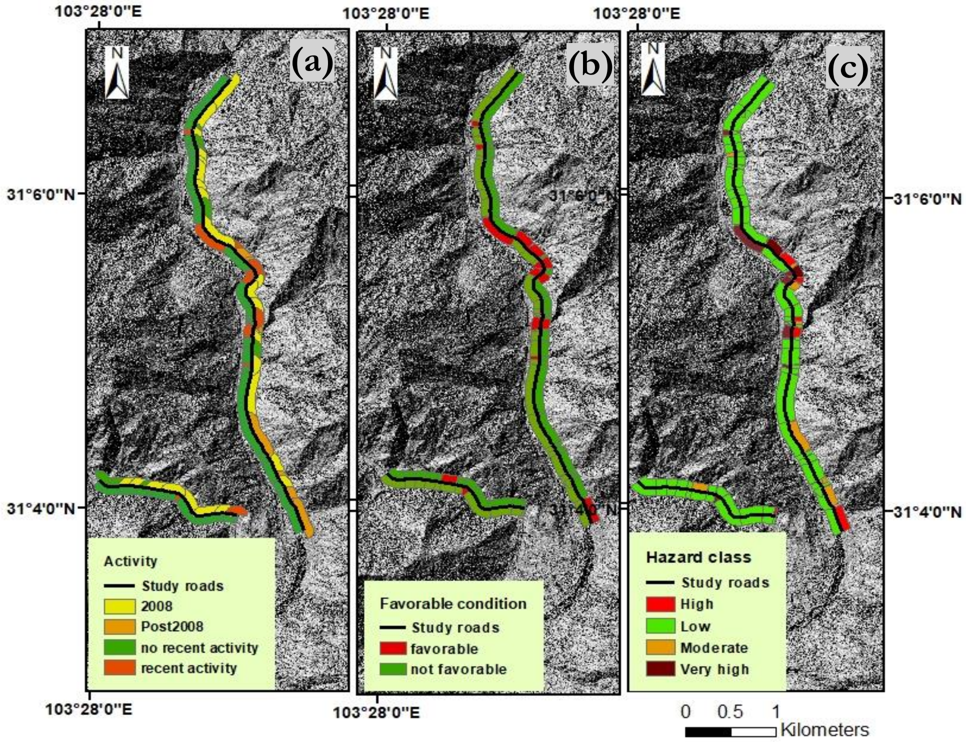


Figure 5.7 The results of applying the hazard assessment method in the S303 and G213 roads (a) different hazard activity (b) the favourable condition for the formation of hazards along roads(c) different level of hazards of each section.

Figure 5.7 (a) shows the hazard activity of each section along the S303 and G213 roads. Four classes are used to express the hazard activity, as mentioned before. It is obvious that the hazard activities are "last activity in 2008" in the upslope parts of most road sections. As only landslide and embankment failure are taken into consideration for downslopes, most downslope parts of road sections are in "no recent activity" class. Figure 5.2 (b) displays the determination of whether the conditions are favourable for producing hazards per road section. The conditions in several sections are favourable but in the majority of road sections not favourable for producing hazard. Figure 5.2 (c) shows the different levels of hazards (very high, high. moderate and low) of these road sections. Although the hazard class in most sections are in the "low" class, for the upslope parts of this road, three sections are in the "high" hazard classes; 5 sections are in the "moderate" hazard classes while the rest are in the "low" hazard class. For down slopes, eight sections are in the "high" hazard level, and only one is in the "moderate" level.

5.2.3. The county road in Longchi Town

The result of applying the rapid hazard assessment method in the county road in Longchi Town are displayed in Figure 5.8. The activity class in two section are in the "post-2008 activity" class which was coloured in orange. Only one section has a favourable condition for producing landslide, and only one section is in the "high" hazard level which was coloured in red.

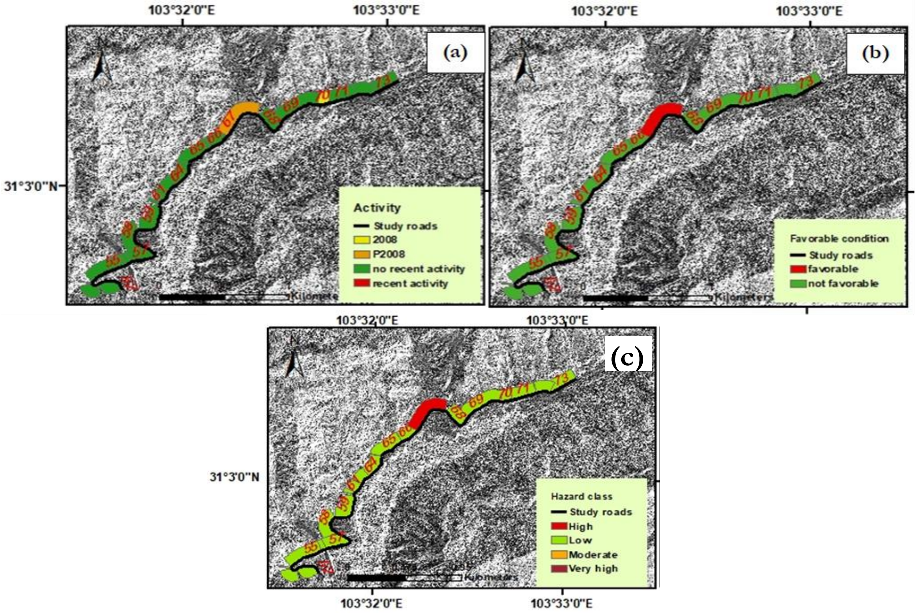


Figure 5.8 The results of applying the hazard assessment method in the county road of Longchi (a) hazard activity (b) the favourable condition for the formation of hazards along roads(c) different level of hazards of each section.

5.2.4. The result for the prioritization class for implementing mitigation works

- **S303 and G213 roads**

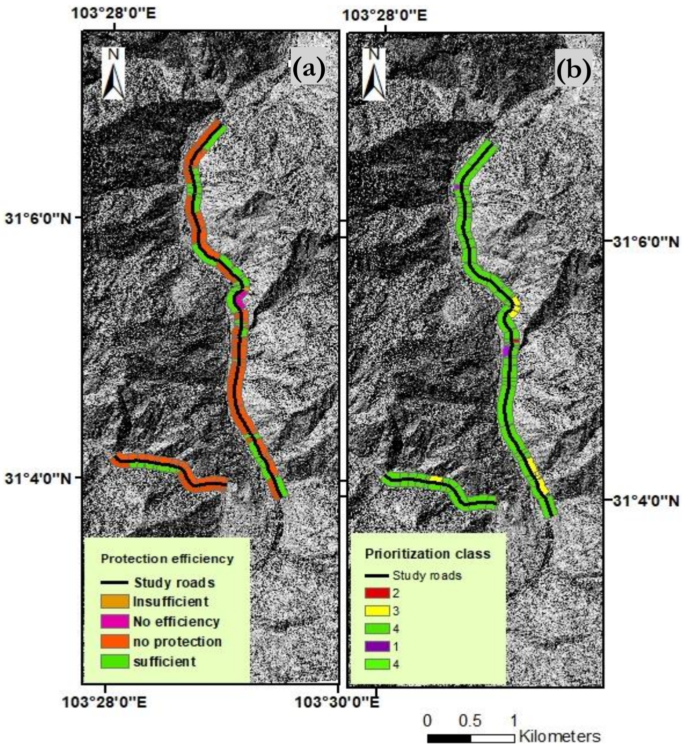


Figure 5.9 The prioritization results (a) The state of protection work in each section (b) The prioritization class of each section

Figure 5.9 shows the prioritisation results. Taking protection work status into consideration, Along the G213 road, for downslopes, two sections are in the top 1 prioritisation class hence they need urgent mitigation works, and the rest are in relatively safe condition. For up slopes, one section is in top 2 class, and two sections are in top 3 prioritisation class. Along the old S303 road, only one section upside is in moderate hazard class with the prioritization class 3.

- **The county road in Longchi Town**

From Figure 5.10, it can be seen that, there are few places where mitigation works were conducted among the 22 road sections. However, only one section is in prioritization class 2, which means some remedial work needs to be conducted in the upslope part of this section.

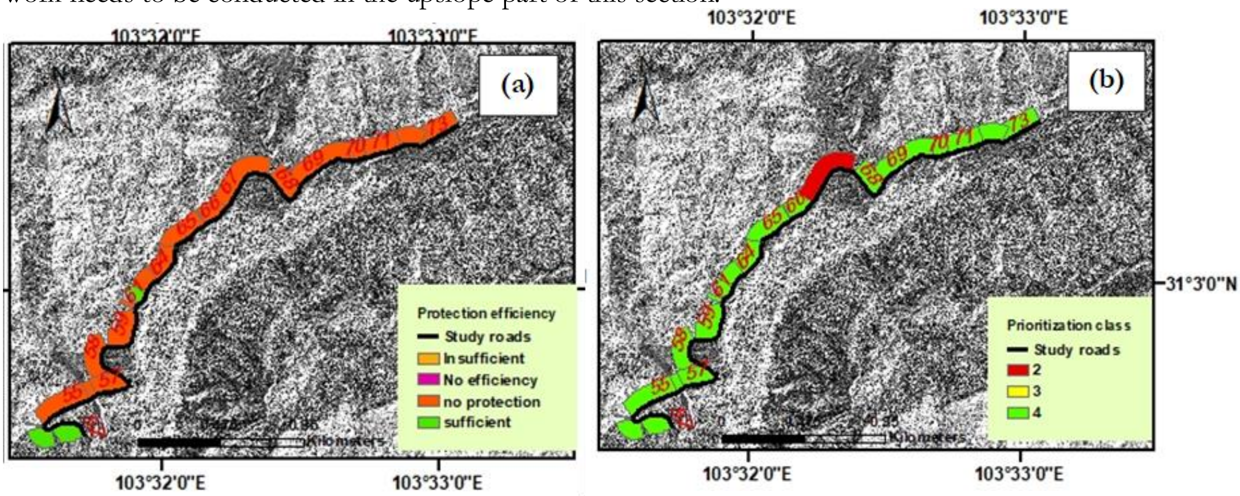


Figure 5.10 The prioritization results (a) The state of protection work of each section (b) The prioritization class of

6. TESTING OF THE METHOD

To check the efficiency of this method, it was tested in the field and in the office by different people with different background.

6.1. Testing initial method in the field

The initial rapid evaluation method was not yet fully developed during the field period, and only a brief introduction of it is presented in this chapter. Therefore, the testing the method in the field at the local level was difficult, and since the method was changed considerably during and after the fieldwork, it is difficult to draw conclusions on the results of the field-based comparison study.

6.1.1. The initial rapid evaluation method

Six initial parameters (types of slopes, topographic characteristics, materials, landuse, protection work types, hazard types) were used to subdivide the roads in study area into homogenous sections. We made road section breaks where there was a variation in these parameters.

And an initial qualitative multi-hazards evaluation questionnaire (Table 6.1) was designed before and during the fieldwork. In this questionnaire, five types of natural hazards (rockfall, debris flow, fast-moving landslide, slow-moving landslide and river undercutting) were considered with different classes (*low, moderate and high*) used to assess the hazard level. This hazard assessment method which is in the form of questionnaire provided a lot of help for the later improvement of the method.

Table 6.1 The initial qualitative multi-hazards evaluation questionnaire

Basic information			What are possible hazards?	Evidence	Protction	Contributing factors(favorable conditions)			Activity	Check the class from hazard sheet				
Segment Code	Profile	What type of section is it?	To which hazards could it be susceptible?	Are there evidences of past events? Explain evidence	Are there protection works? Write codes for Type and State? (code)	Important Topographic factors (Codes)	Important material factors (Codes)	Important landuse & drainage factors (Codes)	Activity (codes)	Suscepti-bility class	Mitigati-on class	Frequen-cy class	Volume class	Hazard class

A list of questions regarding contribution factors (favourable conditions), activity, and the definition of the susceptibility class, mitigation class, frequency class, volume class and hazard matrix were provided in an Excel file to the users. Using the questionnaire, the users needed to check all the provided decision trees in the printed Excel sheets and fill the corresponding question codes or answers in the questionnaire. As explained earlier, a unique code was given to each segment, and a sketch of the road cross section was drawn in the profile column, to show the topographic characteristics in this section. Then based on the testers' field observations of the evidence of past events or according to the landslide inventories to judge which hazards this section could be susceptible. Users also had to check the types of protection works in the decision tree for protection work efficiency. Then they answered all the questions related to the favourable condition of a specific hazard, if the answer to the questions is yes, write down the corresponding question codes in the questionnaire. The hazard activity estimation was also carried out using the "activity decision tree", by answering the questions to judge it. Finally, considering the state of mitigation (no protection, destroyed protection, etc.,), the frequency category, volume class and hazard class, the classification of prioritization was made.

6.1.2. Testing in the field

To find a good way to conducted the field test, students from Chengdu University of Technology (CDUT) and MSc students and teachers from ITC participated in the discussion. As the method used to assess hazard is highly based on field observation, it does not need too much preparatory office work. After showing the workflow of the method, and explaining how to read the criteria sheets and fill out the evaluation questionnaire, a test was carried out that took one day. Ten students (six students from CDUT, two MSc students and one PhD from ITC) and one teacher from ITC carried out the test. Everyone did the test separately, without discussion among participants. The method was tested in a part of the G213 road from Yingxiu town to Wenchuan with a length of 1.5 kilometres.

- **Homogenous road segmentation**

Before going to the field, testers did the first segmentation using the standard way which was only based on Google Earth, as Google Street View is not available in China. They identified the different initial input parameters based on the printed Google Earth images from 2017. Because these parameters are basically covered all the obviously visually physical features of the slopes along roadsides in this study area, the testers made almost the same initial segmentation. However, some real detailed situation could not be revealed in the Google Earth images, like some mitigation measures which were covered by vegetated or shadows on the slope surface. So when they were in the field, they made some modification on the initial segmentation.

When checking the initial segmentation in the field, it was hard to see the situation of the top part of the slope as the slopes in Yingxiu area are very steep and high. It was found that the combination of satellite imagery and field observations is essential so that testers can view the upper situation of the slopes from satellite imagery.

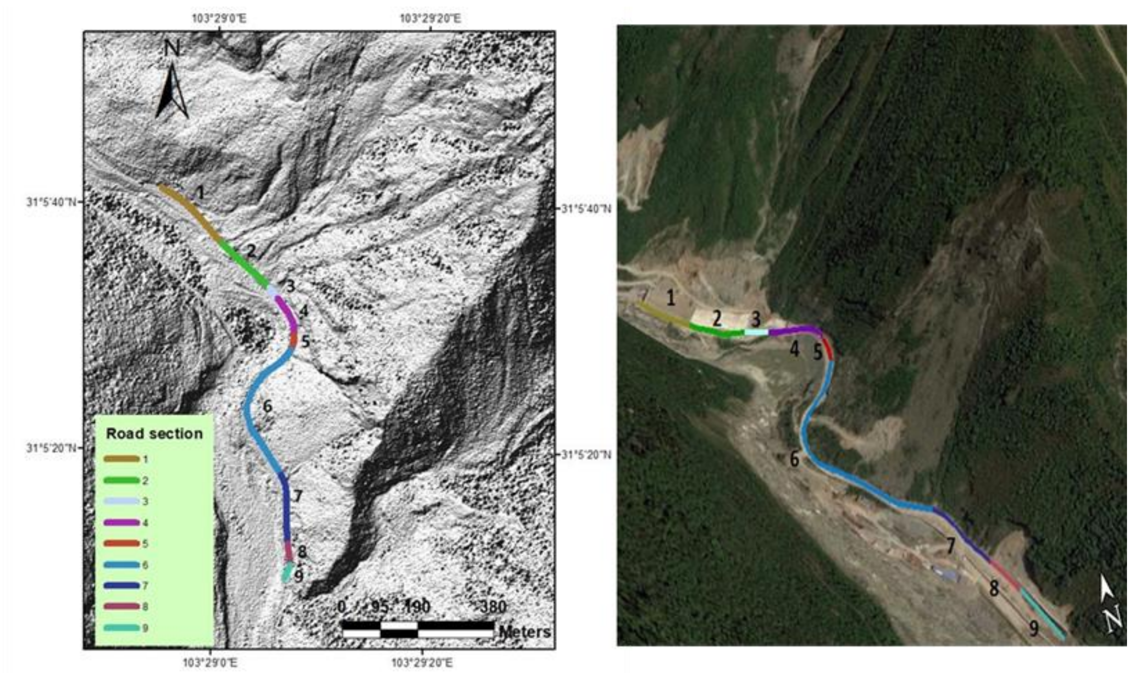


Figure 6.1 Final segmentation result shows in (a)the hillshade map derived from DEM thru 1m spatial resolution and (b)Google earth image dated in 2017.

The final results of segmentation by the testers is presented in Figure 6.1. It shows that the first five road sections, section 7, 8 and 9 are the same for all participants. However, there are some different segmentations in the area of section 6, which is a very large rock fall deposit triggered during the Wenchuan earthquake, and which dammed the main river for some time. Three among the eleven testers divided section 6 into two parts, as lots of rock fall deposits were on the side of the road (Figure 6.2) while the other part only deposits some small rock blocks.

Figure 6.2 Rockfall deposits in section 6.

In order to eliminate the different results of hazard evaluation due to the different results of road segmentation, testers were given the same road segmentation to do the landslide hazard assessment for these fixed sections:

- **Case example result**

A qualitative multi-hazard rapid evaluation method was prepared during the field work. Users needed to fill in the questionnaire, we use a field case example to illustrate the usage of the method

Case example 1: hazard assessment in Section 4 in the field

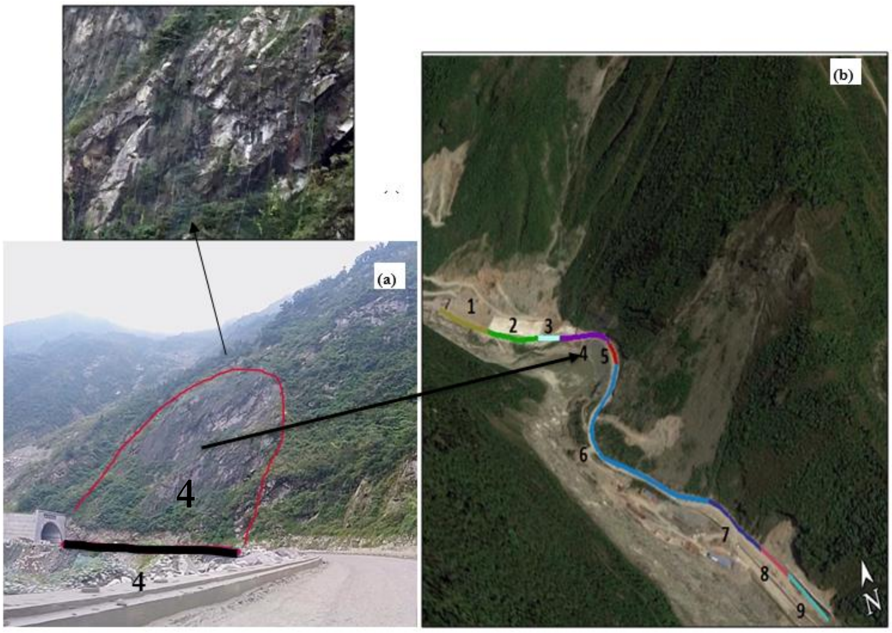


Figure 6.3 (a) Video image taken from field in October 2017 (b) Google Earth image dated 2017

The identifier of this section was 20171018-4. Figure6.3 shows the condition of the section 4. A sketch of the physical characteristics of this road cross section was drawn in the profile column (See Table 6.2). According to the provided legend, the participants used different codes to represent the physical conditions along the cross section from bottom to top. As there was no standard code format provided, participants' codes sometimes different from the code that we considered correct: W-E(S)-R-C(V)-N(S). This means that section is composed of the river below (W), a steep embankment E(S), then the road, and upslope it starts with near vertical cut slopes (C(V)) followed by a steep natural slopes (N(S)).

Table 6.2 the evaluation result recorded in the questionnaire

Basic information			What are possible hazards?	Evidence	Protction	Contributing factors(favorable conditions)			Activity	Check the class from hazard sheet				
Segment Code	Profile	What type of section is it?	To which hazards could it be susceptible?	Are there evidences of past events? Explain evidence	Are there protection works? Write codes for Type and State? (code)	Important Topographic factors (Codes)	Important material factors (Codes)	Important landuse & drainage factors (Codes)	Activity (codes)	Suscepti-bility class	Mitigati-on class	Frequen-cy class	Volume class	Hazard class
2017101 18-4		W-E(S)-R-C(V)-N(S)	Rock fall	ER1,ER3	PR1	RT1,RT2, RT3,RT4	RM1	NO	FR2	HIGH	OK	HIGH	MOD	HIGH
			River undercutting	ER1	PW1	WT1	WM1	NO	FW4	MOD	OK	HIGH	LOW	MOD

Because bare rock is exposed, some rockfall blocks can be seen next to the road and towards river below, the possible hazards are "rock fall" from upslope and "river undercutting". Then based on field observation, the participants checked the questions in the decision trees for historical, evidences, protection works, contributing factors and activity sheets, and they only wrote down the question codes when the answer to the questions was yes. Considering the susceptibility, the state of mitigation, frequency category, volume class and hazard were determined at last. Actually, in the final part, the judgements of susceptible class, the efficiency of mitigation work, volume class and hazard class are more subjective. The result of the assessment is shown in Table 6.2.

- Overall results of the field testing

As the aim of this method was to provide a simple, direct and rapid evaluation method, and the initial method required the estimation of landslide volume, and the judgement of activity was based on the existing evidence of past events. It was found that it was very difficult to estimate the landslide volume if there is no clear observed features. Moreover, estimating the magnitude of the landslide is still difficult (van Westen et al., 2006), this is because unlike another natural hazard such as floods and earthquake, which are controlled by rainfall and ground motion respectively, landslides lack spatially continuous measurable intensity parameters(Das et al., 2011).

Although the method could work in the field test, there were many different results among the evaluation of hazard volume by the testers which also resulted in the different results in the final hazard assessment. For these reasons, the final hazard map reveals the results only for the evaluation which were common for many people in the test (Figure6.4). Among these nine sections, two sections (upslope parts) are in high hazard class (most dangerous). One is susceptible to debris flow (section 2), the other is susceptible to rockfall (section 4). Section 1 and five both are in moderate hazard class; the rest are in low hazard class.

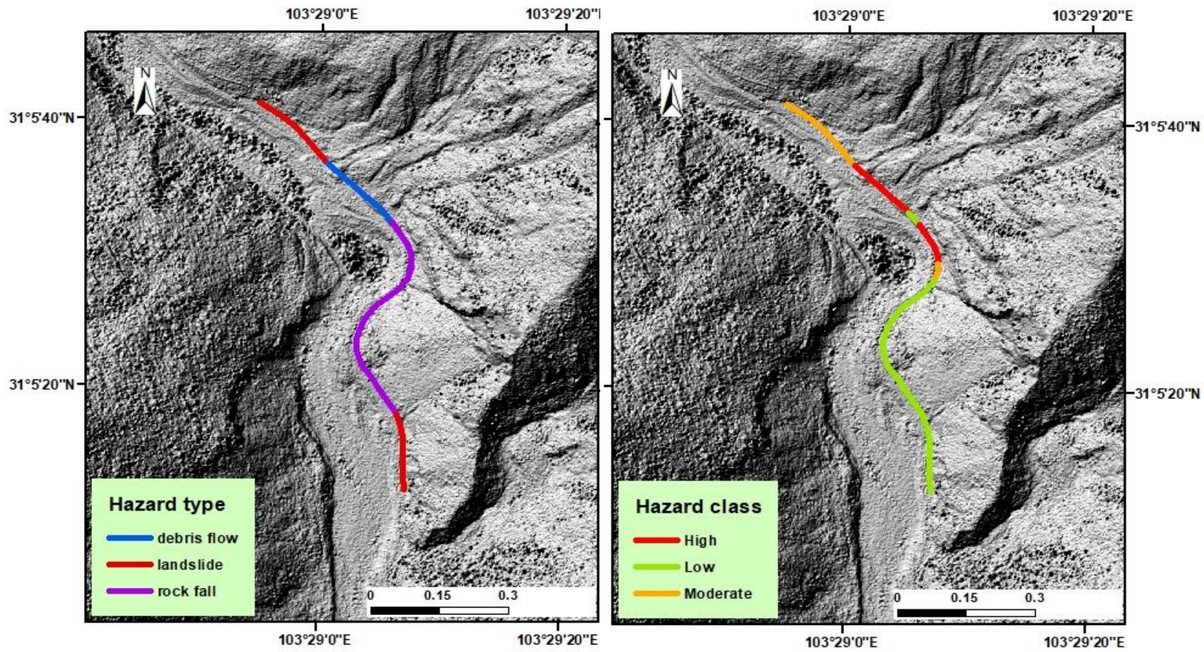


Figure 6.4 The test results (a)the type of hazard that may occur in the road section (b)hazard class for each section

6.1.3. Problems in the initial method testing

During the field testing, we realized that the initial types of parameters used in road segmentation are quite general, as there is a lack of the detailed items listed behind the general categories to guide people to subdivide the road. The drawing of the road cross-sectional profiles and coding the road sections, was actually quite similar among the different testers, although differences in detail occurred dependent on how much they want to show in the profiles. However, the criteria used to determine whether the conditions are favourable were not combined using a decision tree in the initial method. Instead, testers were asked to write down the code number of favourable conditions, but how many factors were used to determine the favourable condition was not mentioned. Moreover, if the area had no historical data and no obvious unstable part exposed, it was very difficult to estimate the volume of the landslide only based on field observation. If there is no evidence of the past events, it is also difficult to judge the hazard frequency. Also the efficiency of the protection work was not evaluated, and participants only wrote down the state of the protection work in the questionnaire.

6.2. Testing the method in the office

In order to evaluate the efficiency of the improved method, it was tested by 13 researchers (2 teachers and 11 MSc students with different backgrounds from ITC) in the office during a course on empirical modelling. In this test, testers only used Google earth, the dash-board camera video taken from field work as well as the application named Mapillary which provide 3D street-level images of the road in the study area.

6.2.1. Homogenous road segmentation

A 600-meter-long road located in G213 road in the Yingxiu study area was selected as the test road. The start and end points of the test road were marked on the Google Earth image. Based on the introduction of the improved method and the explanation of the workflow of the decision tree method, testers knew how to use this method, then made the road segmentation in Google Earth.

Figure 6.5 shows the test results of the homogenous road segmentation. The results are only shown for the segments which were common for many people in the test. As shown in the figure most of the participants made similar segmentations since most of them made 7 or 8 sections.

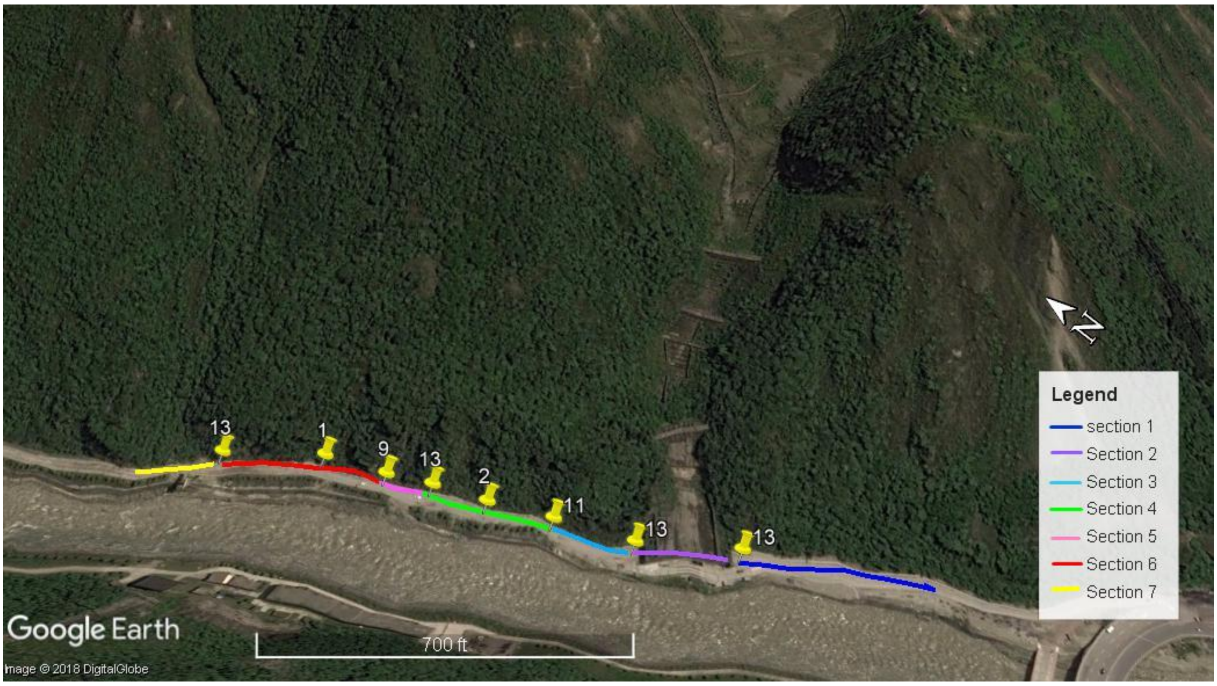


Figure 6.5 The test result of homogenous road segmentation. The numbers indicate number of people who made that segment during the test while different colours line indicate different homogenous sections.

However, there were some differences in sections 4 and 6. In the middle section 4, two participants drew boundaries here. The reason why they drew boundaries there came from that they saw a very small area of bare land (approximate 0.75m²) while the surroundings are vegetated lands, by checking the field video carefully. And the other testers thought that the bareland is too small to be identified from Google Earth and the UAV based image. Such details only can be identified from the careful checking of the videos or 3D street-level images. Hence, most participants ignored this parameter in section 4. And in section 6, only one tester drew the boundary in the middle part. As the tester thought that there are two slopes in this section, he wanted to separate the two slopes. However, these two slopes are natural slopes and have similar characteristics according to the input parameters from Table 4.1. Therefore, these slope are classified as one homogeneous unit, this was done by most of the testers where they did not draw the boundaries in the middle of section 6.

The results signify that the parameters which were used in segmentation are clear hence the participants were able to come to the same conclusions.

6.2.2. Case examples results

Although landslide inventories are available in this area, as this method aims to be used in areas where no sufficient historical data is available, hence in this test, landslide inventories were not provided. The method was tested in three specified road sections. The first section was carried out with the whole group to give them an example on how to do use this method. The other two sections were carried individually by each tester. These two case examples are presented below.

Case example 1:

Location: A part of the G213 road in Yinxiuzhen, Sichuan Province, China

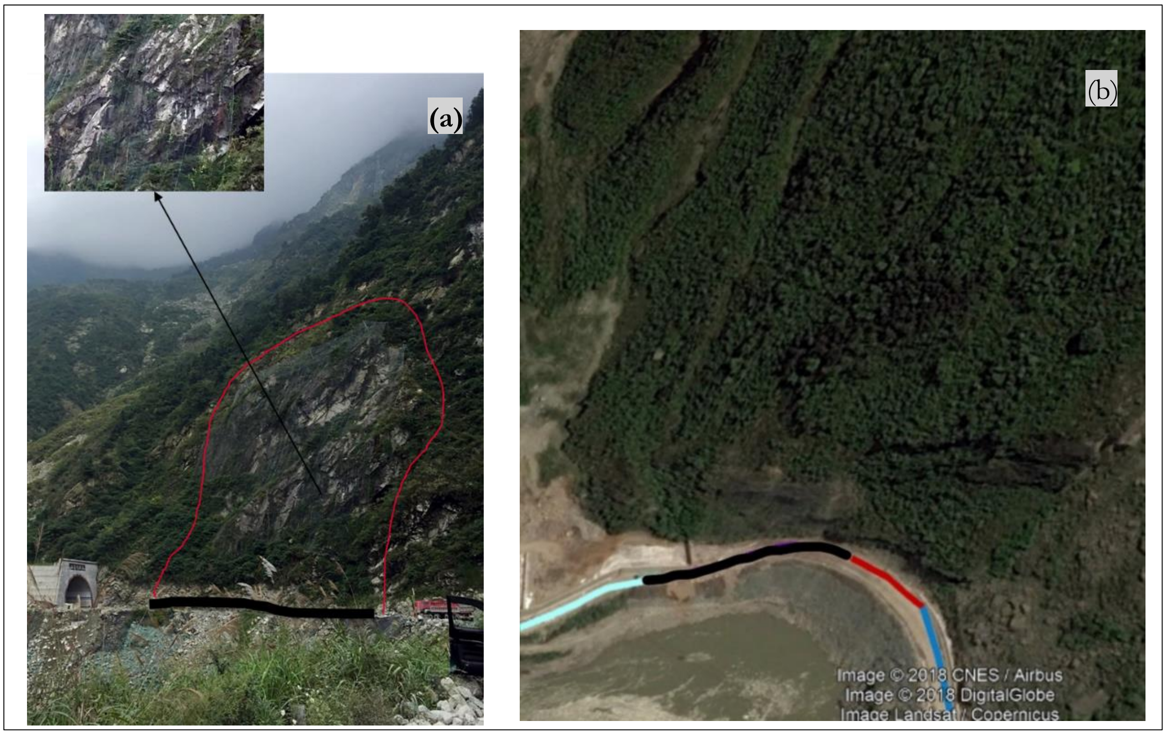


Figure 6.6 (a) photo was taken in October 2017 shows the condition of the test section (b) the image from Google Earth shows the test location(black line)

The evaluation questionnaires (Figure4.8) were provided to tester to fill the resluts. Based on the video and photos (Figure6.6) taken from the field, along the cross section starting from below the road, the testers identified the input parameters for homogenous road segementation in this section. In this road section there is a river (w), a nearly vertical embankment(Ev), the road (R1), and the upslope which is divided into two parts, one is a cut slope (Cv) with rock fall nets (P1) constructed on the surface, the other is a steep natural slope(Ns). According to the code table, using the standard format, the proposed code of this section is W-EvL400-R1-CvL4P1Er-NsL500. Although the standard coding format was given to the testers, not all of them gave the same coding of the road section. Among 13 testers, two testers gave the same road code (W-EvL400-R1-CvL4P1Er), however, they are not the same as the proposed code mentioned before. Only one tester gave the same code as the proposed code, this was given by a tester that was part of the expert group. The rest of the testers had different codes for this road section. The differences from coding may be because the standard coding format is too complicated or because the testers did not understand the method completely. All the testers considered this section is susceptible to rockfall, as they identified some rockfall evidences as well as the rockfall nets were located on the slope surface. Nine testers have identified the rockfall evidence (ER4. scars of past events in the rock face) while the others have written the either ER1(small rock block on the road) or ER4 in the fourth column of the evaluation questionnaire. This could be due to the experience of the testers, where some may not have enough experience to identify scars from past events, but still can see evidence of rockfall from the blocks on the road which are easier to identify.

However, using activity decision tree to evaluate the rockfall activity, six people thought there was no recent activity, six testers thought it was the recent activity and the one thought the last activity was in 2008. These different evaluations may come from the criteria in which the tester considers it a recent activity or not, for example is the test only sees one block along the road in the photographs some may say there is recent rockfall activity while others may say you need to have larger volume of rock to be considered a recent activity. Another cause may be the lack of sufficient historical data and user are not able to really estimate the rockfall activity in the area. Without sufficient historical data and clear evidences to show the recent events, it is difficult to get a right evaluation of the hazard activity. But based on the favourable condition decision tree, all the testers thought this section is favourable for producing rockfall. Using the protection efficiency to judge the efficiency of protection, six participants thought the rock nets provide sufficient protection while the rest seven thought it provide insufficient protection. The criteria use to judge the efficiency of the protection work is highly subjective, since it depends on the users experience to be able to evaluate if there is sufficient protection or not. Based on the results from the activity, favourable conditions and the efficiency of the protection works, the testers gave the prioritization class, but not all of them gave the same prioritization class. Most testers (6/13) thought the prioritization class was 4 in this section which is the lowest prioritization class, that is to say, no need for mitigation works. The rest of the testers gave a prioritization class of 2, which mean that urgent study needed to decide if mitigation works are needed.

Case example 2:

Location: A part of the G213 road in Yinxiuzhen, Sichuan Province, China

Figure 6.7 (a) Satellite image from Google Earth® on 1/5/2017 (circled in red is the a concrete wall, but it does not make part of the section that is being analysied)(b) Dashboard camera image was collected in October 2017 during the field work.

This example was done exactly the same way as example 1, but in another section of the road. Figure 6.7 shows the photo of this road section.Viewing from the bottom to the top, in this section, there is a river (w), a nearly vertical embankment (Ev) with the concrete wall (P4) constructed on its surface, the road (R1), and the upslope which are divided into two parts, one is the cut slope (Cv) with some rock deposits (Er), the higher part is the steep natural slope(Ns) with forest covered (L5). According to the code table, using the standard format, the proposed code of this section is W-EvP40-R1-CvL4 OEr-NvL500. The code shows the cross-sectional features of this road section. However, no testers gave the same code as proposed one.

Obviously, rocks and debris deposits were observed in this section. Eight testers thought it is susceptible to rockfall in this section, three testers thought it is susceptible to landslide and a tester could not judge it is susceptible to rockfall or landslide. But all testers observed that the road was affected by a hazards, however, due to the material of the deposit it is difficult to identify it is a rockfall or a landslide since there is a mixture of block and debris. Actually, no protection works were implemented in this section. Four testers filled the P4 (concrete wall) in the evaluation questionnaire. It could be that they determine this based on the proximity of a concrete wall that is not in the area the area that is being analysed (Red cicle, on Figure 6.7). All the testers thought the hazard activity class is the recent activity and it is in the favourable conditions. Most participants (7/13) considered the prioritization class is 1, that is to say, remedial measures are needed to be conducted urgently. And one tester could not determine whether it is in 1 class or 2. This difference between prioritization class 1 and 2 could be just because the testers are only looking at a single section, but if they had more sections they could give different priority values based on what they observe on the other sections. The rest gave a prioritization value of 3, which mean they need additional information to judge the prioritization.

In conclusion, from the test results, the different evaluation result may come from the follow reasons:

- Insufficient information provided. Only using video or images rather than going to the field, it not easy to know the real condition of the road.
- Lack of basic knowledge of hazards identification. Some participants lack of the basic knowledge, for example, a tester may not know what is bare land, or how to identify scars.
- Differences in subjective judgment. Such as the visual interpretation, for hazard identification.
- Also for the evaluation the efficiency of the protection works, this highly depends on the experience of the tester. Unexperienced users may overestimate or underestimate easily the efficiency of this protection works.

6.3. Discussion

In this study, a simple, rapid and reproducible method to assess natural hazards along roads was developed for areas in which sufficient historical data or thematic data is not available. Observations from the testing results and the application of this method in two study areas, the strong points and the limitations are discussed below.

The first part of the method is the segmentation of the road network into homogeneous sections. For this part, the subdivision is based on six parameters (evidence of past events, terrain parameters, landuse, remedial works type, road infrastructure type and hydrological characteristics), which are selected because they can be observed in the field or imagery. Although there are many other influencing factors (e.g. soil geotechnical properties) that are very important to determine the subdivision of the road sections, it is impossible to take all of them into consideration. For example, the drainage pattern is a very important parameter, but is difficult to determine it in the field because of the vegetation cover, which masks many topographic and hydrographic features, so it was not chosen as an input parameter to make road segmentation. Slope form which shows the land forming processes (erosion and transport on slopes), can be visually observed and is important to make the road segmentation. However, it was not taken into account, because it requires many experience of the person doing the evaluation to make a geomorphological evaluation. Another issue encountered is that here are problems with the scale of the road sections and the definition of the boundaries between homogenous sections. The problem with the scale could also be seen in the office test where two of the testers created another homogenous road section based on the presence of a small are of bare land while the other testers thought it was to small tobe considered a parameter for a homogenous road section. Also it was difficult to judge the possible size of landslides or other hazards. For example, how to determine that a hazard is large enough to be taken into account for the homogenous road section. Choosing these parameters in segmentation is subjective, but after testing the segmentation method by other people, most of them could get similar results.

Two decision tree methods were developed to qualitatively evaluate the hazard activity and the favourable conditions for the hazard. For the activity decision tree, the determination is largely dependent on the observations of the evidence of past events in the field or check of historical events from the multi-temporal images in Google Earth (in the absence of historical inventories). However, if there are no past evidences observed in the road section, it is hard to determine the activity class. And the activity decision tree is not a universal applicable method and needs to be modified when applying it in different areas, as demonstrated for the Yingxiu and Duyun areas. For the favourable condition decision tree, four major potential factors are taken into consideration: topography, slope materials, landuse and drainage factors. Before going to the field, a lot of relevant questions regarding the four factors were listed in an Excel sheet to choose the most relevant questions for developing the decision tree. During the field, testers answered the questions based on what they saw and filled the question codes in the questionnaire. Through the test, it is found that the decision tree method is easy to understand, and based on it, the tester can get the results immediately. And according to the test results, the most relevant questions were put into decision tree and organised in a systematic way.

However, this hazard assessment method describes the hazard in a qualitative way without analysing hazaed intensity. Since analysing hazard intensity is always a major challenge. Unlike floods, earthquakes and other hazards with continuous monitoring, landslides lack a spatial continuous magnitude measurement parameter. Moreover, the landslide volume and velocity are very difficult to estimate in large areas. To simplify the procedure, a hazard matrix method was used to determine the hazard class in this study based on the results from activity and favourable condition decision trees.

This method was tested during the field work and in the office by students and teacher with a different background. After explaining the workflow, most of them expressed that they could understand how to use this method. Since this research aims to develop a rapid and simple method to assess hazard, to keep it simple and easy to use, some procedures were simplified. However, when this method was applied in the Duyun city and the Yingxiu area, according to the evaluation results, it was shown that this method can work and provide some suggestions for prioritizing conducting mitigation measures along roads. But some improvements need to be done in the future, like having access to better quality data to answer more question in the questionnaire, incorporating more influencing factors in the decision tree method and developing semi-automatic or automatic road segmentation procedures.

7. CONCLUSIONS AND RECOMMENDATIONS

This chapter contains two parts: the conclusions of this study as well as some recommendations for future research.

7.1. Conclusions

In this study, the main objective was the development of a method for qualitative assessment of multi-hazard (rock fall, landslide, debris flow and embankment failure) along roadways for areas where there are no sufficient historical events records or detailed thematic data (e.g. geological or lithology map).

The first specific objective of this research was to subdivide roadways into homogenous sections based on the certain features of roads and slopes along the roads. Associated to this sub-objective, the research questions were which attributes and factors can be used to subdivide the road sections into homogenous sections, what the length of homogeneous sections should be and which spatial data can be used for the generation of homogeneous units? In this study, six input parameters were used to identify homogenous road sections, that is, evidence of past events, terrain parameters, landuse, remedial works, road infrastructure types and hydrological characteristics. Regarding the scale level, there is no specific optimal length of sections; it could be several meters or tens of meters, which depends on the variation of factors. If one of the factors changes, the advice is to make a new homogeneous section. The spatial data derived from UAV (e.g. the UAV-based DSM), satellite images, Google Street View and dashboard cameras' images can be used to identify the parameters for the generation of homogenous units. However, in this study, a manual road segmentation method was developed. As the method is subjective, and based on the experience, skill and commitment of the person doing the segmentation, it would therefore be good if the method could be further automated. Some suggestions of the automatic procedures were illustrated later in the recommendation part.

The second specific objective was to develop a simple and rapid hazard assessment method to characterize the hazard per road section. Associated to this sub-objective, the first research question is how to estimate the landslides activities without sufficient historical data? The determination of the hazard activity is based on the identification of the evidence of the past events in the field or checking multi-temporal satellite images from Google Earth. It is attempted to associate the evidence with the temporal occurrence of the events. For example, rockfall activity can be assessed according to the freshness of rockfall deposits in qualitative terms. The second question is how to evaluate the favourable conditions for producing landslides? Five contributing factors (topography, geological, slope materials, land use and the drainage factors) were taken into consideration and were integrated into a decision tree method in a systematic way. Following the decision tree method, it was evaluated if the condition were favourable or not for producing hazards. Then a hazard matrix method was used to determine the hazard level based on the results obtained from hazard activity decision tree and favourable condition decision tree.

The third specific objective is to develop a qualitative method for prioritizing the implementation or repair of remedial works along roads. Associated with this sub-objective, the research question was How to combine the information to prioritise the road sections for construction or repair of remedial works? Using the protection efficiency decision method to evaluated the protection state (no protection, destroyed protection, insufficient protection and sufficient protection), the prioritization class is determined by the combination of the hazard class and protection state. For example, if the hazard class in a section is high and the protection work conducted in this section was destroyed, checking from the prioritization class table (Table 4.6), the prioritization class of this section is 1 which means the highest priority, remedial works are required to be conducted or repaired in the section.

The fourth specific objective is to evaluate the efficiency and the reproducibility of this method, and the associated research question is how reproducible is this evaluation method? To answer the question, this method was tested during the field work and in the office using the video images and other data. This method also was applied in two totally different study areas; one is a very active hazardous area while the other has very few landslide hazard problems. In both cases, it can pinpoint the critical road sections in which need to implement mitigation works. This method is not a site-specific method; but works over large areas. It can be used in other areas, but this should be further tested. It is worth mentioning that when using the activity decision tree to determine the activity levels, some modifications need to be done for the activity class based on the available historical information.

7.2. Recommendations

Some recommendations for future studies are:

- Semi-automatic or automatic methods to make homogenous road segments

Instead of doing all steps manually, some procedures in the road segmentation could be changed into semi-automatic or even automatic procedures. Replacing manual method with automatic one would increase the consistency of homogenous road segmentation and minimise subjective errors in some circumstances caused by testers. Apart from these, using semi-automatic or automatic methods allow people save time to achieve same targets, as they can tackle with a vast amount of data quickly.

Using UAV based high resolution DSM (Digital Surface Model) and images may be helpful achieving semi-automatic work. As the relatively precise road profiles can be generated in the ArcMap, the idea of this semi-automatic procedure is to find the dissimilarity between two adjacent profiles and draw a boundary between two distinct different adjacent profiles. The processes of the possible method are shown in Figure 7.1. First, different distance between two adjacent profiles need to be tested for the sake of determining a rational value of the density of the generation of profiles. Secondly, draw road cross-sectional profile at a regular interval. Then according to the similar shapes of the adjacent profiles, make the first subdivision. After classifying the profile into codes, find the dissimilarity between two adjacent profiles and draw the road section boundary where the two adjacent profiles have different codes.

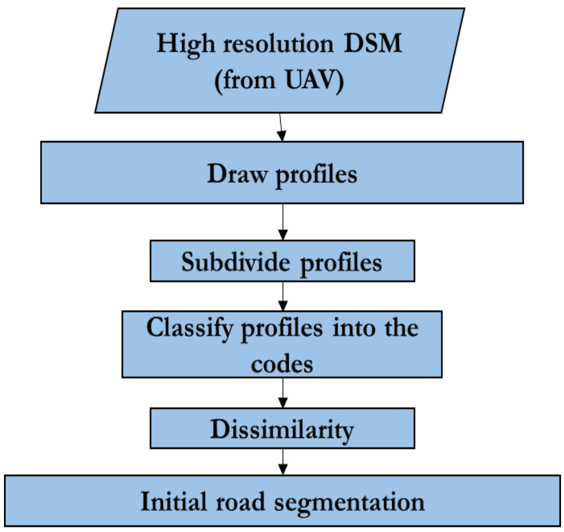


Figure 7.1 The process of semi-automatic road segmentation

- Incorporating empirical models

Some empirical models could be incorporated in this method, as they can provide quick approximation of mass movement runout path and do not require much data. Such as the distributed empirical moedel Flow-R can be used to assess the mass movement runout flow path which is based on the relationships between topographic factors and the length of runout zones(Dorren, 2003). Hence, the Digital Elevation Model (DEM) is the most input data in this model. Moreover, the Flow-R model can be used to estimate the maximum runout distances of different types of mass movements, such as debris flow, rockfall, etc., and their possible trajectories. According to Rana (2017), he incorporated empirical models in the direct method for local scale post-earthquake multi-hazards susceptibility assessment. The multi-hazard susceptibility assessment was based on the terrain unit. The unit which is located in the mass movement runout path has a higher class of susceptibility. Therefore, incorporating empirical models is helpful to estimate the susceptibility of hazards and obtain some information about the magnitudes of rock fall or debris flow.

- Developing an app for the method.

Using a questionnaire to fill the available information on the road section and the evaluation results is not very convenient and the procedure of this method is a little bit tedious. As the simple design of the mobile GIS application, users can easily use this application without too much guidance or explanations. Hence, it would be better to implement the method in an app rather than using the evaluation questionnaire and checking many tables or figures. The application may contain two parts: GIS analysis which can be visualized by maps and the formatted questions of the three decision tree ("activity decision tree", "favourable condition decision tree" and "protection efficiency decision tree"). These questions will be visible on the screen. And GIS data should be stored in the app which users could check them easily.

Overall, the present study is an attempt to develop a simple and direct hazard assessment method along roads. To know the efficiency and reproducibility of this method, it was tested in the field and the office by people with different background. Based on the test results, the proposed method could work and provide some suggestions for prioritizing conducting mitigation measures along roads. However, further testing is needed to examine the effectivity and reliability of the proposed method.

LIST OF REFERENCES

Abellán, A., Jaboyedoff, M., Oppikofer, T., & Vilaplana, J. M. (2009). Detection of millimetric deformation using a terrestrial laser scanner: experiment and application to a rockfall event. *Natural Hazards and Earth System Science*, *9*(2), 365–372. https://doi.org/10.5194/nhess-9-365-2009

Braam, R. R., Weiss, E. E. J., & Burrough, P. A. (1987). SPATIAL AND TEMPORAL ANALYSIS OF MASS MOVEMENT USING DENDROCHRONOLOGY, *14*, 573–584. Retrieved from file:///C:/Users/AO/Downloads/braam_87_spatial.pdf

Budetta, P. (2002). Risk assessment from debris flows in pyroclastic deposits along a motorway, Italy. *Bulletin of Engineering Geology and the Environment*, *61*(4), 293–301. https://doi.org/10.1007/s10064-002-0161-6

Budetta, P. (2004). Assessment of rockfall risk along roads. In *Natural Hazards and Earth System Sciences* (Vol. 4, pp. 71–81). https://doi.org/10.5194/nhess-4-71-2004

Bunce, C. M., Cruden, D. M., & Morgenstern, N. R. (1997). Assessment of the hazard from rock fall on a highway. *Canadian Geotechnical Journal*, *34*(3), 344–356. https://doi.org/10.1139/t97-009

Castellanos Abella, E. A., & Van Westen, C. J. (2008a). Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. *Geomorphology*, *94*(3–4), 453–466. https://doi.org/10.1016/j.geomorph.2006.10.038

Castellanos Abella, E. A., & Van Westen, C. J. (2008b). Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. *Geomorphology*, *94*(3–4), 453–466. https://doi.org/10.1016/J.GEOMORPH.2006.10.038

Colombo, A., Lanteri, L., Ramasco, M., & Troisi, C. (2005). Systematic GIS-based landslide inventory as the first step for effective landslide-hazard management. *Landslides*, *2*(4), 291–301. https://doi.org/10.1007/s10346-005-0025-9

Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., & Smith, J. T. (2014). Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment*, *73*(2), 209–263. https://doi.org/10.1007/s10064-013-0538-8

Cruden, D. M. (1991). A simple definition of a landslide. *Bulletin of the International Association of Engineering Geology*, *43*(1), 27–29. https://doi.org/10.1007/BF02590167

Dai, F. ., Lee, C. ., & Ngai, Y. . (2002a). Landslide risk assessment and management: an overview. *Engineering Geology*, *64*(1), 65–87. https://doi.org/10.1016/S0013-7952(01)00093-X

Dai, F. C., Lee, C. F., & Ngai, Y. Y. (2002b). Landslide risk assessment and management: An overview. *Engineering Geology*, *64*(1), 65–87. https://doi.org/10.1016/S0013-7952(01)00093-X

Das, I., Stein, A., Kerle, N., & Dadhwal, V. K. (2011). Probabilistic landslide hazard assessment using homogeneous susceptible units (HSU) along a national highway corridor in the northern Himalayas, India. *Landslides*, *8*(3), 293–308. https://doi.org/10.1007/s10346-011-0257-9

Domènech, G., Corominas, J., Mavrouli, O., Merchel, S., Abellán, A., Pavetich, S., & Rugel, G. (2017). Calculation of the rockwall recession rate of a limestone cliff, affected by rockfalls, using cosmogenic chlorine-36. Case study of the Montsec Range (Eastern Pyrenees, Spain). https://doi.org/10.1016/j.geomorph.2017.04.005

Domínguez-Cuesta, M. J., Jiménez-Sánchez, M., & Berrezueta, E. (2007). Landslides in the Central Coalfield (Cantabrian Mountains, NW Spain): Geomorphological features, conditioning factors and methodological implications in susceptibility assessment. *Geomorphology*, *89*(3–4), 358–369. https://doi.org/10.1016/J.GEOMORPH.2007.01.004

Donati, L., & Turrini, M. C. (2002). An objective method to rank the importance of the factors predisposing to landslides with the GIS methodology: Application to an area of the Apennines (Valnerina; Perugia, Italy). *Engineering Geology*, *63*(3–4), 277–289. https://doi.org/10.1016/S0013-7952(01)00087-4

Dorren, L. K. A. (2003). A review of rockfall mechanics and modelling approaches. *Progress in Physical Geography*, *27*(1), 69–87. https://doi.org/10.1191/0309133303pp359ra

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008a). Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. *Engineering Geology*, *102*(3–4), 99–111. https://doi.org/10.1016/j.enggeo.2008.03.014

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008b). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. *Engineering Geology*, *102*, 85–98. https://doi.org/10.1016/j.enggeo.2008.03.022

Griew, P., Hillsdon, M., Foster, C., Coombes, E., Jones, A., & Wilkinson, P. (2013). Developing and testing a street audit tool using Google Street View to measure environmental supportiveness for physical activity. *International Journal of Behavioral Nutrition and Physical Activity*, *10*(1), 103. https://doi.org/10.1186/1479-5868-10-103

Gu, F. (2015). *Quantifying some components of resilience by analysing the changes of elements-at-risk in the Wenchuan epicentral area*. University of Twente. Retrieved from https://ezproxy.utwente.nl:2315/library/2015/msc/aes/gu.pdf

Hadmoko, D. S., Lavigne, F., Sartohadi, J., Hadi, P., & Winaryo. (2010). Landslide hazard and risk assessment and their application in risk management and landuse planning in eastern flank of Menoreh Mountains, Yogyakarta Province, Indonesia. *Natural Hazards*, *54*(3), 623–642. https://doi.org/10.1007/s11069-009-9490-0

Hungr, O., Evans, S. G., & Hazzard, J. (1999a). Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. *Canadian Geotechnical Journal*, *36*(2), 224–238. https://doi.org/10.1139/t98-106

Hungr, O., Evans, S. G., & Hazzard, J. (1999b). Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. *Canadian Geotechnical Journal*, *36*(2), 224–238. https://doi.org/10.1139/t98-106

Jaiswal, P., & van Westen, C. J. (2013). Use of quantitative landslide hazard and risk information for local disaster risk reduction along a transportation corridor: A case study from Nilgiri district, India. *Natural Hazards*, *65*(1), 887–913. https://doi.org/10.1007/s11069-012-0404-1

Jaiswal, P., van Westen, C. J., & Jetten, V. (2010). Quantitative landslide hazard assessment along a transportation corridor in southern India. *Engineering Geology*, *116*(3–4), 236–250. https://doi.org/10.1016/J.ENGGEO.2010.09.005

Jaiswal, P., Van Westen, C. J., & Jetten, V. (2010). Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India. *Natural Hazards and Earth System Science*, *10*(6), 1253–1267. https://doi.org/10.5194/nhess-10-1253-2010

Jaroszweski, D., Chapman, L., & Petts, J. (2010). *Assessing the potential impact of climate change on transportation: the need for an interdisciplinary approach*. *Journal of Transport Geography* (Vol. 18). https://doi.org/10.1016/j.jtrangeo.2009.07.005

Jiménez-Perálvarez, J. D., El Hamdouni, R., Palenzuela, J. A., Irigaray, C., & Chacón, J. (2017). Landslide-hazard mapping through multi-technique activity assessment: an example from the Betic Cordillera (southern Spain). *Landslides*, *14*(6), 1975–1991. https://doi.org/10.1007/s10346-017-0851-6

Ko Ko, C., Flentje, P., & Chowdhury, R. (2004). Landslides qualitative hazard and risk assessment method and its reliability. *Bulletin of Engineering Geology and the Environment*, *63*(2), 149–165. https://doi.org/10.1007/s10064-004-0231-z

Losasso, L., Rinaldi, C., Alberico, D., & Sdao, F. (2017). Landslide Risk Analysis Along Strategic Touristic

Roads in Basilicata (Southern Italy) Using the Modified RHRS 2.0 Method (pp. 761–776). Springer, Cham. https://doi.org/10.1007/978-3-319-62392-4_55

Martinović, K. (2017). *Landslide risk assessment for engineered slopes on transport infrastructure*. University College Dublin.

Mattsson, L.-G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems–A discussion of recent research. *Transportation Research Part A: Policy and Practice*, *81*, 16–34.

Misra, R., & Das, A. (2003). Identification of Homogeneous Sections from Road Data. *International Journal of Pavement Engineering*, *4*(4), 229–233. https://doi.org/10.1080/10298430410001672237

Modarres, M. (Mohammad). (2006). *Risk Analysis in Engineering: Techniques, Tools and Trends*. Boca Raton : CRC.

Moreiras, S. M. (2005). Landslide susceptibility zonation in the Rio Mendoza Valley, Argentina. *Geomorphology*, *66*(1–4), 345–357. https://doi.org/10.1016/J.GEOMORPH.2004.09.019

Niculiţă, M., Mărgărint, M. C., & Santangelo, M. (2016). Archaeological evidence for Holocene landslide activity in the Eastern Carpathian lowland. *Quaternary International*, *415*, 175–189. https://doi.org/10.1016/j.quaint.2015.12.048

Pantelidis, L. (2011). A critical review of highway slope instability risk assessment systems. *Bulletin of Engineering Geology and the Environment*, *70*(3), 395–400. https://doi.org/10.1007/s10064-010-0328-5

Pierson LA, & Van Vickle R. (1993). Rockfall Hazard Rating System. Publication No. FHWA SA-93. *U.S. Department of Transportation. Fedeal Highway Administration.*

Popescu, M. (2001). A suggested method for reporting landslide remedial measures. *Bulletin of Engineering Geology and the Environment*, *60*(1), 69–74. https://doi.org/10.1007/s100640000084

Rana, S. (2017). *Development of a direct method for local scale post-earthquake multi- hazards susceptibility assessment Development of a direct method for local scale post-earthquake multi- hazards susceptibility assessment*. University of Twente.

Ray, R. L., Jacobs, J. M., & Cosh, M. H. (2010). Landslide susceptibility mapping using downscaled AMSR-E soil moisture: A case study from Cleveland Corral, California, US. *Remote Sensing of Environment*, *114*(11), 2624–2636. https://doi.org/10.1016/j.rse.2010.05.033

Remondo, J., Bonachea, J., & Cendrero, A. (2008). Quantitative landslide risk assessment and mapping on the basis of recent occurrences. *Geomorphology*, *94*(3–4), 496–507. https://doi.org/10.1016/j.geomorph.2006.10.041

Royán, M. J., Abellán, A., & Vilaplana, J. M. (2015). Progressive failure leading to the 3 December 2013 rockfall at Puigcercós scarp (Catalonia, Spain). *Landslides*, *12*(3), 585–595. https://doi.org/10.1007/s10346-015-0573-6

Santana, D., Corominas, J., Mavrouli, O., & Garcia-Sellés, D. (2012). Magnitude–frequency relation for rockfall scars using a Terrestrial Laser Scanner. *Engineering Geology*, *145–146*, 50–64. https://doi.org/10.1016/J.ENGGEO.2012.07.001

Tang, C., Van Westen, C. J., Tanyas, H., & Jetten, V. G. (2016). Analysing post-earthquake landslide activity using multi-temporal landslide inventories near the epicentral area of the 2008 Wenchuan earthquake. *Natural Hazards and Earth System Sciences*, *16*(12), 2641–2655. https://doi.org/10.5194/nhess-16-2641-2016

Tonini, M., & Abellan, A. (2014). Rockfall detection from terrestrial LiDAR point clouds: A clustering approach using R. *JOURNAL OF SPATIAL INFORMATION SCIENCE Number*, *8*, 95–110. https://doi.org/10.5311/JOSIS.2014.8.123

van Westen, C. J., van Asch, T. W. J., & Soeters, R. (2006). Landslide hazard and risk zonation - Why is it still so difficult? *Bulletin of Engineering Geology and the Environment*, *65*(2), 167–184. https://doi.org/10.1007/s10064-005-0023-0

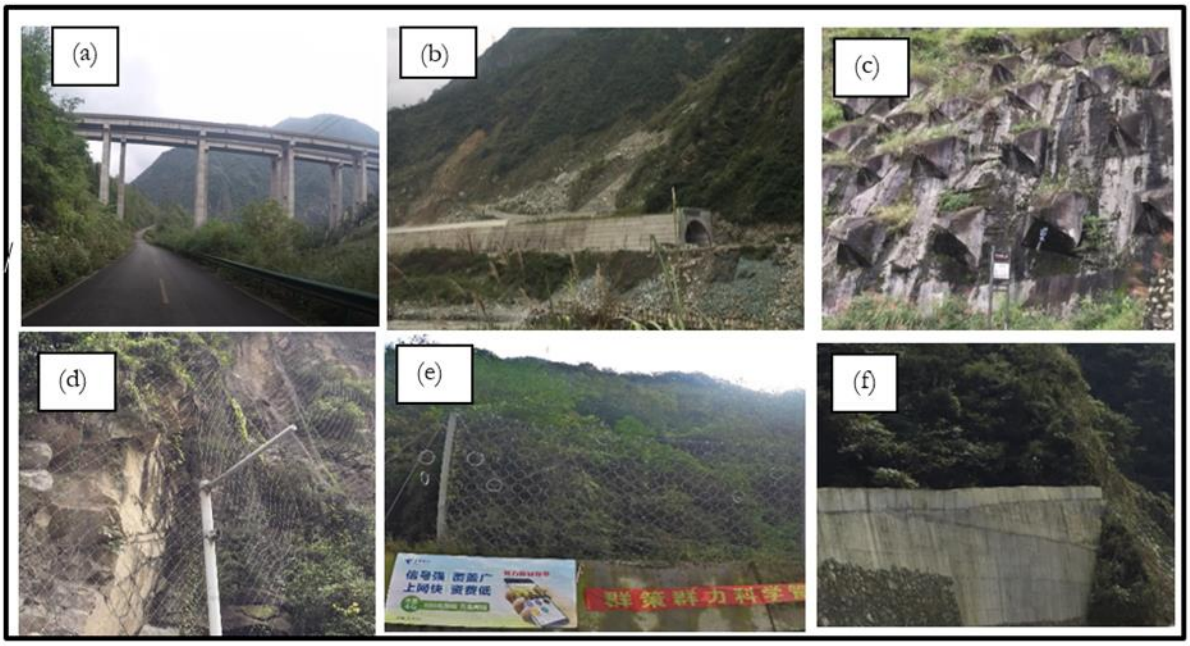
Wang, P., Liu, L., Li, X., Naumann, G., Spinoni, J., Vogt, J. V, Yusof, N. M., Pradhan, B., Bock, Y., Melgar, D., Mohd, N., Yusoff, R. N., Zulhaidi, H., Shafri, M., Muniandy, R., Hillier, J. K., Macdonald, N., … Dixon, N. (2017). Extending natural hazard impacts: an assessment of landslide disruptions on a national road transportation network. *Environ. Res. Lett*, *12*. Retrieved from http://iopscience.iop.org/1748-9326/12/1/014010

Yin, Y., Wang, F., & Sun, P. (2009). Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China. *Landslides*, *6*(2), 139–151. https://doi.org/10.1007/s10346-009-0148-5

Zêzere, J. L., Oliveira, S. C., Garcia, R. A. C., & Reis, E. (2007). Landslide risk analysis in the area North of Lisbon (Portugal): Evaluation of direct and indirect costs resulting from a motorway disruption by slope movements. *Landslides*, *4*(2), 123–136. https://doi.org/10.1007/s10346-006-0070-z

APPENDIX

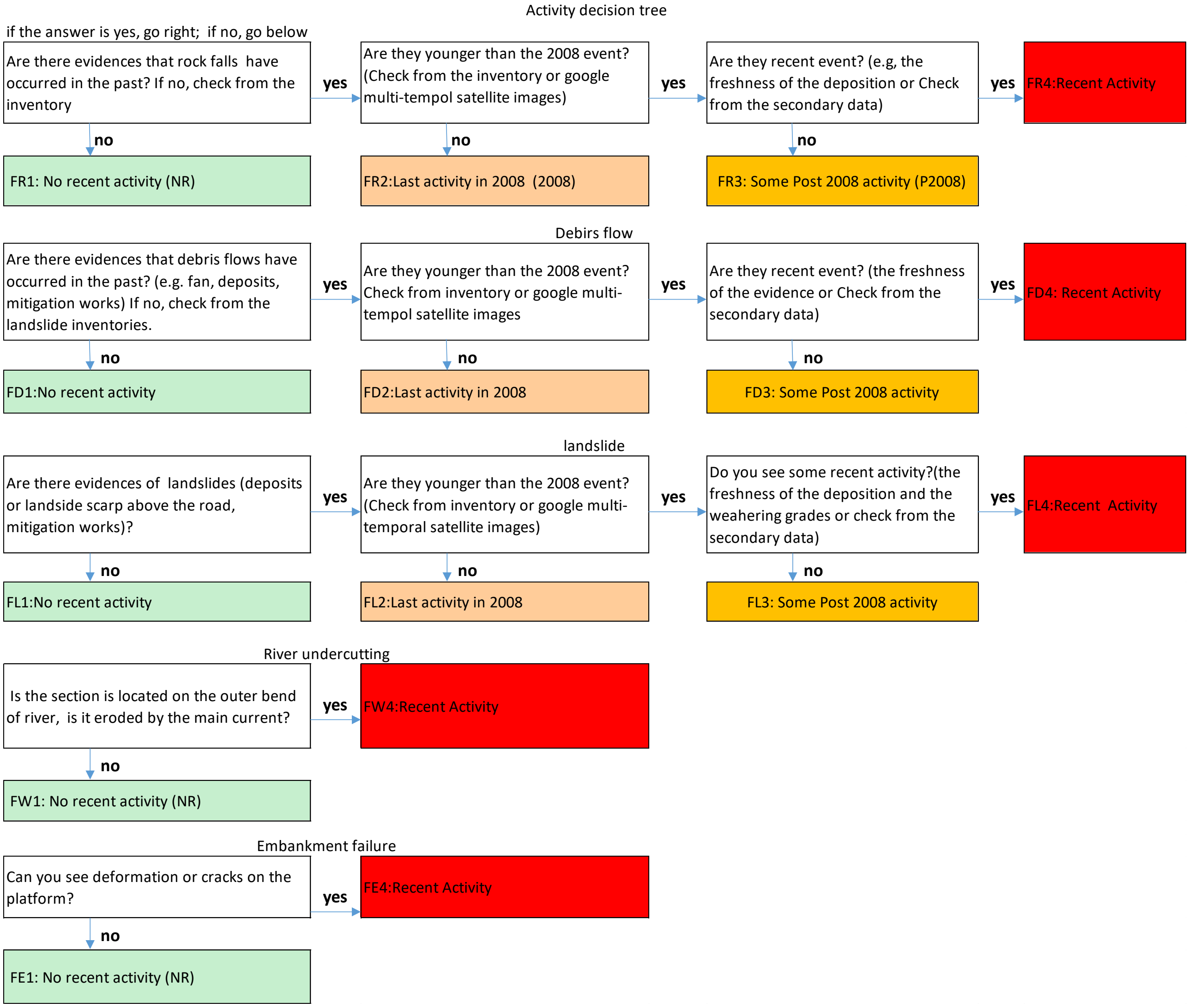
Appendix 1: Common types of protection works seen in the field



Appendix 2. Evidences Excel sheet

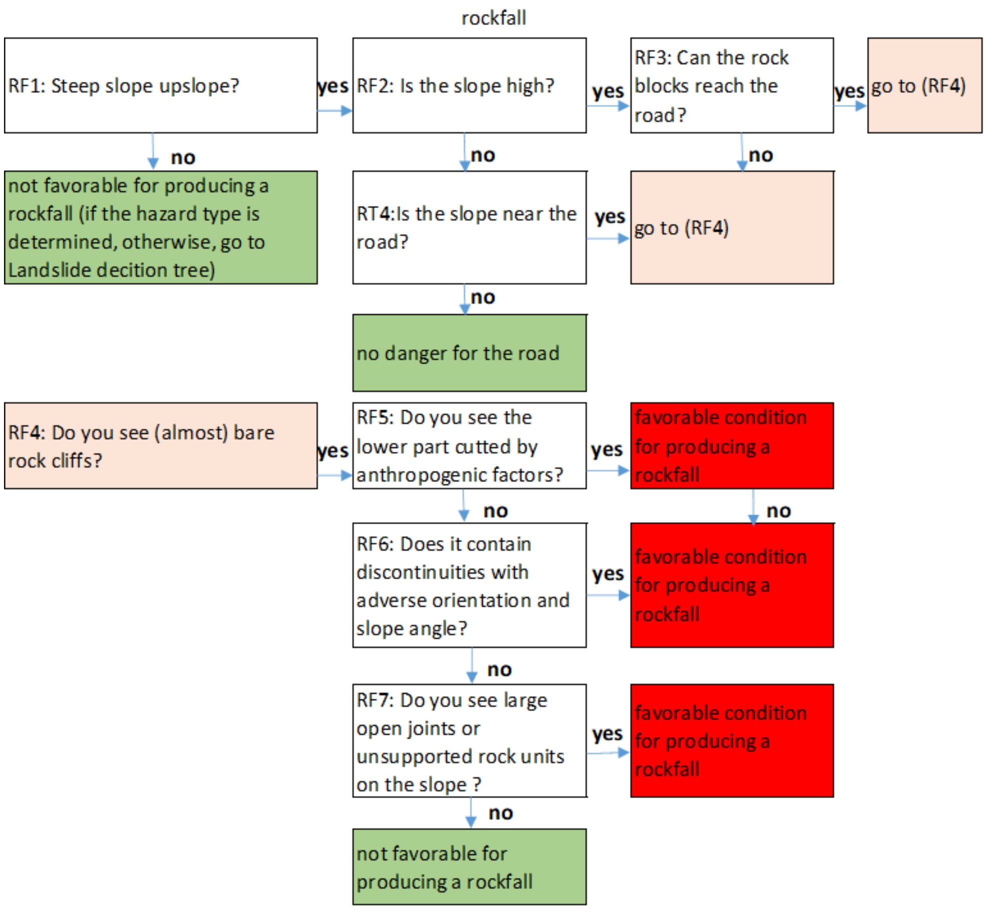
Rockfall	Landslide	Debris flow	River undercutting	Embankment failure
ER1. Are there small rock blocks on or below the road?	EL1. Are there landslide depositions on or below the road?(Information from road maintenance personel)	ED1.Is there an existing debris fan?	EU1: Is the section located on the outer bend of river, eroded by the main current?	EL3.Can you see deformation or cracks on the platform?
ER2. Do you see large rockfall deposits?	EL2.Can you see small steps, scarps often associated with cracks?	ED2.Are the banks of gully eroded?		
ER3. Is the road surface, railing or posts damaged by impact of blocks?	EL3.Can you see deformation on the platform?	ED3.Are there unvegetated parts or very wet areas that could indicate possible active movement?		
ER4. In the rock face do you see scars of past events?	EL4.Evidences of landslide scars above the road?	ED4: Are there mitigation works that are indicative of old activity?		
ER5. If there are trees above or below the road, do you see impacts of rocks on their trunks?	EL5.Vegetation anomalies (e.g. tilted trees?)	ED5. Do you see evidence of past events in Google Earth historical images?		
ER6. Is there a record of blocks that were removed? If yes, when and how large were the blocks.	EL6.Is there irregular, hummocky relief on the slope?			
ER7. Do you see evidence of past events in Google Earth historical images?	EL7. Do you see evidence of past events in Google Earth historical images?			

Appendix 3: Activity decision tree

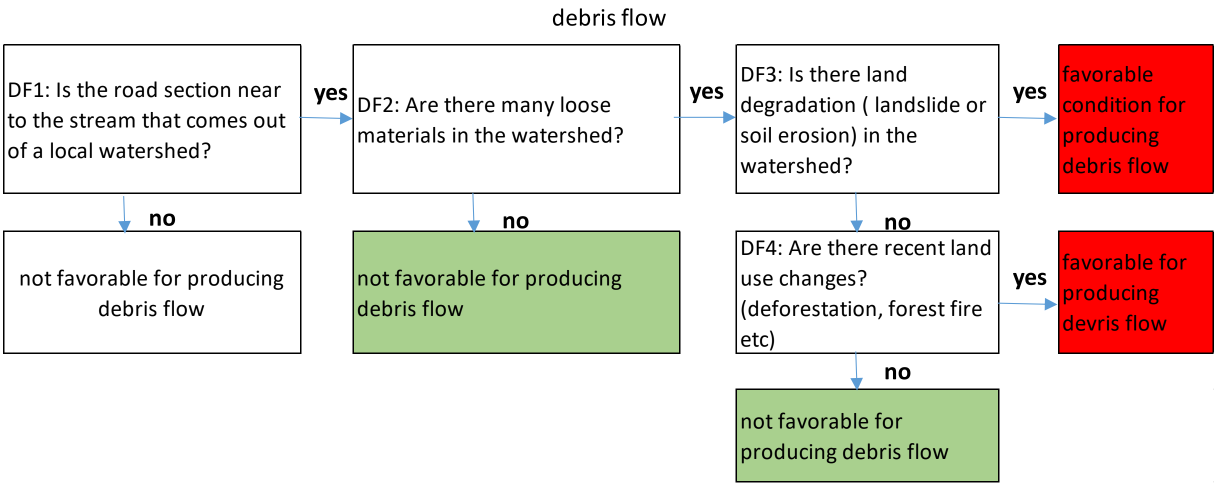


Appendix 4. Favourable condition decision tree

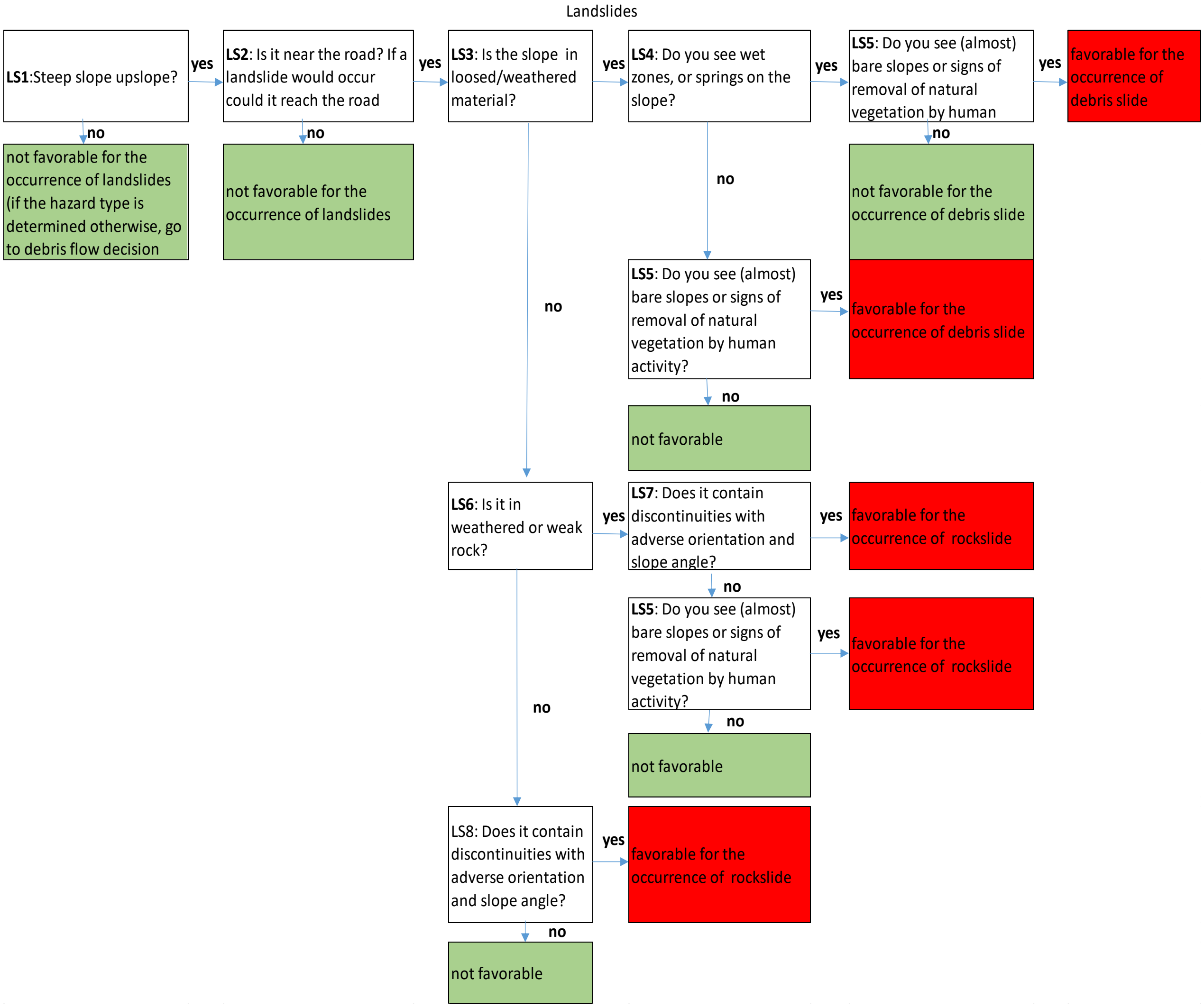
Appendix 4.1: rock decision tree



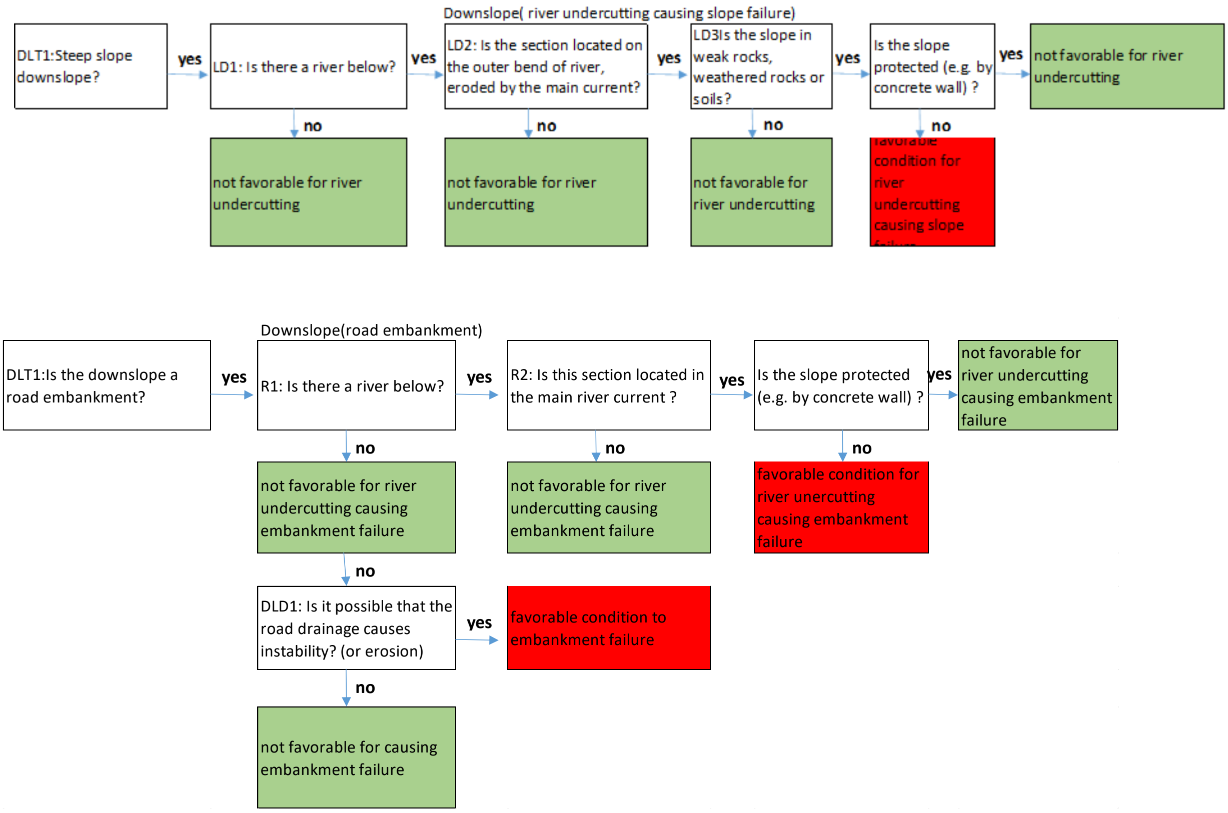
Appendix 4.2: debris flow decision tree



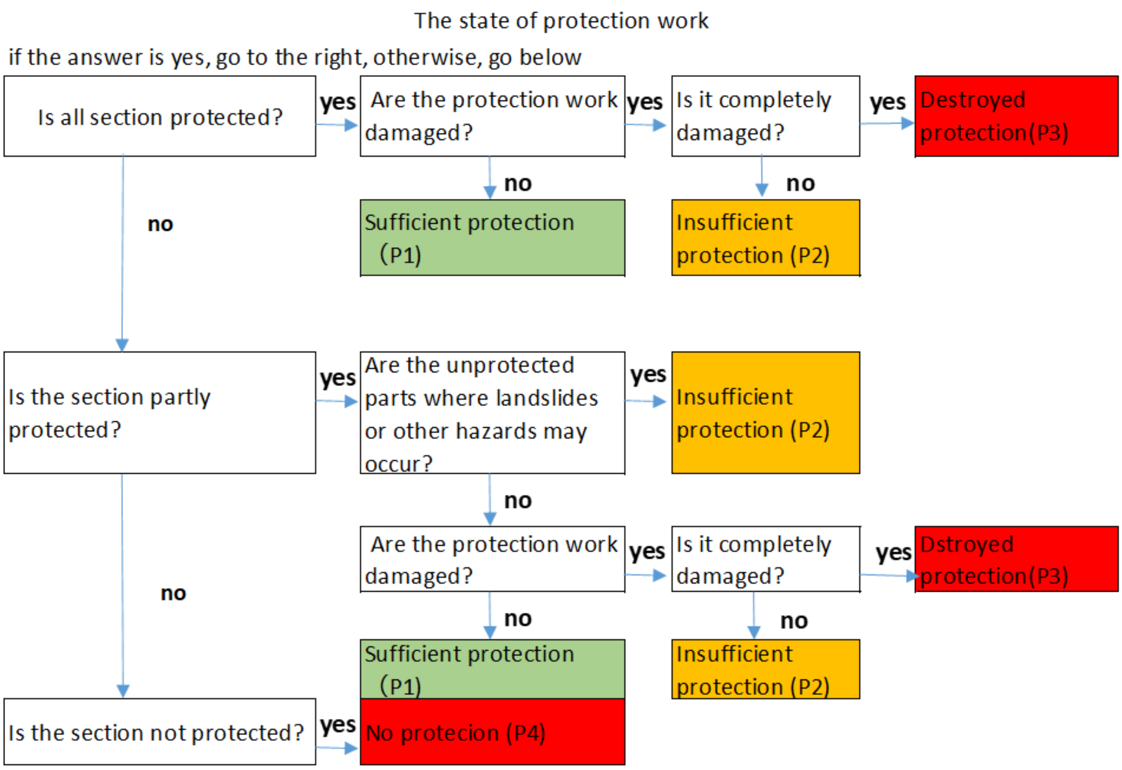
Appendix 4.3: landslide decision tree



Appendix 4.4 favorable condition decision tree for downslope



Appendix 5. Protection efficiency decision tree



Appendix 6: The details of the 20 road sections in Duyun area

Section No.	code of section	Length (m)	To which hazards could it be susceptible? (left/right side)	Are there evidences of past events? Check from evidence sheet (left/right side)	Are there protection works? Write the type. (left/right side)	Evaluate the activity (left/right side)	Evaluate the favorable conditions (left/right side)	Evaluate the efficiency of the protection work (left/right side)	Prioritization class (left/right side)
1	NmL100-R1-NmL100	132	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
2	0L200-R1-NfL200	378	No hazard / no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
3	0L100-R1-NmL100	113	Landslide/no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
4	0L100-R1-NmL500	99	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
5	Nm000-R1-Nm000	87	Landslide/landslide	No/EL4,EL5	No/EL4,EL5	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
6	0L100-R1-Ns0P7Ed	49	Debris flow/no hazard	No/ED1,ED4,ED5	No/debris flow check dam	No recent/ Post 2000	not favorable/ favorable	no protection/ sufficient protection	4/4
7	NmL500-R1-Nm000	147	Landslide/landslide	No / No	No / No	No recent/ Post 2000	not favorable/ not favorable	no protection/ no protection	4/3
8	0L100-R1-0L100	59	No hazard / no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
9	0L500-R1-NmL100	197	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
10	NmL500-R1-NmL100	157	No hazard/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
11	Nm000-R1-NmL500	98	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
12	NmL300-R1-Nm000	197	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
13	0L100-R1-0L100	131	No hazard/no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
14	0L100-R1-NmL400	89	Landslide/no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
15	NmL100-R1-NmL100	91	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
16	Cv000-R1-Nm000	155	Landslide/landslide	EL1,EL4,EL5/NO	No /No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
17	Nm00El-R1-Nm000	87	Landslide/landslide	No / No	No / No	Post 2000/ No recent	favorable/ not favorable	no protection/ no protection	2/4
18	NmL100-R1-Nm000	152	Landslide/landslide	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
19	0L300-R1-NmL100	129	Landslide/ no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4
20	0L200-R1-NfL200	281	No hazard / no hazard	No / No	No / No	No recent/ No recent	not favorable/ not favorable	no protection/ no protection	4/4