Rainfall Induced Landslides—A Review

Ruchi R. Kadamb and Purnanand P. Savoikar

Abstract Major landslides take place in the world due to several reasons like human activities, heavy rainfall, snow melts and deforestations. A thorough study of landslide prone regions is required for ensuring the safety against this disaster. The triggering factors of landslides include climatic conditions of an area, soil-water characteristics, ground water conditions, quality of soil, topography and slope modifications. In most of the landslides that have occurred in the past, the common reason observed for the slope failure is the heavy rains at hilly regions. The present study aims to analyze slope failures or landslides occurring at several place in India and world due to high and continuous rainfall. Few other uncertainties may also be the root cause of landslide hazards. Rainfall threshold and antecedent rainfall are the elementary parameters of this study. The review includes a vast area of study with different methodologies and remedial systems provided for rainfall includes landslides. Few remedial measures for several landslide locations are discussed in the present study.

Keywords Rainfall · Landslides · Antecedent rainfall · Rainfall thresholds · Slope failures

1 Introduction

Natural disasters are the uncertain and uncontrollable circumstances which needs pre-disaster management installation. Few major disasters are caused due to floods, hurricanes, earthquakes, storms and other geological processes. Some of the common geological disasters include avalanches, rock falls, landslide, and sink holes. Generally, the impact of such disasters is severe in developing countries and in countries with high population. Landslides occur in all parts of world due to several reason like heavy rainfall, snowmelts, changes in ground water, human activities like mining, construction, slope modifications, deforestations etc. Landslides are slope failures

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caused due to movement of rock mass, debris flow down a slope under gravity. They include different types of slope movements such as topples, slides, spreads, flows and falls. Largely landslides happen due to heavy rainfall that saturates the slope or soil mass by water due to which soil shear strength is reduced and the disasters take place.

Landslides also effects the human settlements, communication modes and land properties. It is a necessity to study these failures to take further precaution for any similar situations. Normally landslides are labelled as shown in Fig. 1. Landslides are classified according to its movements, materials involved, activity and movement velocity. They are also divided into different types with respect to depth of slide as surface slides, shallow slides, deep slides and very deep slides. According to movement type, they are classified as falls, topple, slides, spreads, flows, and complex. The different material classification is rock, debris and earth. Therefore, the landslides types are rock falls, debris fall, Earth fall or Rock topple, debris topple and earth topple. Similarly, the other movements and material types are combined. The different types of landslide are as shown in Fig. 2.

The basic causes of landslides include: physical, geological, morphological and human activities. Physical changes such as ground water level, increase in pore pressures, snow melts, earthquake forces, heavy flooding, rapid drawdown, leaching of salts, heavy rainfalls etc. are the major reason of landslides. The geological causes include bedding, faults, unconformity, weak materials, sheared or jointed materials, and weathered materials. Slope inclinations, uplifts, slope loadings, vegetation

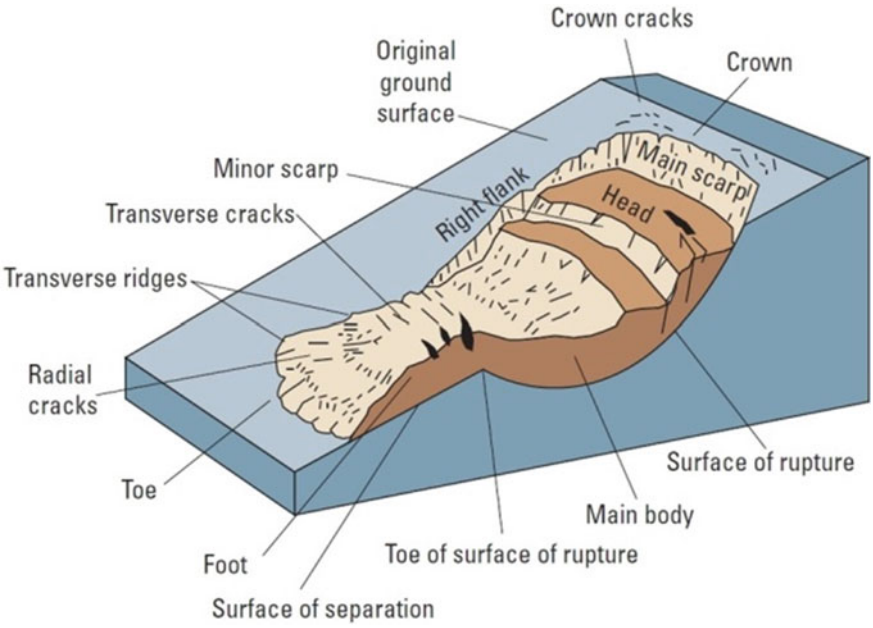

Fig. 1 Nomenclature for labelling the part of landslides (Spiker and Gori 2003)

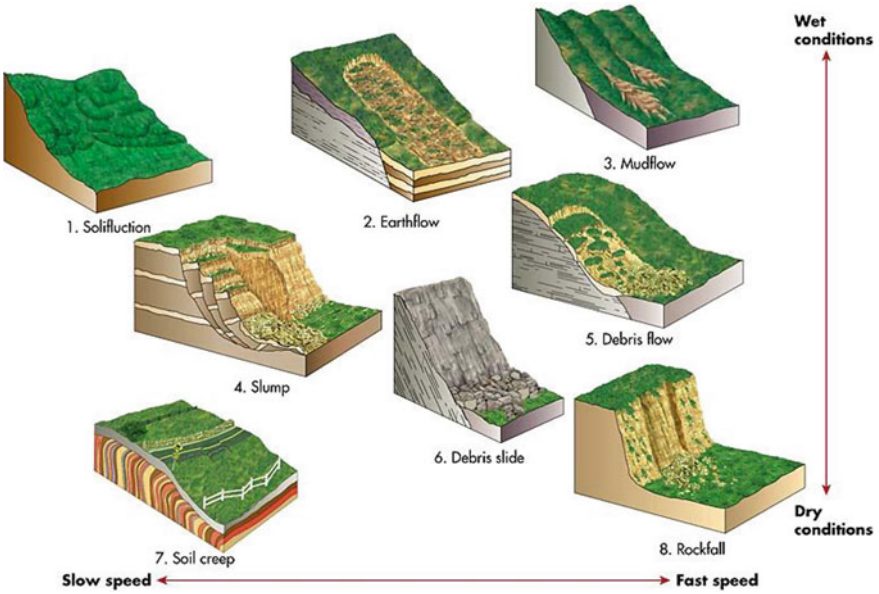

Fig. 2 Types of landslide (www.gsi.org)

removals, tectonic or volcanic uplifts are morphological causes. Human activities like excavation, mining activities, quarrying, vibrations, deforestation, water leakages in pipe line and sewer are few reasons that cause the landslides. But predominantly, increase in shear stress and reduction in material strength are the two main influential parameters of landslides.

2 Rainfall Induced Landslides

In general, landslide occurs in any climatic conditions. But it is mainly observed in area with heavy rainfall. Rainfall induced landslide are common and recurring issue for hilly slopes. The damage caused by rainfall induced landslides incorporates economic losses, property damage, and loss of human and transportation route blockage. Types of landslide that take place due to heavy rainfall are shallow, small but moves rapidly. They further transform into fast moving slurries mixed with water, rock and soil to form debris flow. Landslides induced by rainfall can take place after several hours of rainfall or even immediately after or during its course. In unsaturated areas rainfall induced slides are due to change in ground water conditions. It is the most influential parameter to persuade hill slope instability and reduce the material strength. The effect of pore water pressure also dominates in rainfall induced landslides. Extreme rainfall infiltration mainly forms deep-seated rotational or shallow

translational slides. But if these landslides occur on steep slopes, they are dreadful and dangerous.

According to many researchers, on average short duration high intensity rainfall triggers shallow soil slips and debris flow and long duration, low intensity rainfall triggers deeper debris avalanches and slumps. In general, rainfall increases moisture content of the soil which decreases the soil shear strength. Also, there is increase in pore water pressure and reduction in capillary tension due to continuous rainfall. Therefore, causing slope saturation. This in turn increases the self-weight of soil and leads to collapse.

3 Review of Literature on Landslides

The review study includes several concepts for analysing landslides or slope failures used by several researchers. Different methods of back analysis are referred through literature survey for investigating rain fall induced landslides. Few other uncertainties due to landslide hazards and control measure for such slides occurring at similar location are reviewed in this paper. Rainfall induced landslide are observed in all parts of the world. Few major rainfalls induced landslides are taken for study in this review ranging from year 1980 to 2019.

3.1 Rainfall Induced Landslides in the World

Back in the 1980s some of the rainfall induced landslide studies were conducted by researchers. One such study was viewed by the university of Colorado, the researcher published different records of rainfall intensity and duration in relation with debris flow and shallow land sliding. The data sets of rainfall intensity and rainfall duration were considered from the year of 1960 to 1979. In general, the rainfall threshold for debris flow type of failure was suggested based on rainfall database observation. In most cases the slopes were not modified by any human activities or stream erosions. The threshold was decided based on a graph produced on rainfall duration and intensities. It was observed that a fairly minimum rainfall can also cause slope failure of undisturbed slopes (Caine 1980).

For the landslide that occurred in Tuscany region was evaluated to study the relation between mass movement, interstitial pressures and to find the critical pluviometric threshold for the slide. Here, Gumble's law was used to interpret the annual rainfall. The critical precipitation coefficient was analyzed using probabilistic diagrams of maximum heights distribution of annual precipitation along with cumulative curves of daily rainfall (Canuti et al. 1985). Due to cyclonic rainfall after an abnormally dry summer, North-wales experienced debris flow which caused blockage of road and needed remedial works immediately. After studying all soil properties, it

was found that due to high variable particle parameters colluvial sediments pore pressure rapidly increased and caused failure (Addison 1987).

Every decade improved methods of rainfall induced landslide study has been observed. In china analysis for landslides that happened in 1981 proclaimed that there were two types of serious debris flow, one which triggers by sustained regional rainfall and other that triggers by local heavy rainfall (Ze-Yi 1992). In 1993 the study on slope failure due to rainfall in Hong Kong in a hilly terrain concluded that in large area with heavy rainfall numerous slope failures occur. It was noticed, that the failure occurred when rainfall intensity within 24 h exceed 70 mm and also that possibility of major failure increases with high intensity rainstorms (Au 1993).

Brunetti et al. (2010) analysed the rainfall triggered landslides to provide new rainfall threshold for Italy and Abruzzo region. For study purpose a detailed catalogue of rainfall induced landslides was complied with certain information like time, date, rainfall intensity, rainfall duration, antecedent rainfall, landslide type, rock type, climatic information etc. The new rainfall threshold was decided based on Bayesian inference method (suitable for small data sets) and Frequentist method (suitable for large dataset). The study revealed that national thresholds are lower compared to regional threshold which is usually not the case.

Hasnawir and Kubota (2012) have made a study on 36 landslides occurring in Kelara, Indonesia, water shed areas. The main aim of the study was to determine rainfall thresholds for these shallow landslides. Landslides are also initiated due to transient loss of shear strength due to increase in pore water pressure. The watershed area map and annual rainfall intensity for past 30 years were observed in this study, with a complied inventory of slope failure information over the past years. Empirical threshold method was adopted in which, the regression curve is taken reliable on rainfall intensity—duration threshold. Concluding that for this rainfall induced shallow landslides, threshold rainfall is very important to provide warnings in such watershed areas.

Hasan and Najjar (2013) states that, when there are uncertainties in soil properties, slope failure may occur. A detailed study of slope stability issue that occurred along the highway proposed at Algeria was performed justifying the statement. Using Bayesian technique of back analysis, the effects of pore pressure, prior shear strength, correlation between shear strength parameters, failure location and geometry of slope were obtained. This method is based on limit equilibrium analysis assuming the factor of safety as unity. It was concluded that this approach is suitable when there is uncertainty in pore pressures and shear strength parameters of slope. Ng et al. (2014) presented a slope failure investigation of a man-made slope at Putrajaya Malaysia using numerical back analysis method. In this case remedial measures suggested were designing new slope, installation of slope stabilization methods based on the threshold values.

3.2 Rainfall Induced Landslides in the India

Ering et al. (2015) reported a detailed analysis of slope failure which occurred in the Malin Village, in Pune district of India in July 2014. After detailed investigation of nearby rain gauges it was found that slope failure occurred due to rainfall infiltration and mass movement. Back analysis was conducted to gain in-depth knowledge of slope stability parameter such as pore water pressure and soil shear strength at the moment of failure. For the verification of this analysis, the problem is examined using finite difference program FLAC2D. It was concluded that due to heavy rainfall matric suction in unsaturated part of slope is lowered. As the water starts infiltrating in the soil negative pore pressure dissipates due to increase water content in soil. This decreases the shear strength parameters in soil layers close to the surface which caused failure. Hence unsaturated soil mechanics and rainfall frequency analysis should in-corporate for stability of soil slope subjected to rainfall.

Savoikar and Hede (2018) investigated three landslides in south Goa district involving forensic study. The soil from these site were tested to find the geological properties such as gravel content, sand content, Silt and clay content, specific gravity, dry density, liquid limits and plastic limits. Further using Geo-Studio 2012 software these slopes were analysed for static and seismic slope stability. Morgensten-Price method was used for static analysis and for seismic analysis time history record of Kobe earthquake was used under QUAKE/W module of GEO-STUDIO suite. After the analysis slope protection methods were suggested for the three sites. Ambajim and Canacona sites were suggested soil nailing protection technique and Raia site was suggested Gabion RE wall protection measures. After implementing protection measures Optum G2 software was, used for stability analysis.

It is found that after protection measures were implemented the factor of safety has increased by about 50% in each case. It was concluded that the landslide prone area should follow the land use policies and regulations for better protections. Similarly, suitable landslide protection techniques such as RCC retaining walls, gabion walls, reinforced earth walls, soil nailed walls, and tie back walls should be implemented in such areas. Mardolkar and Souza (2019) investigated the different types of landslides in Ponda–Goa. Goa lies in the west coastal lateritic zone of India. There are around nine major lateritic formations which lie between low lands and high lands. These formations often fail causing spread or rotational type of landslides. Some of the landslides are studied and GeoStudio is used to find its factor of safety. In all six different landslides are presented in this study with its physical and geological properties.

4 Analysis of Rainfall Induced Landslides

Analysis of rainfall induced landslides include forensic investigations of landslides which had occurred in past including finding the water content and geotechnical properties that had resulted in the landslides. Continuous infiltration leads to increase in positive pore pressures which further reduce the shear strength of the soil. Determination of soil water characteristics of the soil is very important for forensic studies of past landslides.

4.1 Stability Analysis of Rain Induced Landslides

New methods were introduced for landslide hazard assessment which utilizes landslide database and geology maps based on GIS. The rainfall data was presented and studied with the help of histogram and antecedent rainfall curves. It was concluded that the assessment of existing landslides and urbanization of hilly areas are the priorities in risk managements (Chowdhury and Flentje 1998). Theoretical approaches of back analysis were demonstrated, which included methods such as Bayesian probability method. On the basis of limit equilibrium method slope stability analysis was performed to learn the effects of three dimensional and two-dimensional failures. It was found that the mobilized strength at the base of slope was of average strength (Gilbert et al. 1998). Certain studies were also conducted using finite element programs. One such case, involved rain records evaluation to identify the cause of failure using SEEP/W to analyze its pore water pressure. It is observed that due to antecedent rainfall, the soil permeability increases due to decrease in matric suction, which causes the failure (Rahardjo et al. 2001). The rainfall data was also analyzed in terms of antecedent rainfall percentage exceedance time (APERT), which determines the relative frequency of rainfall (Chowdhury and Flentje 2002). Another rainfall induced landslide study by Bacchini and Zannoni (2003) revealed that the triggering mechanism of debris flow prove that short duration, high intensity rainfall causes superficial landslides.

Mechanism of rainfall-induced landslide initiation in unsaturated slopes is performed using transient seepage and stability analyses combined with probabilistic back analysis using softwares like FLAC^{2D}. Back analysis determine the causes of failure like the shear strength parameters, pore water pressure and other conditions at the time of failure. It requires determination of soil-water characteristic curve and its parameters (van Genuchten curve fitting parameters). In addition it requires rainfall data, geotechnical properties of soil like natural moisture content, dry and saturated unit weight, specific gravity, liquid and plastic limit, grain size analysis, cohesion and friction angle, etc. Soil-water characteristic curve (SWCC) is the plot between the matric suction (u_a-u_w) and volumetric water content (θ_w). It determines the hydraulic and mechanical behaviour of unsaturated **soils** and to predict **soil water** storage. Matric suction is the difference between pore air pressure (u_a) and pore

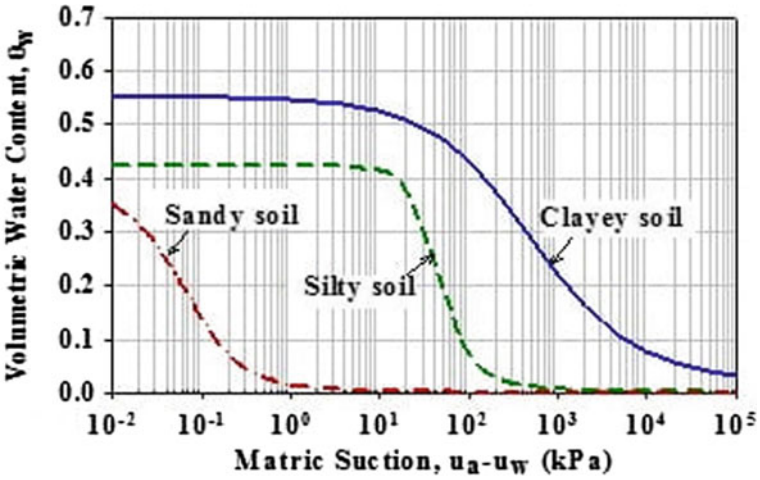

Fig. 3 Typical soil water characteristic curves for different types of soils (Fredlund et al. 2012)

water pressure (u_w). Matric suction influences the behaviour of unsaturated soils in both terms of shear strength and permeability. Figure 3 shows the typical soil water characteristic curves for different types of soils.

4.2 Finding the CRT Value Using Rainfall Data

The rainfall threshold is an important parameter for analysis of rainfall induced landslides. Critical rainfall threshold gives an idea at what value of rainfall, landslides will be triggered. This concept can help in providing warning system to landslide prone regions as well as inform the locals around, regarding such risky situations. The main element to evaluated the CRT value, is the rainfall data such as rainfall intensity, rainfall duration, cumulative rainfall for the past decades. Large data sets can calculate more accurate values and give better predictions. One of the simplest solutions to evaluate the critical rainfall threshold using a probabilistic and empirical method was stated by Huang et al. (2015). This technique is the simplest method to evaluate the rainfall threshold value. In this technique, a curve is plotted for cumulative rainfall (R_t) versus rainfall intensity (I_h). Cumulative rainfall can also be referred to as accumulated precipitation. The total amount of rainfall in 7 days including the day of rainfall that caused the failure is called the accumulated precipitation. In J. Huang's method he has considered two types of envelopes in his graphical representations one is termed as lower envelope of landslide occurrence and the second is termed as upper envelope of landslide occurrence. Figure 4 shows the graph of cumulative rainfall versus rainfall intensity.

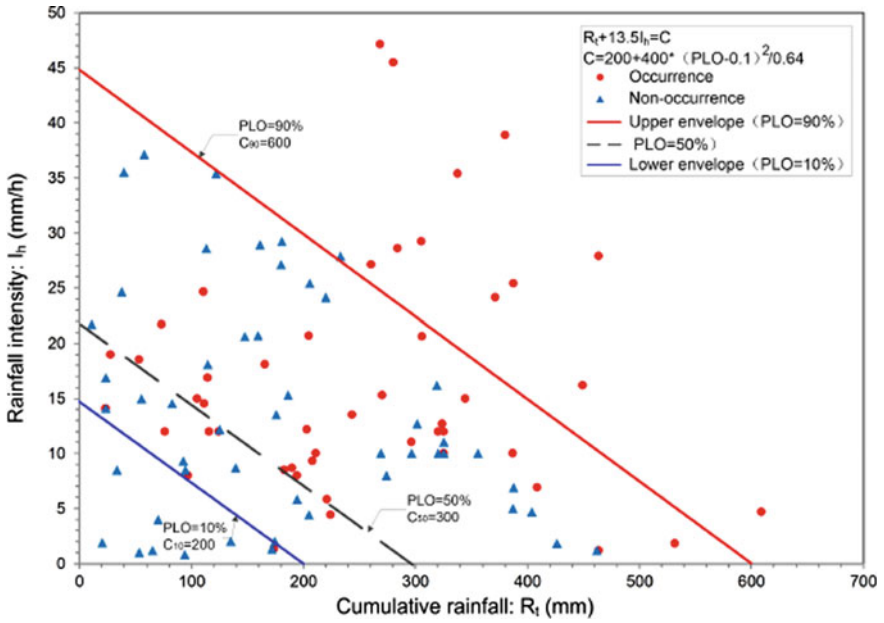

Fig. 4 R_t–I_h graph for occurrence and non-occurrence (Huang et al. 2015)

In the above Fig. 4, the blue line is drawn in such away that the points that are seen below the line are the point that has the minimal possibilities of landslide occurrence (10% probability). This is the lower envelope of landslide occurrence. Similarly, the upper envelope is represented by the red line above which the points that have maximum possibility of landslide occurrence are placed (90% probability). Between the two lines, a dotted black line depicts the probability line which is defined by an algorithm that is in Eq. 1

$$R_t + \alpha I_h = C \tag{1}$$

where R_t = accumulated precipitation in mm; I_h = hourly intensity in mm/hr; C = numerical constant and α = slope of the curve.

The most dangerous area is the one represented with 90% possibility of landslide occurrence which is at high risk where the local habitats are made aware of the situation. Based on this graph, the present situation of rainfall can be superimposed to predict the critical value of rainfall threshold and based on which the warning message can be given to the local habitats of possible landslide.

5 Conclusions

Landslide is a serious natural disaster, that cause intense damage to life and livelihood which needs to be controlled to avoid destruction. The climatic conditions, topography, soil conditions and groundwater table play a significant role in triggering landslides. In most cases, it is observed that the main causes of landslides are human activities like slope modifications and deforestations and further triggered by continuous rainfall. Most of the slopes where landslides occurred were observed with colluviums at the foot-steps of the terrains. Regions with intense heavy rain falls were largely affected by such disaster due to water infiltration, rising of pore water pressure and soil shear strength failures. Back analysis is predominantly used for investigating the reasons of slope failure and to improve knowledge on slope stability parameters and requires geotechnical properties along with determination of soil-water characteristic curves. Determination critical rainfall threshold based on cumulative rainfall data is very important in predicting the impending landslides during prolonged rainfall spells. Based on these studies, possible remedial measures can be suggested and landslide warning systems can be developed.

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