Probabilistic back analysis of rainfall induced landslide- A case study of Malin landslide, India

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A R T I C L E   I N F O
Article history:
Received 7 November 2015
Received in revised form 7 May 2016
Accepted 7 May 2016
Available online 10 May 2016

Keywords:
Landslides
 Unsaturated soils
 Back analysis
 Slope stability
 Seepage analysis
 Matric suction
 Probability
 Bayesian analysis

A B S T R A C T
On 30th July 2014, a devastating landslide resulted in the burial of a village called Malin in western India and led to about 160 deaths. The catastrophic failure was triggered by heavy rainfall over the last 3 days. Site investigation was conducted to obtain representative information about the area. To understand the relevant physics, which initiated landslide, seepage and back analysis of the unsaturated slope was performed. Transient seepage analysis was carried out using finite difference method to simulate the slope behavior during rainfall infiltration. A coupled fluid flow analysis was employed to capture the fluid/mechanical interaction in unsaturated soils accurately. The results show that antecedent rainfall played a role in slope instability; rainfall intensity and duration also have a big impact on slope instability. This paper presents a methodology to back analyse the slope so as to identify the mechanisms responsible for landslide initiation. Back analysis is performed using a probabilistic method based on Bayesian analysis. Probabilistic methods can back-analyse numerous sets of uncertain slope stability parameters. The uncertain parameters are imported as random variables in the analysis and are described by their probability distributions. Bayesian analysis updates these distributions based on the observed slope behavior. The method evaluates the reduction in matric suction which initiated landslide in Malin slope. The results show that the decrease in matric suction of about 100% in addition to the development of positive pore pressures decreases the mobilized shear strength in soil below the threshold value required to maintain equilibrium in the slope and hence the slope failed.

1. Introduction

The landslide is one of the greatest natural disasters which can cause significant damage to lives and property. It is attributed to many factors, namely earthquakes, rainfall (Collins and Znidarcic, 2004; Rahardjo et al., 2005) and weak layers of soil (Georgiannou and Burland, 2006; Hsu and Nelson, 2006). Rain-induced failures are the most common landslides around the world (Brand, 1984; Fukuoka et al., 1980; Fourie et al., 1989; Lim et al., 1996; Prennich et al., 1986; Wolle and Hachich, 1989). The conventional methods employed to perform stability analysis are based on assumptions of saturated behavior, but the majority of hill slopes is in unsaturated state. Yeh et al. (2004) postulated that stability analyses of unsaturated slopes require an extensive and detailed saturated-unsaturated transient seepage analysis because slope failures in unsaturated slopes are closely related to rainfall infiltration. Fredlund and Rahardjo (1993) and Rahardjo et al. (1995) concluded that rainfall infiltration results in decrease of matric suction (negative pore water pressure) in the soil, which can result in decrease of shear strength and trigger landslide. Yeh et al. (2008) also concluded that unsaturated soil landslides are mainly triggered by effective degree of saturation or matric suction in response to rainfall events. Several researchers (Gasmo et al., 2000; Tsaparas et al., 2002; Rahardjo et al., 2001, 2005, 2007a, 2007b, 2008) have performed numerical analyses of rainfall-induced landslides to study the effects of antecedent rainfall and parameters controlling slope instability. A three-dimensional numerical analysis of groundwater response to rainfall was conducted by Ng et al. (2001). They postulated that changes in pore-water pressures in unsaturated slopes are significantly affected by rainfall pattern, duration, and its return period.

Rahardjo et al. (2010) conducted parametric studies to understand the effects of ground water table position, rainfall intensity and soil properties on slope stability. Collins and Znidarcic (2004) developed a method to incorporate rainfall into conventional slope stability analyses and explain the various possible failure mechanisms.

These researchers concluded that rainfall induced landslide initiation is a complex process which incorporates the analysis of seepage forces, soil infiltration characteristics and soil shear strength (Collins and Znidarcic, 2004). Several researchers carried out transient seepage and infiltration analyses to explain landslide initiation in unsaturated slopes. Harris et al. (2012) and many researchers analyzed the seepage

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http://dx.doi.org/10.1016/j.enggeo.2016.05.002
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and deformations generated in slopes by using uncoupled fluid flow techniques (SEEP/W and SLOPE/W). The uncoupled analysis performs flow modelling and mechanical modelling separately. The combined modelling of fluid flow and mechanical behavior is important because the pore pressures generated due to fluid flow controls or causes deformation in porous media but these deformations in-turn causes changes in fluid pressure. Hence, the response of unsaturated soil slopes subjected to infiltration is influenced by both fluid flow and deformations and these mechanisms are interdependent. A coupled analysis in which the flow modelling is in parallel to mechanical modelling is more appropriate to capture the fluid/solid interaction in unsaturated soils. Many researchers have concluded that rainfall infiltration induces decrease in matric suction which triggers landslide. Collins and Znidaric (2004) concluded that the development of positive pore pressure causes failure in coarse grained soil slopes and the reduction of matric suction causes failure in fine grained soils. But under normal conditions majority of hill slopes consist of both coarse and fine grained soils. Hence, it is important to analyse the failure mechanism in these types of soil slope conditions. Also to date, it is not known how much decrease in matric suction can initiate landslide. Hence, to provide an insight into the physics of rainfall-induced landslide initiation and improve understanding regarding the factors controlling stability of unsaturated slopes, it is essential to carry out coupled fluid flow and stability analyses in conjunction with back analysis of the failed slope.

Back analysis is an effective approach to improve knowledge on parameters controlling the slope stability (Zhang et al., 2010a). The analysis determines shear strength parameters, pore water pressure and other conditions at a factor of safety value. Deterministic (Wesley and Leelaratnam, 2001; Tiwari et al., 2005) and probabilistic (Luckman et al., 1987; Gilbert et al., 1998; Zhang et al., 2010a, 2010b; Ng et al., 2014) methods are used to perform back analysis. Deterministic method calculates a unique set of stability parameters by considering factor of safety is equal to unity (Jiang and Takuo, 2008). Probabilistic methods have the ability to determine numerous sets of stability parameters with uncertainty. The method acknowledges that there could be various combinations of stability parameters that can result in slope instability, but their relative likelihoods are different and can be quantified by probability distributions (Zhang et al., 2010a). Many probabilistic methods have been used to back analyse soil parameters namely least squares method (Xu and Zheng, 2001), maximum likelihood method (Ledesma et al., 1996; Wang et al., 2013) and Bayesian method (Zhang et al., 2010a, 2010b; Miranda et al., 2009; Juang et al., 2013). Bayesian method allows the probability distribution of input parameters to be updated or improved when the observations are available (Miranda et al., 2009). Juang et al. (2013) presented a Bayesian method to update soil parameters in a multi-stage braced excavation using field observations. The posterior distributions of soil parameters were derived using Markov chain Monte Carlo (MCMC) method. They concluded that Bayesian updating is effective in reducing uncertainty of soil parameters. Zhang et al. (2010b) used field observed performance of slopes to back analyse the input soil parameters. They presented a probabilistic method which combines MCMC simulation with response surface method (RSM) to back analyse slope failures. Response surface method was used to approximate the slope stability model. The observed data for the probabilistic back analysis of slope failure is the factor of safety. They concluded that the correlation between input parameters does not significantly affect the slope remediation design. But the prior distribution of input parameters does influence the remediation design of slopes. Li et al. (2016) presented a method which couples Bayesian method and multi-output support vector machine (MSVM) to back analyse a high abutment rock slope. It is a back analysis method based on displacements. This method combines MSVM, Bayesian method and displacement back analysis. They concluded that probabilistic back analysis provides much more information than deterministic back analysis and matches the practice of geotechnical engineering in real world reasonably. Wang et al. (2013) used maximum likelihood method to back analyse a rock slope failure. In their study they used two methods: MCMC simulation and maximum likelihood method. Although both the methods yielded similar results, maximum likelihood method offered less computational effort and easy implementation. They postulated that proper slope remediation measures can be identified based on the improved knowledge of soil parameters.

In case of unsaturated soil slopes apart from soil properties such as cohesion and friction, modelling of soil water characteristic curve (SWCC) is also important. The uncertainty associated with these parameters also needs to be assessed. Chiu et al. (2012) presented a method based on Bayesian analysis to determine the reliability of SWCC parameters. In their study, Bayesian analysis was used to update probability distributions of SWCC parameters using data of three different soil classes. Monte Carlo simulation was then used to generate samples of SWCC parameters and the confidence intervals of parameters were evaluated. Zhou et al. (2014) presented a model to consider the influence of initial dry density of granular soils on SWCC. The uncertainty of SWCC fitting parameters was analyzed using Bayesian method and based on this, SWCC and relative permeability functions were predicted at different percentiles. Many researchers (Babu and Murthy, 2005; Tan et al., 2013; Tan et al., 2014) have performed reliability and sensitivity analysis of unsaturated slopes subjected to rainfall infiltration. Tan et al. (2014) performed reliability and sensitivity analysis of unsaturated slopes under rainfall to evaluate slope stability and determine the factors influencing it. They concluded that cohesion, friction angle and SWCC parameters affect slope stability strongly among all other parameters.

This paper investigates a rainfall-induced landslide which occurred on 30th July 2014, resulting in the burial of a village called Malin, in western India and also led to about 160 deaths. Ering et al. (2015) have performed forensic analysis of Malin landslide using numerical analysis and basic unsaturated soil mechanics. This paper presents a systematic methodology to explain the mechanism of rainfall-induced landslide initiation in unsaturated slopes. In this study, transient seepage and stability analyses combined with probabilistic back analysis are conducted. This approach provides rational explanations to landslide initiation due to rainfall infiltration.

Numerical analyses using FLAC (Fast Lagrangian analysis of continua) are performed based on the actual rainfall data, saturated-unsaturated seepage theory and the mechanical theory of unsaturated porous media to simulate the slope in Malin that failed during rainfall infiltration. Stability of slope and pore pressures generated are examined during the analysis using coupled fluid flow and mechanical analysis. The effect of antecedent rainfall, rainfall intensity and duration are also studied. The results of deterministic analyses in FLAC are used as input for the probabilistic back analysis of the slope. The probabilistic back analysis method is based on Bayesian analysis and produces multiple sets of stability parameters with uncertainty. The uncertain stability parameters used in the study are cohesion, friction angle and matric suction (c, φ, ψ) since these parameters are understood to significantly affect the slope stability. They are imported as random variables in the analysis and their probability distributions are updated based on the observed slope information.

With this method, the possible mechanisms for landslide initiation can be identified. The stability parameters are updated based on the field observations and it is possible to evaluate the reduction in matric suction which is detrimental to slope stability. Many researchers have used probabilistic back analysis for slope failure but most of them considered only soil parameters (c, φ) as the controlling factors for slope failure. Matric suction which is also an important factor in controlling the slope failure was not updated or included in the back analysis. Although some researchers did include pore water pressure as a stability parameter in the back analysis, t<sub>r</sub> which is defined as the ratio of pore water pressure to total vertical stress was used to incorporate uncertainty in pore water pressure. But t<sub>r</sub> cannot represent the pore water pressure distribution in the slope accurately (Zhang et al., 2010a). In