Landslide Susceptibility Mapping Along Highway Corridors in GIS Environment

Sandeep Panchal and Amit Kr. Shrivastava

Abstract The hilly regions are developing at a very rapid rate. The anthropogenic activities due to road construction increase the instability of slopes along highways. Aim of this study is to prepare a landslide susceptibility map along State Highway 32. Landslide susceptibility maps along road section prove a good tool for effective mitigation and management of the landslide hazards. The parameters considered in this study are slope, aspect, elevation, drainage density, lithology, soil and distance from fault. Analytic hierarchy process (AHP) is used for evaluating various parameters and ranking them. Landslide Susceptibility Index (LSI) is calculated by using weighted linear combination (WLC) technique. The final landslide susceptibility map is divided into four categories from low to very high susceptibility zones. It is found that around 65% of the area lies under high and very high landslide susceptibility. The results of the study can be used by the urban planners, transportation planners and highway engineers.

Keywords Analytic hierarchy process · Landslides · Susceptibility mapping · Weighted linear combination

1 Introduction

Highways in a city play a very important role in its development. The transportation network is considered as lifeline of a city. Landslide is a common phenomenon along highways in the hilly regions. So, the disaster like landslides should be planned carefully in a smart city. Safety of transportation infrastructure is a matter of concern in the smart cities. The landslide susceptibility maps can play a major role in planning and mitigation of landslide events which take place along the highways. The landslide susceptibility maps are used for the safe and economical route planning of transportation infrastructure in a smart city.

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Many researchers have defined landslide in many ways. According to a research paper published by Cruden in 1991, a landslide is a downward movement of material under the effect of gravity. This was the first technical definition in the literature. Landslides are a type of “mass wasting”, which denotes any down-slope movement of soil and rock under the direct influence of gravity (Highland; 2008). Highway construction projects involve a huge amount of cutting and filling work. Whenever a new road is constructed or an existed road is upgraded in hilly areas, the slopes along highways get disturbed. Due to this disturbance, there is a danger of slope failures. The mass movement of failed slopes is called landslides. Landslides are very common along highways and are responsible for economic losses [1]. A landslide along a highway section can block the traffic resulting in delay and discomfort to the passengers. Slope failures along highways are instant phenomenon that can even cause losses of life in adverse conditions [2].

The landslides are responsible for the huge economic losses which can be counted in monetary form. The losses due to landslides also include the traffic jams, delay in journey, minor injuries and deaths. These losses can’t be calculated in the monetary form. The economic impact of landslides can be direct and indirect. The direct impact can be calculated easily. The debris and the failed material come to the road. The direct cost of cleaning and the maintenance of roads can be calculated. The cost of damaged vehicles and the accident cost can also be calculated. The landslides can cut off the mode of communication in the areas which are situated remotely. The houses which are situated in landslide-prone areas can be damaged partially or fully. The differential settlement of the foundations can take place. The cost of damage and cost of maintenance of affected infrastructure can be calculated. The triggering factors like earthquake and rainfall can increase the cost of damaged infrastructure.

Landslide susceptibility mapping is an important tool for planning the mitigations to the landslide hazards [3]. A landslide susceptibility map helps in understanding the chances of occurrence of landslides in different parts of the study area. The study area is divided in some parts on the basis of their susceptibility towards landslides [4]. A lot of methods are proposed by various researchers for mapping the landslide susceptibility of different areas. There are many qualitative, quantitative and semi-quantitative techniques available for landslide mapping. The direct methods of landslide susceptibility mapping are easy to implement. The methods which involve human expertise are known as expert methods [5]. The methods like analytic hierarchy process (AHP) and analytic network process (ANP) are improved form of human-driven approaches [6]. There are many data-driven approaches also. The mathematical models are used for forecasting the landslides. The statistical techniques give good results in case of landslide susceptibility mapping. The probabilistic approach is based upon the theory of probability which is considered good for landslide susceptibility mapping at regional level [7]. The methods like fuzzy logic and artificial neural network are new methods which can give highly accurate results [8].

Geographic information system (GIS) is an effective tool which is used to store, capture, analyse, query, manage and manipulate the data [9]. The GIS is used to show the cumulative effect of various factors. The main advantage of GIS is that the input can be varied to vary the output. So, it proves very effective tool for the planners. A landslide susceptibility map shows the cumulative effect of its causative factors. The parameters which are responsible for the occurrence of landslide event are slope, aspect, curvature, drainage and hydro-geological characteristics of the area. GIS proves very effective in finding the cumulative effect of these factors.

The proposed study area lies between 76°15′ and 76°35′ longitude and 31°28′ and 31°37′ latitude in hilly terrain of lower Shiwalik in Himachal Pradesh (H.P.) from Una to Bhota. The topography and geology of the area are such that it is prone to landslides. The proposed road section is upgraded from one lane to two lanes, recently. This disturbance in natural slope had made the slopes along roadside highly susceptible to failures. The road stretch is 67 km long, and the landslide susceptibility mapping is done along this road. The method used for the purpose of landslide mapping is analytic hierarchy process (AHP).

2 Parameters of Landslides

Seven parameters those influence the occurrence of landslides are considered in this study. These seven parameters are slope, aspect, plan curvature, drainage density, lithology/geology, soil type and distance from fault which are considered. Eighth layer is landslide inventory that is prepared by field survey. The landslide inventories give an idea of relation of occurrence of landslides and the causative factors. A landslide inventory can also be prepared from Google Earth. The field surveys can be done for preparation of event-based landslide inventories.

2.1 Lithology

Occurrence of landslides depends upon the lithology and geology of the area. The study area consists of mainly sandstones with shale, sandstone with clay and boulder conglomerate along the road section. A small area is covered with the alluvium soil near rivers. Lithology is given weightage 0.132 according to analytic hierarchy process (AHP). It is found according to the landslide inventory maximum number of landslides occurred on the sandstone with clay type of lithology. For observing the effect of lithology of the area on the occurrence of landslides, the study area is divided into four regions. Figure 1 shows lithology along SH-32.

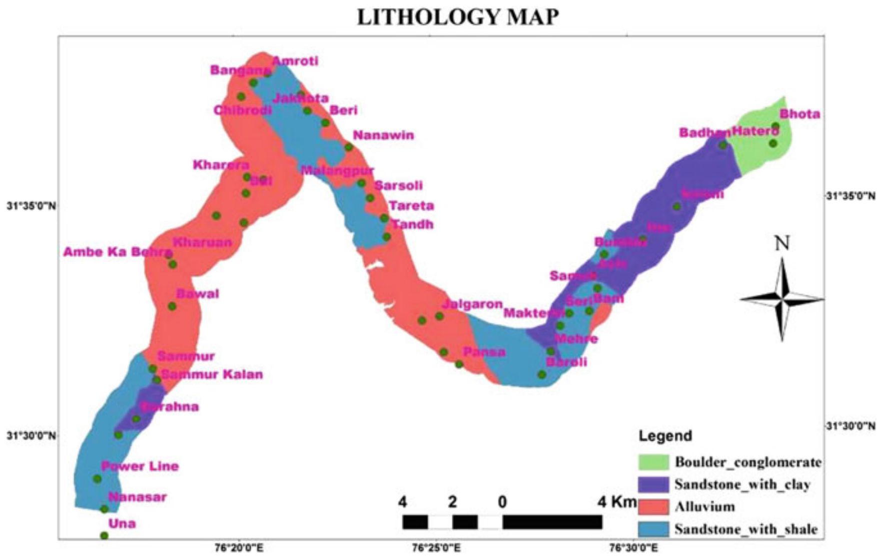

Fig. 1 Lithology characteristics

2.2 Soil Type/Geology

Occurrence of landslides also depends upon the soil characteristics of the particular area. The study area consists of mainly loamy soil with fine or coarse grains. Also, the area has some parts with sandy soil. Most of the landslides occur in the loamy soils. The loamy soils whenever come in contact of water, get weaker and tend to failure. Hence, the study area is divided into two type of soils, i.e. sandy and loamy. Maximum number of landslides took place in area with loamy soil. The AHP ranking of loamy soil is taken 0.8. Figure 2 shows the type of soil along SH-32.

2.3 Slope/Aspect

Slope angle is the most important factor that affects the slope stability. Slope angle may be defined as the rate of change of elevation w.r.t change in distance. So, landslide susceptibility of an area depends upon the slope angle (Fig. 3).

Aspect may be defined as the direction of steepest slope. Figure 4 shows the aspect along State Highway 32 (SH-32). The aspect affects the stability of slopes when these are subjected to high rainfall, weathering or other environmental factors. The slopes with aspect South (S), Southeast (SE) and Southwest (SW) direction.

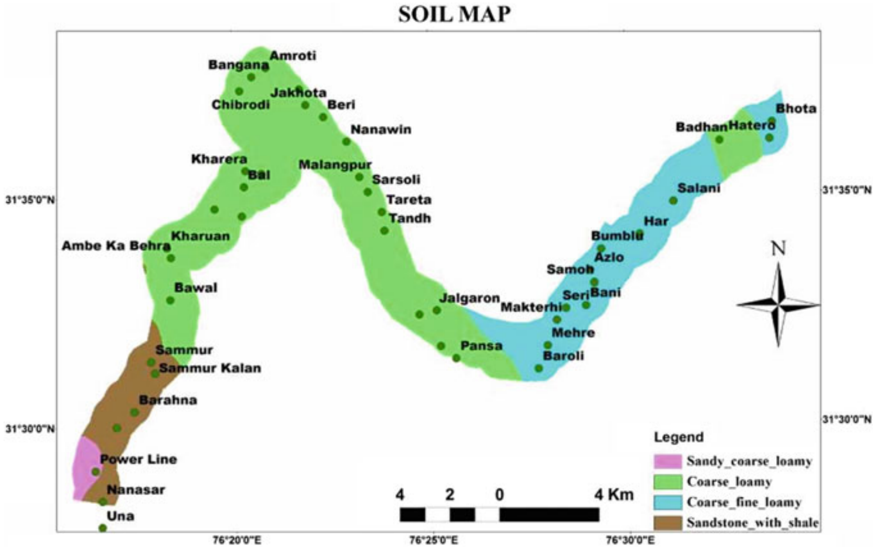

Fig. 2 Soil layer

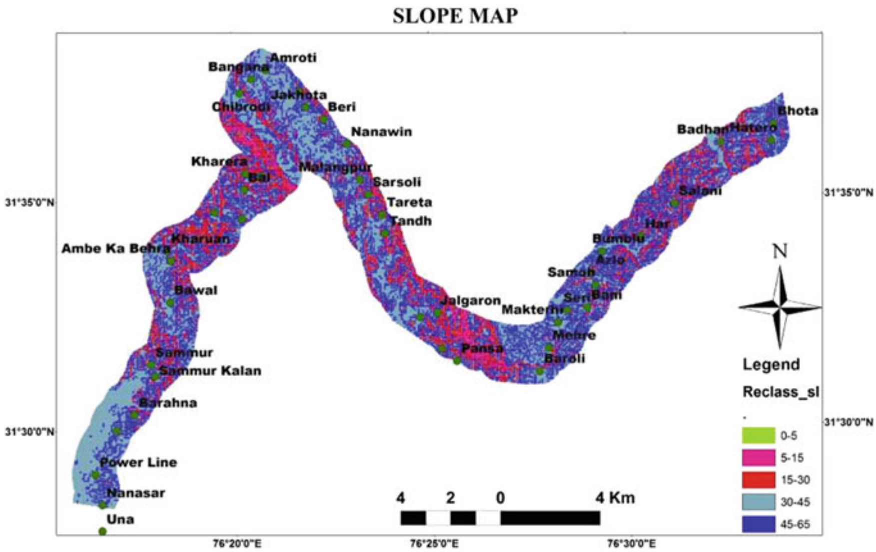

Fig. 3 Slope layer

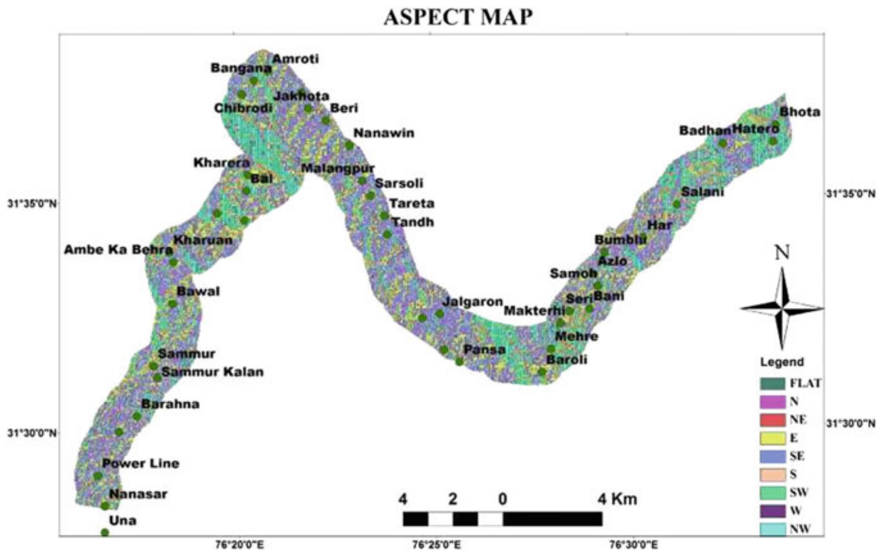

Fig. 4 Aspect layer

2.4 Curvature

Curvature is an important factor in mapping sensitivity to landslides. The curvature controls the soil's effect of water. Convex slopes are found to be more susceptible to failure after rainfall than convex slopes. The negative value of curvature represents the concave surface, and the positive values show convex surface. Zero value of curvature represents the flat surface.

Curvature layer is also prepared by using Spatial Analyst. Figure 5 shows the curvature along SH-32. The curvature can be of profile type or plan type.

2.5 Distance from Drainages

Landslide susceptibility of an area depends upon drainage characteristics of that particular area. Drainage characteristics are represented by drainage density. Drainage density may be defined as length of stream per unit area of the basin.

If the slopes are near to streams or the drainage density of the area is high, then the soil may get saturated due to the effect of these drainages. Such kind of saturated soil is more susceptible to failure.

Alluvium type of soil is found near the streams. Hence, alluvium is affected by the drainage characteristics of the area mostly. Figure 6 shows the drainage characteristics along SH-32.

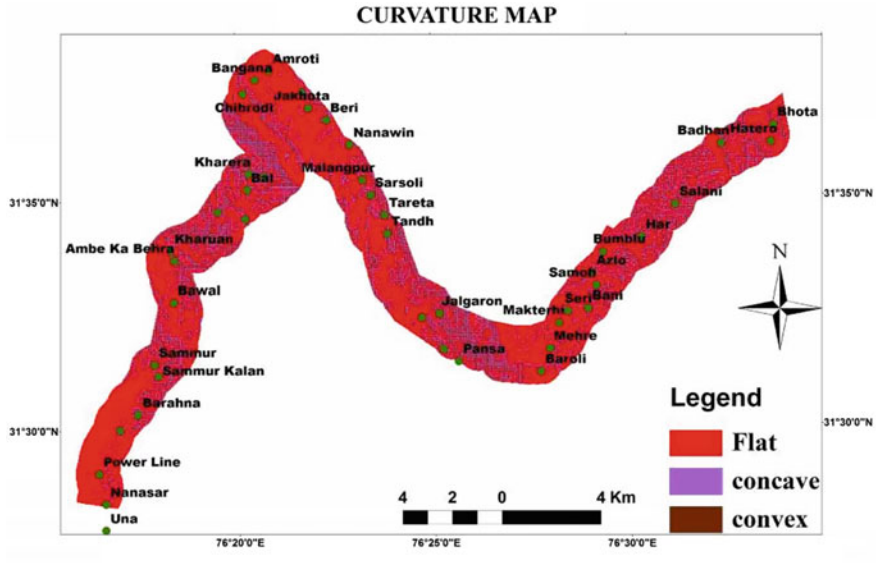

Fig. 5 Curvature layer

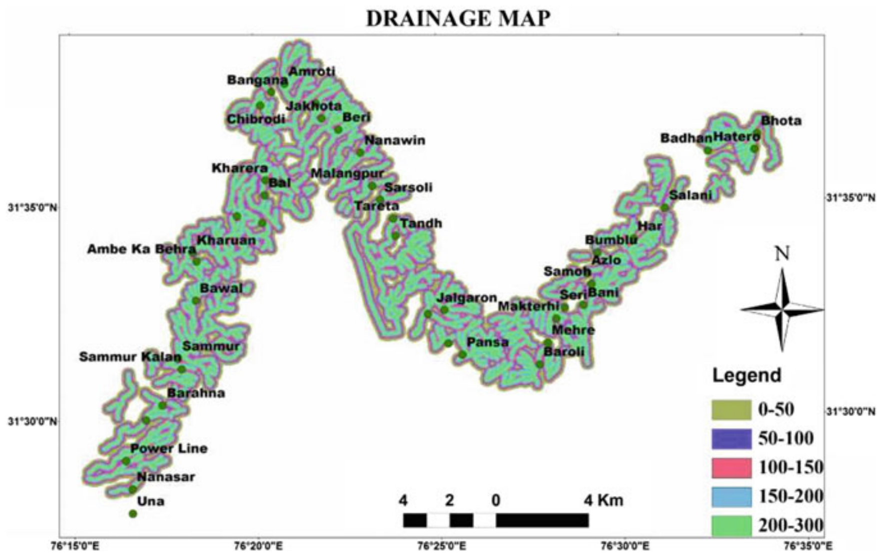

Fig. 6 Distance from streams

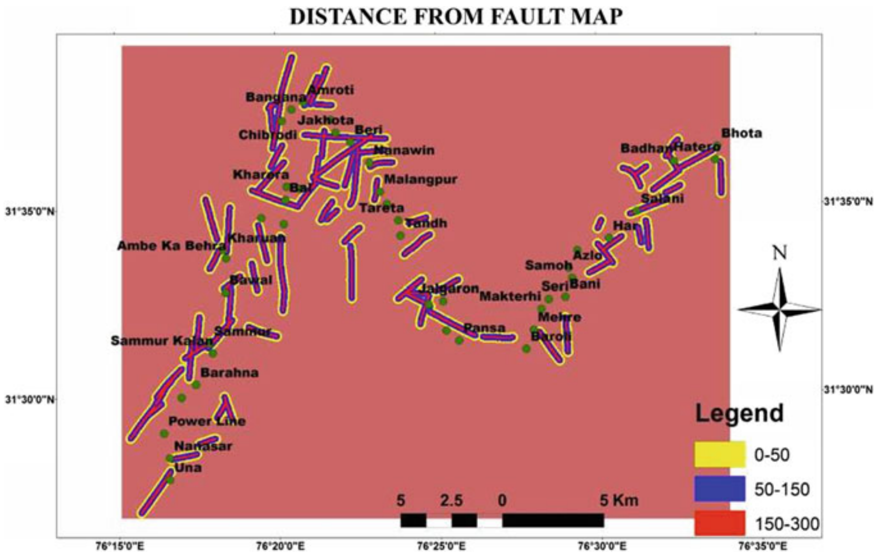

Fig. 7 Distance from faults

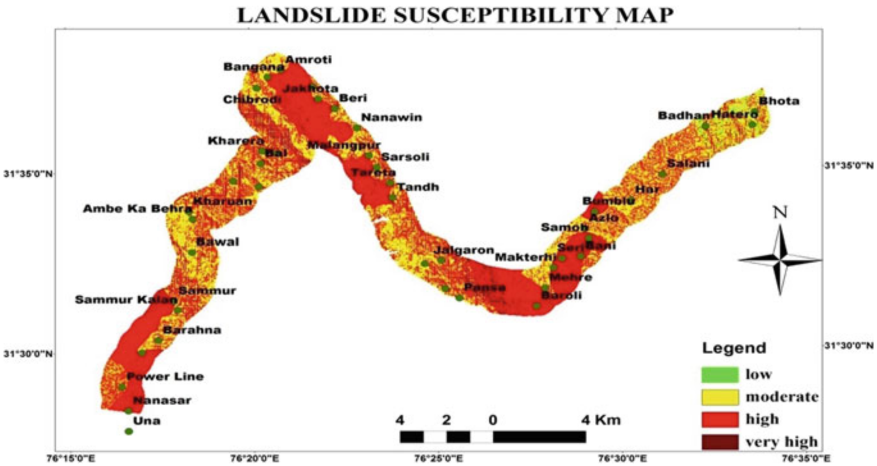

Fig. 8 Landslide susceptibility map

2.6 Distance from Faults

The distance of slopes from the faults also affects the stability of the slopes. The faults are symbol of weakness in the geological structure. Hence, these are very important to consider in the susceptibility mapping.

Faults are digitized on a map of scale 1:50,000. Buffering of fault layer is done to analyse the effect of faults on landslide susceptibility. The fault distance is divided into 250 m. Figure 7 shows the distance from faults.

3 Data Collection and Landslide Inventory

The basic principle of landslide susceptibility mapping is 'past is the key to future' [10]. So, the first step in landslide susceptibility mapping is to prepare a landslide inventory from the data of landslides occurred in the past. The data in this study is collected by field surveys. For the purpose of collection of data about landslides, a format is prepared. This format contains some characteristics of different landslides to recognize their properties required in landslide inventory. Landslide inventory consists of information like location of landslide, area of landslides, type of landslide, classification and date of occurrence of landslide if available. A photograph of each landslide is also taken with this information.

The location of landslide is defined by its longitude and latitude, that is, find out with the help of Global Positioning System (GPS). The areal extent of landslide gives information about the size of landslide. The type of slope failed is defined by the type of material it contains and the type of movement of the mass. For example, if the failed material has coarse particle about 80% and it has fall movement, then it is called 'Debris Fall'.

The maps of different layers are taken from Survey of India. The different topographic and hydrological maps are on a scale of 1:50,000 except soil map. The scale of the soil map is 1:2,200,000. The soil map available is of Himachal State. From this map, the study area is extracted.

A landslide inventory is an important part of landslide susceptibility mapping. In the present study, a basic level landslide inventory is prepared by field surveys. The landslide inventory includes information about longitude, latitude, type of landslide, classification of landslide, date of survey, date of occurrence and activity of landslide event. The location of the landslide is taken with the help of Global Positioning System (GPS). A format for the collection of landslide data for the inventory is prepared. A photograph is included with the landslide collection format for each landslide. In landslide inventory, about 20 landslides are recognized. Most of the landslides are found in the area where rock type is sandstone with clay.

4 Methodology

A landslide inventory is prepared by field surveys as described in Sect. 3. The proposed road section is digitized from the topographic map of the area. A buffer of 500 m each side of the proposed road is taken. Lithology, soil type, drainages and faults are digitized in GIS environment. From the topographic map, contours are digitized. These digitized contours are used to make Digital Elevation Model (DEM) of the area. Slope, aspect and curvature layers are extracted from this DEM. These layers are ranked with analytic hierarchy process (AHP) using online AHP calculator. These maps are overlaid according to their ranking and final map of landslide susceptibility map is derived.

Analytic hierarchy process (AHP) is used to rank the different criterions according to their effect on the occurrence of landslides [11]. The ranking for the main factors like slope, aspect, curvature, etc. is done by pairwise comparison in AHP calculator, and it is found that slope is the most important parameter. The different parameters are given a rank according to expert judgment on a scale from 1 to 9. After giving expert rankings, the parameters are compared and AHP rankings are calculated. If the value of consistency ratio is more than 10%, then the assigned rating is improved. If consistency ratio is less than 10%, then the ratings are consistent and can be used. The landslide susceptibility index (LSI) is calculated from the weightages of criteria and sub-criteria. The final map is based upon the landslide susceptibility index.

5 Results and Discussion

A landslide map shows the areas with different colour combination on the basis of their susceptibility towards the landslides. A landslide susceptibility map is created by overlaying the different layers in GIS environment. The map is divided into four categories low, moderate, high and very highly susceptible areas. The red and dark red colour shows high and very high susceptibility of area towards occurrence of landslides. The green and yellow colours show low and moderate susceptibility of area towards landslides. Figure 8 shows the final landslide susceptibility map.

It is found that around 65% area is under the high and very high susceptibility zone. The construction activities in such areas should be planned carefully to avoid the disaster. The retaining walls can be provided in the region of high susceptibility. The gabion walls are a suitable solution to stop the earth or rock mass. The vegetation can be provided on the slopes to reduce the landslide events.

6 Conclusion and Recommendations

Analytic hierarchy process (AHP) is a user perception-based method. The perception of expert is an advantage of this method. Hence, the ranking given in AHP depends upon the expertise of the user. Therefore, the accuracy of susceptibility maps prepared using AHP depends upon the realistic rankings given to the different parameters. The maps prepared using AHP are accurate enough at regional level. If more factors on which occurrence of landslide depends are considered, the accuracy of susceptibility maps can be increased. The present study is an attempt to prepare a susceptibility map at a preliminary level that can be extended to hazard and risk assessment. The results of the study can be used in planning and management by the road administrators.

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