Failure analysis of Malin Landslide

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ABSTRACT

A recent slope failure in India which resulted in the burial of a village called Malin and claimed large number of lives is presented. In this study, Forensic analysis is conducted which focuses on understanding what went wrong, what could have happened and how failure can be prevented using engineering analysis principles. The analysis helps identify the causative factors of slope failure. The paper discusses various lessons learnt from the slope failure, which might help to foresee and mitigate such failures in the future.

INTRODUCTION

Forensic geotechnical engineering is an emerging discipline with a focus on understanding what went wrong, what could have happened and how failures can be prevented using engineering analysis principles in the case of failures of geological/geotechnical origin. It involves scientific investigations and deductions to detect the causes as well as the process of distress in a structure. The standard procedures of testing, design and analysis are not adequate for forensic analysis. It requires detailed investigation of failure incident that results in uncovering the probable causes of failure and answer to questions like “What happened”, “Why did it happen”, “Whose fault it is” and “How can it be fixed”.

In this study, a slope failure which occurred on 30 July 2014 in western India and led to about 160 deaths is investigated. The causative factors of slope failure are investigated. The mechanisms responsible for initiation of landslide are also identified. The investigation involves following steps: collection of data, distress characterisation, development of failure hypothesis, field and laboratory tests, and back analysis. Probabilistic back analysis is performed in the study, it has the ability to diagnose failure mechanism while considering uncertainty. It is important to consider uncertainty in the analysis because uncertainty arises at all stages in the resolution of the problem, from material property evaluation to analysis and consequent assessment.

This paper presents a case study of Malin landslide where Forensic geotechnical engineering is effectively utilized to investigate the failure mechanism. Important lessons learnt from the failure incident are also discussed, which is essential to mitigate landslide risk in the future and for remediation of the problem.

SITE DESCRIPTION

Fig. 1 shows the site located in the Malin village of Pune District in western Maharashtra, India. The area is located about 95 km away from Pune city at an elevation of 760 m (Ering et al., 2015). A devastating landslide occurred in the area on 30 July 2014 and claimed 160 lives

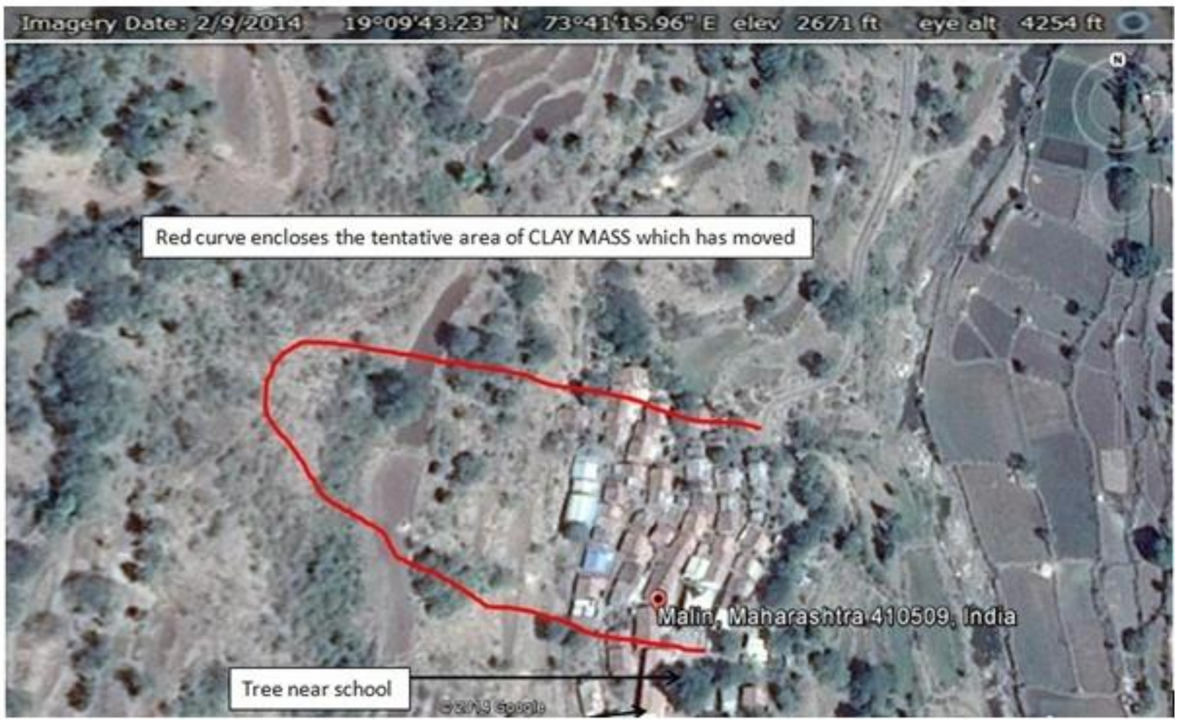

Figure 1: Landslide area

METHODOLOGY

The methodology involved in Forensic analysis consists of six stages. This kind of methodology is required to provide rational explanations for failure incident.

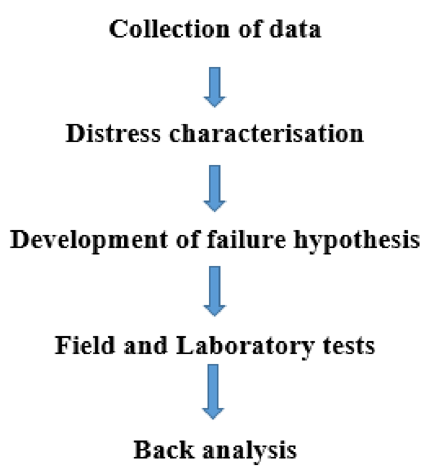

Figure 2: Different stages in failure analysis.

These stages are discussed in the following sections.

Stage 1: Collection of Data

A post-failure investigation was conducted around the Malin landslide area. The findings of the investigation are the basis of this study. A site investigation was carried out to obtain representative information about the landslide area. The hill slope where the slide occurred, was divided into four zones: Zone 1, 2, 3 and 4. The site consisted of thin forest in pre-slide scenario. These trees may have played a role in restricting the lateral extent of the landslide and spread of its debris. A longitudinal section A-A' is drawn on the southern side of the slide from across the ground level up to the crown level of landslide and this section reveals the pre-slide slope configuration of the slided area. Different zones in the section have different slope angles as shown in Table 1.

Table 1: Slope angles in different zones

Zone 1	Zone 2		Zone 3	Zone 4		
20°	10°	25°	30°	18°	25°	50°

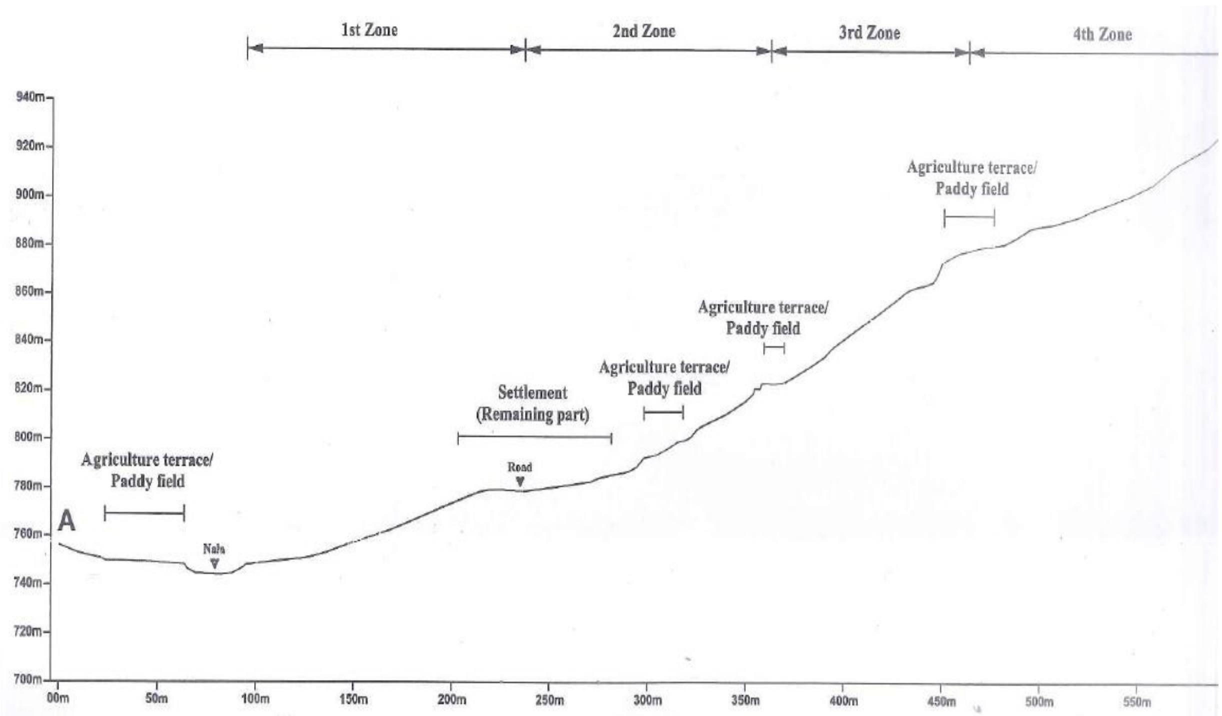

Figure 3: **Longitudinal section**

First zone has fairly uniform slope angle of 20°, zone 2 comprises of two local slopes: the lower part shows 10° while the upper part shows 25°. Zone 3 represents a uniform slope which measures 30°. Zone 4 can be roughly divided into three parts: the lowermost part shows 18°, while the middle and top part shows 25° and 50°. The slope length of zone 1 is 142 m while that of zone 2, 3 and 4 are 130 m, 80 m and 137 m respectively.

The urgency to clean up the failed site limits the time available for investigation and makes it essential that all relevant data are recorded before the evidence is removed. Representative soil samples are collected inside and outside the distressed zone of failed slope to determine their geotechnical properties.

Based on site investigation and discussion with the public it was learnt that landslide occurred after three days of high intensity rainfall. Hence, rainfall data of Malin area was collected from the nearby rain gauge station.

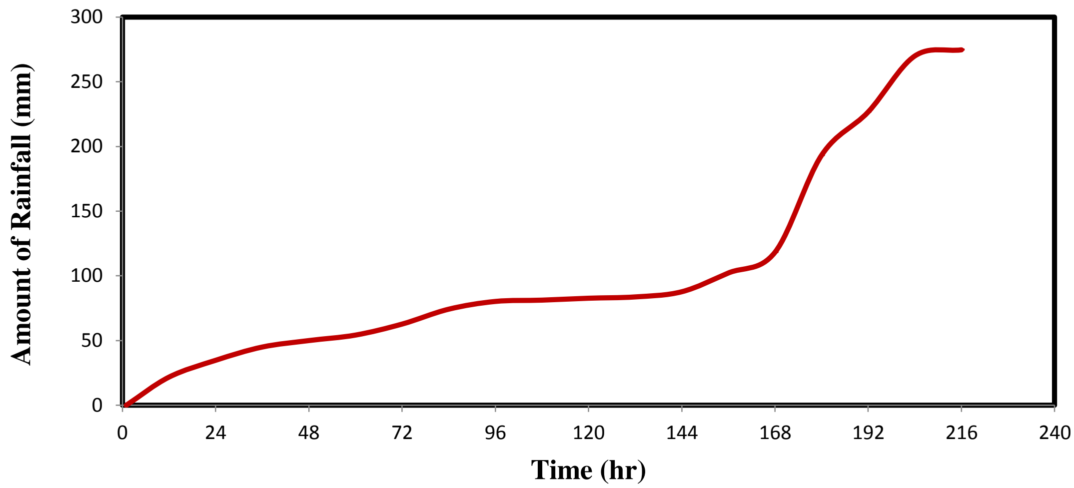

Figure 4: Rainfall data

It can be noted that during previous few days i.e from July 22 to 28, the antecedent rainfall was nothing extraordinary. However the rainfall record for 29th July i.e after 168 hours shows high amount of rainfall (108 mm). This may have played a significant role in slope instability.

Stage 2: Distress characterisation

A decade earlier (in 2003) signs of distress were witnessed by some NGOs in the region (Ramasamy et al. 2015). The villagers also observed appearance of cracks in the hills. Due to such signals indicating possible landslides, the villagers were evacuated to the adjacent area and housed in specially erected shelters; but they returned to Malin village which led to the large-scale causalities.

From the field observations, height of the landslide is roughly estimated as 190 m while the width of the slide varied from 45 m to 134 m (Ering et al., 2015). The entire length of the slide from crown to toe is 514 m. The landslide affected area is 44245 m^2 . Part of zone 4, entire zone 3 and maximum part of zone 2 are depleted by the landslide. A zone of accumulation was formed by the lowest part of zone 2 and zone 1, unfortunately this zone of accumulation is the settlement area of Malin village. The approximate thickness of slided material in the zone of accumulation is 7 m.

Stage 3: Development of failure hypothesis

Development of failure hypothesis is important to identify all the possible causes of failure. Failure analyses are usually carried out to find evidence in support of the hypothesis.

From the field observations, heavy rainfall over three days seem to have triggered the landslide in the area. This rainfall infiltration might have decreased the mobilized shear strength in soil below the threshold value required to maintain equilibrium in the slope.

Stage 4: Field and Laboratory tests

Failure analysis requires fresh field and laboratory tests apart from collection of all available data. Soil samples collected from the slided area are tested in laboratory to determine their geotechnical properties. Grain size analysis, moisture content, dry density and consistency limits are determined. Laboratory shear tests are performed to evaluate shear strength parameters of the soil samples. Table 2 shows the result of geotechnical tests.

Table 2: Geotechnical parameters of soil samples

Parameter	Value
Moisture content (%)	27.3
Dry density (kg/m^3)	1336
Bulk density (kg/m$^{3)}$	1700
Specific Gravity	2.56
Grain Size analysis	Silty clay
Liquid limit (%)	52
Plastic limit (%)	29
Plasticity Index	23
Cohesion (kPa)	36
Friction angle (°)	22

Field tests were not performed as the slided area was the settlement area of Malin village, in addition most of the nearby areas were converted to paddy fields making it more difficult to carry out geotechnical investigations.

Stage 5: Back analysis

Landslide initiation is a complex problem and it is important to understand the relevant physics behind it. For this purpose, back analysis is carried out on the failed slope in Malin. The analysis carried out to identify the cause of slope failure is known as back analysis. It can be utilized to determine the shear strength parameters, pore water pressure and other conditions at the time of failure. It is an effective approach to provide an insight into the underlying failure mechanism. While majority of hill slopes are in unsaturated state, the conventional methods of stability analysis are performed based on assumptions of saturated behaviour. Slope failures triggered by rainfall infiltration essentially occurs in unsaturated slopes. Hence, an extensive and detailed saturated-unsaturated transient seepage analysis is required for such case.

In this study, a systematic methodology is presented to explain the mechanism of rainfall-induced landslide initiation in unsaturated slopes. Transient seepage and stability analyses are combined with probabilistic back analysis to provide rational explanations to landslide initiation. Numerical analyses using FLAC (Fast Langrangian 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. The results of deterministic analyses in FLAC are used as input for the probabilistic back analysis of the slope. The two phase flow option in FLAC is used and it enables numerical modeling of flow of two immiscible fluids (air and water) through porous media. In FLAC, soil water characteristic curve and relative permeability of fluids are built-in and based on the empirical laws of the van Genuchten form (van Genuchten, 1980). The slope is composed of silty clay which is modeled as Mohr-coulomb material with cohesion 36 kPa and friction angle 22°.The soil and fluid properties used in the analysis are given in Table 2 and 3.

Table 3: Fluid properties

Parameter	Value
Wetting fluid density (kg/m3)	1000
Non-wetting fluid density (kg/m3)	0.0
van Genuchten parameter, *a*	0.281
van Genuchten parameter, *b*	0.0
van Genuchten parameter, c	0.5
van Genuchten parameter, P_0 (Pa)	4350
Wetting fluid modulus (MPa)	1.0
Non-wetting fluid modulus (Pa)	1.0
Mobility coefficient (m^2/ Pa-sec)	$7.074*10^{-11}$

The van Genuchten parameters a, b, c for a typical silty clayey soil are taken from Leij et al. (1996). The FLAC model is 340 m wide and the highest elevation from the base is 180 m as given in Figure 5. Zone 1 is not included in the model since it was not depleted during the landslide and only formed the zone of accumulation.

The slope is analysed for two successive rainfall events of increasing intensity and decreasing duration. The rainfall data is divided into two parts: 1) First rainfall event in which 260 mm of rain accumulates in a period of 57 days (1st June to 27th July) and 2) Second rainfall event in which 182 mm of rain accumulates in three days (28th July to 30th July). The numerical simulation is run in two stages: first rainfall event has intensity of $5.192*10^{-8}$ m/sec and second rainfall event has intensity of $7.05*10^{-7}$ m/sec.

Probabilistic back analysis is used in the study as it has the ability to determine numerous sets of stability parameters with uncertainty. The method acknowledges that there could be various combinations of parameters that can result in slope instability, but their relative likelihoods are different and can be quantified by probability distributions. Probabilistic method used in the analysis is based on Bayesian analysis. The method uses the measurements of observable parameters to infer the values of the parameters that characterize the system. Detailed explanation of this back analysis method is given Ering and Babu (2016).

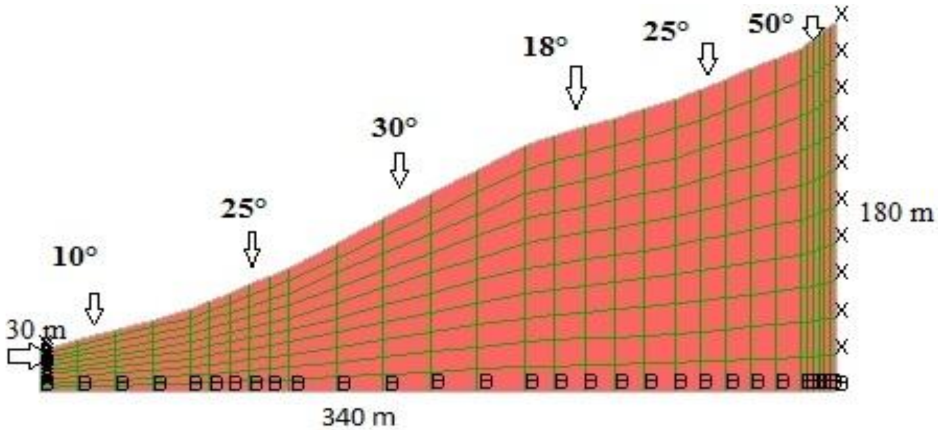

Figure 5: Slope geometry

Tarantola (2005) provided a probabilistic method to back analyze the slope stability parameters. A slope stability model is represented by R(x) and x is the set of uncertain input parameters. The uncertain input parameters used in this study are cohesion, friction angle and pore water pressure or matric suction. The probabilistic back analysis approach updates the probability distribution of x based on the observed slope behavior. A multivariate normal distribution with mean μ_x and covariance matrix $\mathbf{C}_x$ is employed to represent the prior probability distribution of x. The prior distribution as given by (Tarantola, 2005) is:

$$f(x) = const.\ \exp\left[-\frac{1}{2}(x-\mu_x)^T C_x^{-1}(x-\mu_x)\right] \quad (1)$$

Where a normalization constant is required to make the probability density function f(x) valid. The actual response (y) of the system is different from the observed one (y_{obs}) because of observational uncertainty. The probability density function of y given y_{obs} as given by Tarantola (2005) is

$$f(y|y_{obs}) = const.\exp\left[-\frac{1}{2}(y-y_{obs})^T C_y^{-1}(y-y_{obs})\right] \quad (2)$$

In addition, model uncertainty induces difference in the predicted response R(x) and the actual response y of the system. To incorporate the model imperfection effect in the system response, the model uncertainty can be assumed as a random variable z with mean μ_z and covariance matrix C_z

$$z = y - R(x) \quad (3)$$

Incorporating model uncertainty in the analysis, the probability density function of y given x is

$$f(y|x) = const.\exp\left[-\frac{1}{2}\left(y-R(x)\right)^T C_z^{-1}\left(y-R(x)\right)\right] \quad (4)$$

Based on these assumptions, the improved distribution of x considering the prior distribution f(x) and observed data y_{obs} can be described as:

$$f(x|y_{obs}) = const.f(x)\exp\left[-\frac{1}{2}(R(x)-y_{obs})^T C_M^{-1}(R(x)-y_{obs})\right] \quad (5)$$

Expanding f(x) in the above equation, the posterior distribution of x given y_{obs} becomes

$$f(x|y_{obs}) = const.\exp\{[R(x)-y_{obs}]^T C_M^{-1}[R(x)-y_{obs}] + (x-\mu_x)^T C_x^{-1}(x-\mu_x)\} \quad (6)$$

Where y_{obs} is the observed data; C_x is the prior covariance matrix of x; $C_M = C_y + C_z$, C_y is the covariance of actual system response (y) and C_z is the covariance of model uncertainty (z).

From equation (6), the posterior density function follows a Gaussian distribution so there must be a point such that the posterior density function can be written as:

$$f(x|y_{obs}) = const. \exp\left[-\frac{1}{2}\left(x - \mu_{x|y}\right)^T C_{x|y}^{-1}\left(x - \mu_{x|y}\right)\right] \quad (7)$$

Tarantola (2005) postulated that for a linear prediction model, the solution for the above equation is a closed form one and is given by:

$$\mu_{(x|y)} = \mu_x + C_x G^T (G\, C_x G^T + C_M)^{-1} (y_{obs} - G\,\mu_x) \quad (8)$$

$$C_{(x|y)} = (G^T C_M^{-1}\, G + C_x^{-1})\text{^} - 1 \quad (9)$$

$$G = \frac{\partial\, R(x)}{\partial x}\Big|_{x=\mu_x} \quad (10)$$

Where R(x) = G μ_x is a linear prediction model; G is the row vector which describes the sensitivity of R (x) with respect to x at point μ_x; $\mu_{x|y}$ and $C_{x|y}$ are the posterior mean and covariance of x respectively. In equation (8), R(x) = G μ_X is a biased model with mean model uncertainty μ_z hence an unbiased prediction model can be written as R(x) = G μ_x + μ_z. The unbiased posterior mean can be determined as (Tarantola, 2005):

$$\mu_{(x|y)} = \mu_x + C_x G^T (\, G\, C_x G^T + C_M)^{-1} \,(y_{obs} - G\,\mu_x - \mu_z\,) \quad (11)$$

Back analysis is required to provide technical evidence to prove or to disprove the hypotheses made on the cause of failures and to establish scenarios of failure. The objective of back analysis in this case study is to identify triggering factors of slope failure and to investigate the mechanisms which initiated landslide. Although from the previous studies, it has been concluded that rainfall infiltration in unsaturated slopes reduces matric suction or shear strength which leads to failure. However, till date it has not been establish how much decrease in matric suction can initiate landslide.

RESULTS

Heavy rainfall over three days before the slope failure is identified as the triggering factor for landslide because seismic activities were not recorded in the area. From numerical analysis, it is observed that the factor of safety of slope decreases from 1.475 in its initial state to 1.46 after the first rainfall infiltration. The stability further decreases and failed after the second rainfall infiltration. Figure 6 and 7 shows the state of slope after first rainfall and second rainfall event respectively. This reduction in factor of safety can be attributed to the lowering of shear strength of soil due to changes in pore water pressure and saturation contours in the slope during rainfall infiltration.

Figures 8, 9 show the saturation and pore water pressure at different depths. The depth zero corresponds to the top surface of the slope. It is observed that the saturation of the slope increases due to rainfall infiltration. During the second rainfall infiltration, the slope becomes fully saturated upto some decent depth as saturation increases from 0.55 to almost 1. The pore pressures generated in the slope changes from negative to positive values due to rainfall infiltration. During the second rainfall infiltration, the pore water pressures in the upper layers become positive. This is due to the complete saturation of the soil particles. From the results it can be concluded that rainfall infiltration did affect the stability of slope and the slope eventually failed. Rainfall infiltration increased the saturation in the slope and decreased negative pore water pressure or matric suction. This type of deterministic analysis is helpful in providing insights of the failure mechanism.

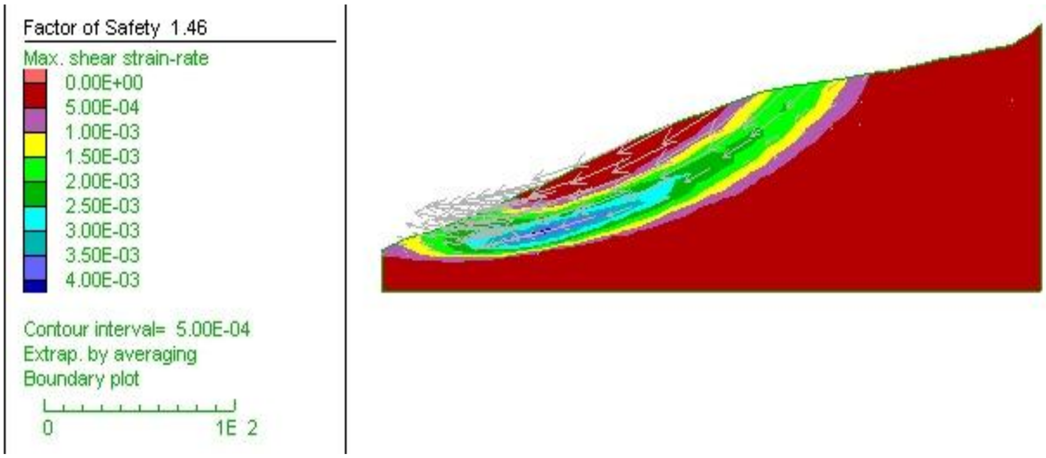

Figure 6: Factor of safety after First rainfall event

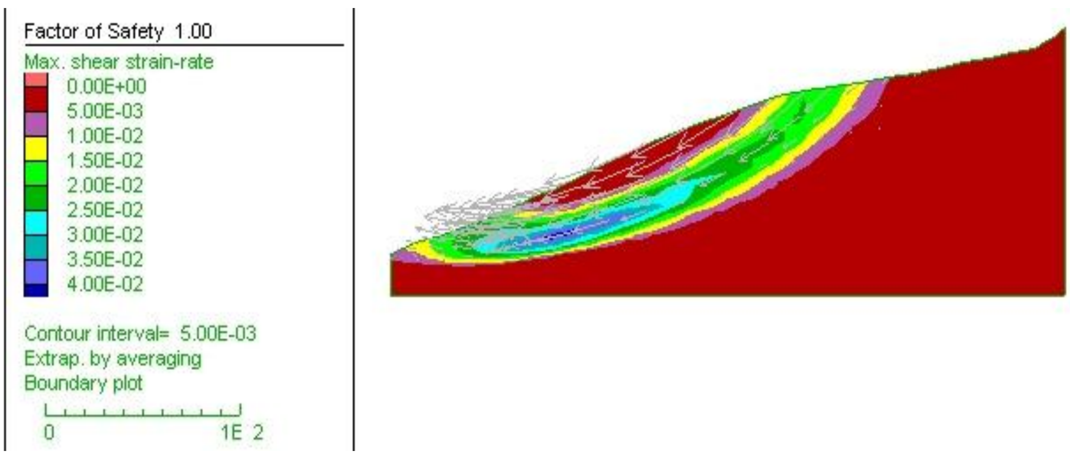

Figure 7: Factor of safety after second rainfall event

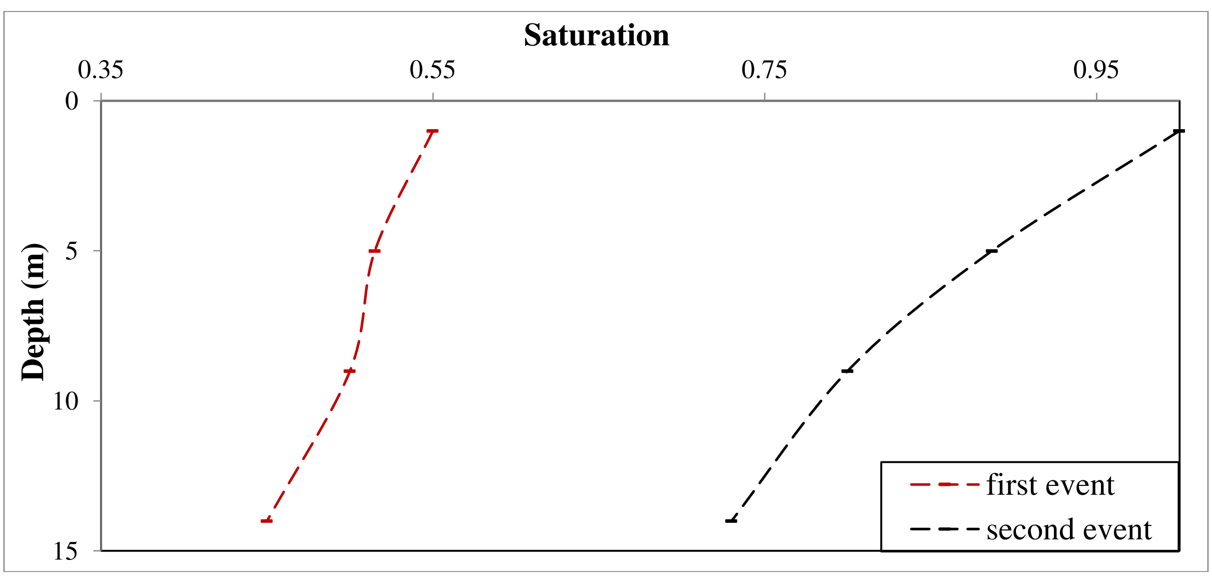

Figure 8: Saturation contours

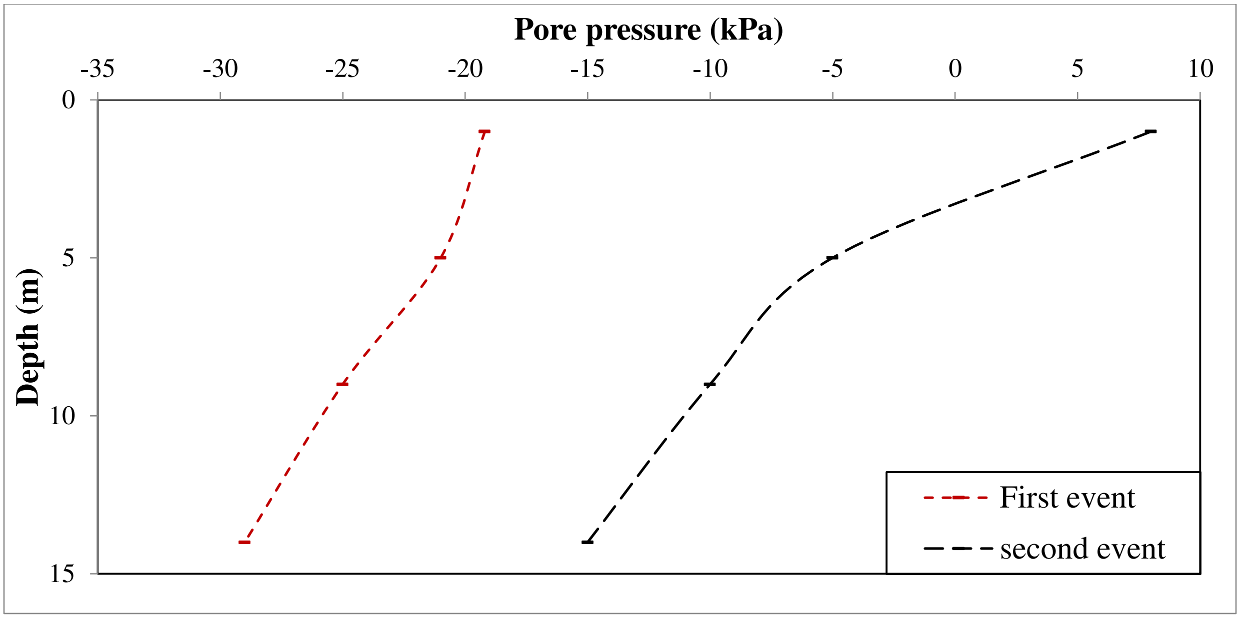

Figure 9: **Pore water pressure contours**

However, slope stability problems are dominated by uncertainty and this uncertainty arises at all stages in the resolution of the problem. Hence, it is important to incorporate uncertainty in the analysis.

Probabilistic back analysis based on Bayesian method is employed to incorporate uncertainties in the analysis. The input parameters (c, φ, ψ) are assumed to be statistically independent and a multivariate normal distribution with mean $\mu_x = \{36, 22, 19.5\}^T$ describes the prior distribution of x. The coefficient of variation of input parameters is given in Table 4. These values are taken from Babu and Murthy (2005).

Table 4: Coefficient of variation of parameters

Parameter	Mean value	COV (%)
Cohesion	36 kPa	10
Friction angle	22°	10
Matric suction	19.5 kPa	40

The covariance matrix of multivariate normal distribution is

$$C_x = \begin{bmatrix} 3.6^2 & 0 & 0 \\ 0 & 2.2^2 & 0 \\ 0 & 0 & 7.8^2 \end{bmatrix} \qquad (12)$$

The model uncertainty of slope stability model can be assumed as a random variable with mean (μ_z) 0.05 and standard deviation (σ_z) 0.07 (Zhang et al., 2010a). The analysis is conducted in two stages: first, to obtain posterior distributions of x due to first rainfall infiltration during which the slope is stable and second, to obtain posterior distributions of x due to second rainfall event during which the landslide occurred. From the field observations, the slope was stable during and after the first rainfall event. Hence, the observed data or observed factor of safety (y_{obs}) can be taken as 1.5. The posterior mean of x can written as:

$$\mu_{(x|y)} = \mu_x + C_x G^T (G\, C_x G^T + \sigma_z^2)^{-1} (1.5 - R(x) - \mu_z) \quad (13)$$

Where μ_x, C_x are prior mean and covariance of x; G is a row vector which describes the sensitivity of R(x) w.r.t x at μ_x; G^T means transpose of G; σ_z^2 and μ_z are the covariance and mean of model uncertainty.

$$\mu_{(x|y)} = \mu_x + C_x G^T (G\, C_x G^T + 0.07^2)^{-1} (1.5 - R(x) - 0.05) \quad (14)$$

Posterior covariance of x can be obtained by

$$C_{(x|y)} = \left(\frac{G^T G}{\sigma_z^2} + C_x^{-1}\right)^{-1} \quad (15)$$

Sensitivity G of R(x) at μ_x is obtained by running (2n+1) numerical analysis where n is the number of input parameters. R(x) is computed with respect to change in an individual input parameter while keeping all other parameters same. The samples of input parameters are generated in MATLAB with mean and standard deviation obtained from the analysis. Field observations revealed that the slope failure occurred after the second rainfall event. Hence y_{obs} is 1 in this case. The improved mean based on updated information is given as:

$$\mu_{(x|y)} = \mu_x + C_x G^T (G\, C_x G^T + 0.07^2)^{-1} (1 - R(x) - 0.05) \quad (16)$$

The prior mean and covariance for this analysis is the same as posterior mean and covariance obtained from the previous analysis or first rainfall event. Given the prior mean, covariance of x; model uncertainty mean and covariance, the posterior mean and covariance of x can be obtained. The first stage involves updating the probability distributions of x based on the first rainfall event. The value of R(x) at this stage is 1.475 which is evaluated from the FLAC analysis. The sensitivity G is [0.029 0.131 0.004] where the first value is the sensitivity of cohesion, second is that of friction angle and the last is that of matric suction. Solving equations (14) and (15), we get posterior mean and covariance as

$$\mu_{(x|y)} = \begin{bmatrix} 35.9059 \\ 21.8412 \\ 19.4391 \end{bmatrix} \quad (17)$$

$$C_{(x|y)} = \begin{bmatrix} 11.5451 & -2.3870 & -0.9162 \\ -2.3870 & 0.8132 & -1.5456 \\ -0.9162 & -1.5456 & 60.2468 \end{bmatrix} \quad (18)$$

Equation (18) gives covariance matrix of correlated normals. Hence, to generate the samples of input parameters or x, Eigen value transformation is performed to convert correlated normals to uncorrelated normals in MATLAB. Figures 10, 11 and 12 shows the improved distributions of cohesion, friction angle and matric suction respectively.

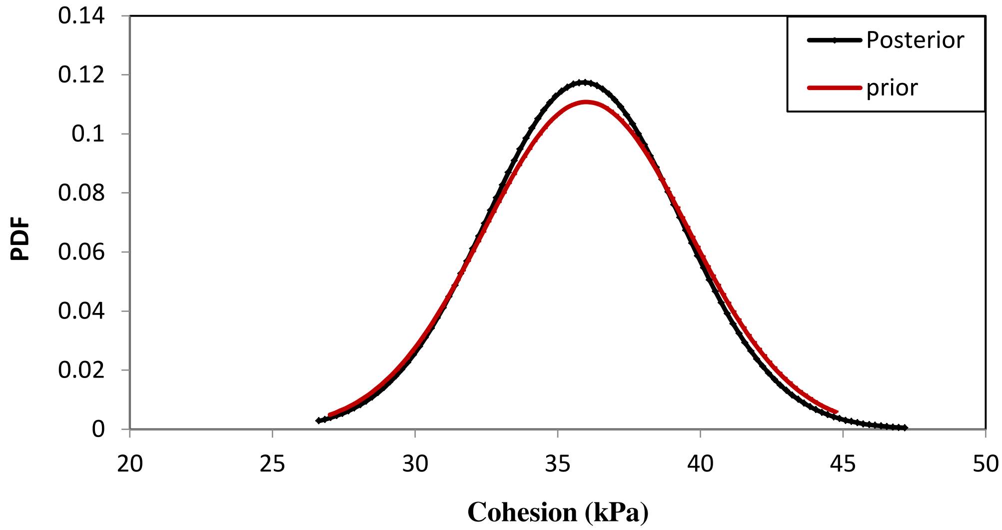

Figure 10: **Probability distribution of cohesion**

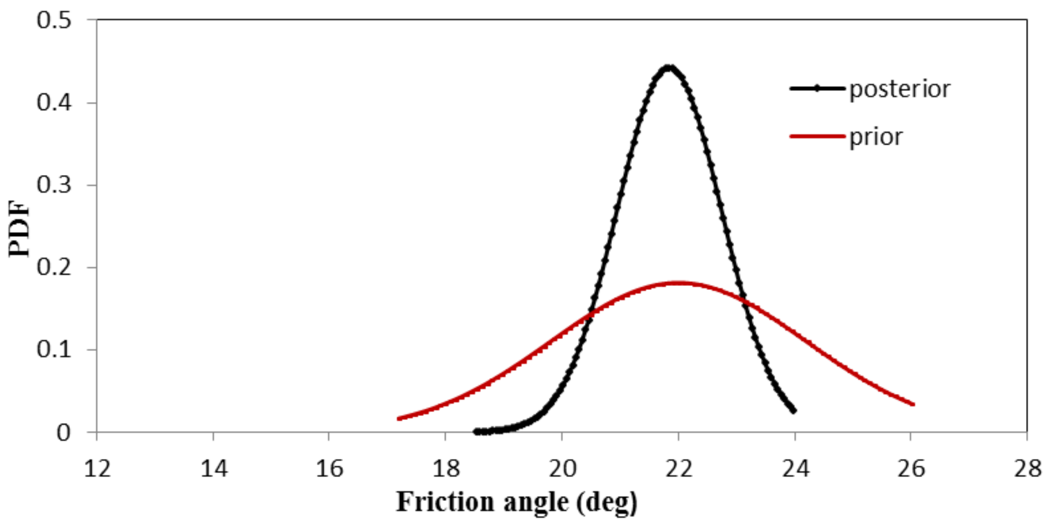

Figure 11: **Probability distribution of friction angle**

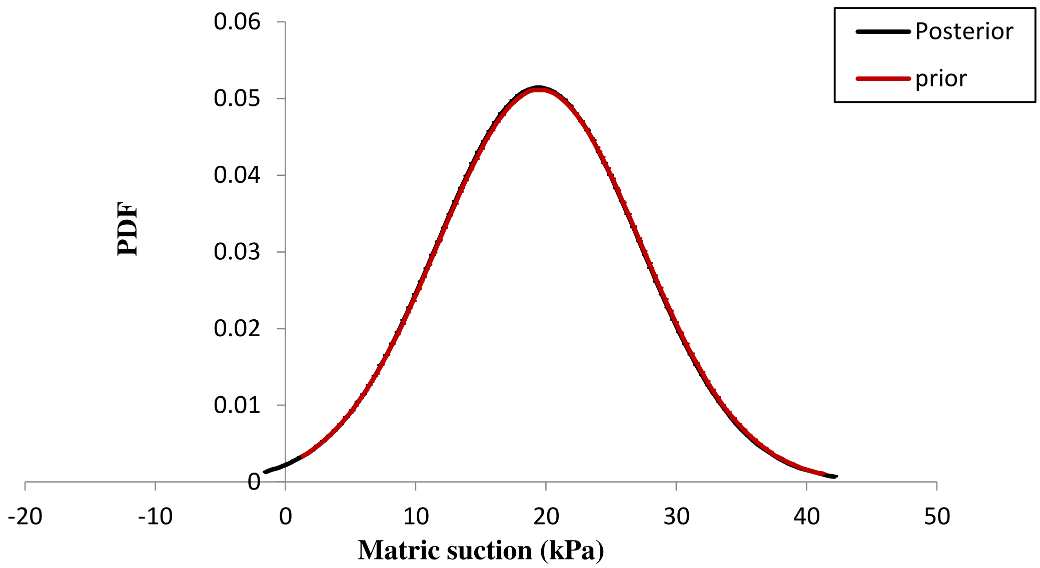

Figure 12: **Probability distribution of matric suction**

It is observed that the cohesion remains almost the same before and after the first rainfall event. The mean value of friction angle remains same but the coefficient of variation is less in the posterior distribution. The improved distribution of matric suction coincides with the prior distribution which indicates that there is no significant reduction in matric suction due to first rainfall event. These results explain that since shear strength parameters and matric suction did not change after the first rainfall event, the slope remains stable during and after the first rainfall event.

The second stage involves updating the above distributions of x based on the second rainfall or slope failure information. The prior mean and covariance of x is same as (17) and (18). At this stage, the value of R(x) is 1.46, observed slope data is 1 and the sensitivity is [0.002 0.002 0.012]. Solving equations (16) and (15), the improved or posterior mean and covariance is obtained. The improved mean and covariance at second stage are:

$$\mu_{(x|y)} = \begin{bmatrix} 35.6290 \\ 22.6615 \\ -7.7115 \end{bmatrix} \tag{19}$$

$$C_{(x|y)} = \begin{bmatrix} 11.5451 & -2.3752 & -1.3060 \\ -2.3752 & 0.7783 & -0.3906 \\ -1.3060 & -0.3906 & 22.0210 \end{bmatrix} \tag{20}$$

Equation (19) implies that after second rainfall event, friction angle increases and matric suction becomes negative. Figures 13, 14 and 15 shows the posterior distributions of cohesion, friction angle and matric suction. From Figure 15 it is observed that the pore pressures in the slope changed from negative to positive values or matric suction values changed from positive to negative. This reduction in matric suction values along the slip circle to about 100% can be attributed to the rainfall infiltration.

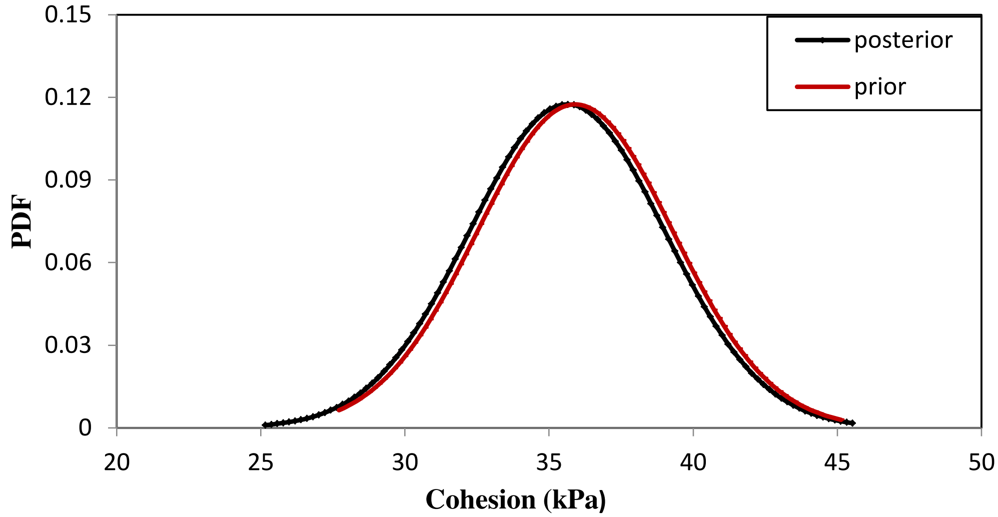

Figure 13: **Probability distribution of cohesion**

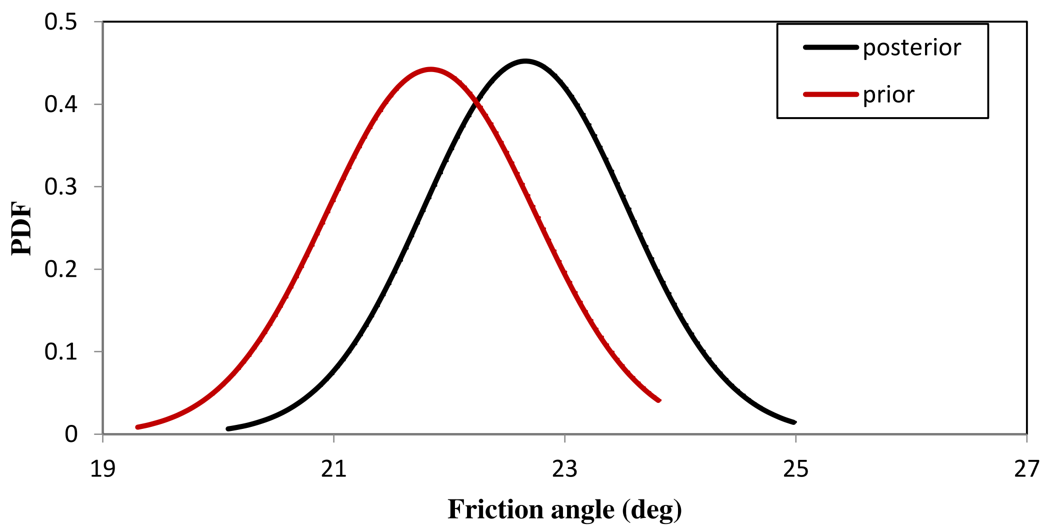

Figure 14: **Probability distribution of friction angle**

The matric suction is reduced to such a value that it no longer provides additional cohesion or strength to the soil slope and the development of positive pore pressures increase the stresses induced in the slope such that equilibrium can no longer be maintained in the slope. Hence, the reduction in matric suction to about 100% and the development of positive pore pressures together has caused the landslide in Malin area.

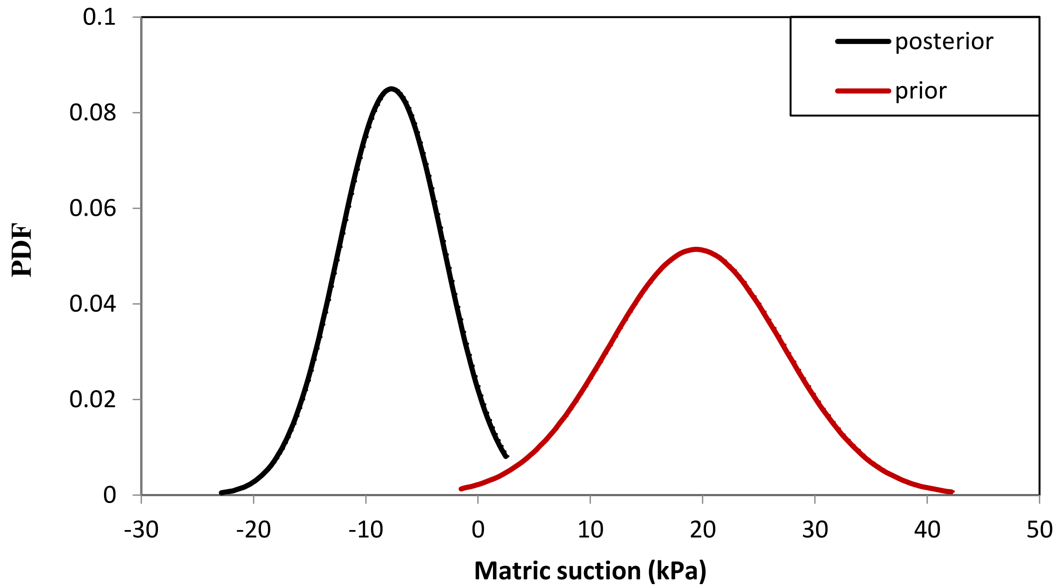

Figure 15: **Probability distribution of matric suction**

CONCLUDING REMARKS

The disaster in Malin has taught us lessons especially in Indian scenario that we are yet to evolve comprehensive, protective and predictive mitigation strategies for such disasters. It is time to start working on strategies to prevent such costly disasters in the future rather than leaving everything to the heroic deeds of National Disaster Response Force (NDRF). Following are some of the important points derived from the failure incident in Malin:

1. The results of failure analysis reveal that landslide initiation is a complex problem. To understand the physics behind or to answer the question "why did it happen", it is essential to investigate the disaster to the last detail. Different stages of investigation are employed to give rational explanations to the failure. For landslide analysis, it is important to develop a framework which incorporates unsaturated soil mechanics into the traditional slope stability analyses. Conventional stability analysis which assumes saturated behaviour of soils underestimate the soil strength and might give misleading failure scenarios.
2. Uncertainty is inherently present at all stages in the resolution of problem, from the material property evaluation to analysis and consequent assessment. Hence, it is essential to involve uncertainty in failure analysis. Probabilistic back analysis was carried out on the failed slope in Malin and all the possible combinations of parameters that can result in slope instability are determined. Although there can be various failure scenarios but it is observed that the reduction in matric suction value of about 100% and development of positive pore water pressure was the most probable failure mechanism.
3. Heavy rainfall is considered as the triggering factor for the disaster but the fact is rainfall has always been a seasonal visitor in the area. Human activities such as deforestation, improper land use planning also have contributed to the slope failure. Amongst all other factors which trigger landslide, rainfall is the easiest one to quantify correctly. Rainfall induced landslides can be prevented by formulating a relationship between rainfall intensity, duration and occurrence of landslides. Though global rainfall thresholds for

landslide occurrence are developed but these types of thresholds should also be developed for regional scales.

4. As discussed earlier, signs of distress and cracks were witnessed by the villagers but they chose to move back to the village without understanding the risk associated with it. It is important to perform risk assessment of the area which involves characterisation of consequence scenarios, determining elements at risk and their vulnerability, evaluate probability of landsliding and severity of consequences. Such assessment or zoning may help people in avoiding those danger areas.
5. The disaster in Malin could have been avoided if efficient early warning systems were used. It is important to monitor inclinations, deformations and pore water pressures in the slopes among others. Slope health monitoring is essential to reduce the risk of landsliding in the area. It is only a matter of time that the slope will fail because all slopes which look like they are about to fail will eventually fail and all slopes which look stable will also eventually fail due to the effect of gravity and other factors. Hence, installation of early warning system become essential to mitigate slope failures in the future.
6. It is important to develop people-centred early warning system. As it is observed from the Malin incident that people were warned of the risk of landslide but they moved back in the area. Communication or dissemination of alerts and warnings should be efficient such that the local bodies should respond to the warnings. People living in landslide risk zones should be educated about the risk of landslide and their consequences.

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