

Probabilistic rock slope stability analysis for Himalayan condition

Shubh Pathak · Bjørn Nilsen

Abstract Quantification of variable input parameters (groundwater pressure, active friction angle and seismic acceleration) is often a difficult task in slope stability analysis for Himalayan conditions. The objectives of the study were to estimate the value of these variable parameters and study their sensitivity in rock slope stability analyses for Himalayan conditions.

A road cut at the Desander back slope of the Kali Gandaki hydropower project of Nepal is considered as a case history as it is representative of a common stability problem in Himalayan conditions. It is concluded that the probabilistic approach is the most realistic way of determining input parameters for slope stability analysis.

Résumé La quantification de paramètres tels que la pression interstitielle, l'angle de frottement et l'accélération sismique représente souvent une tâche difficile dans les études de stabilité de pentes en contexte himalayen. Les objectifs de cet article sont l'estimation de ces paramètres et la réalisation d'analyses de sensibilité.

Une tranchée routière sur le versant de Desander, près du projet hydroélectrique de Kali Gandaki au Népal, constitue une étude de cas de référence. L'étude conclut qu'une approche probabiliste s'impose pour la prise en compte des paramètres nécessaires aux études de stabilité de pentes.

Keywords Probabilistic analysis · Rock slope stability · Variable input parameters · Himalayan conditions

Mots clés Analyses probabilistes · Stabilité de versants rocheux · Paramètres de calcul · Contexte Himalayen

Introduction

Geotechnical engineers have always been familiar with the concept of uncertainties. The uncertainty may be in the form of a large scatter in rock test results, or it may be associated with a substantial deviation of the field-measured property from its predicted value. Undoubtedly, engineering judgement has played a significant role in the treatment of unavoidable uncertainties (Tang 1993). In the late 1960s, probabilistic methods were introduced, most notably by Wu and Kraft (1970), to identify the sources of geotechnical uncertainties and to study the effects of those uncertainties on the reliability of slope stability analysis. The rationale of the probabilistic approach is using probability theory to provide a systematic procedure for treating the uncertainties quantitatively. In rock slope stability analysis, quite different conclusions may be reached depending upon the selection of the input parameters. Therefore, great care has to be taken during the selection of input parameters.

The main input data for rock slope stability analysis are geometry, groundwater pressure, friction resistance and seismic acceleration. In the probabilistic approach, parameters related to geometry and unit weights are known as constant parameters. Water pressure, the active frictional angle and seismic acceleration may however vary within wide limits. They do not have one single, fixed value. There is no way to predict exactly what the value of these parameters will be at any location hence these parameters are described as variable input parameters. The objective of the work reported here was to determine the value of these variable parameters and study their sensitivity for rock slope stability analysis for Himalayan conditions.

Case study

To determine the variable input parameters for the probabilistic rock slope stability analysis, a road cut at the Desander back slope of the Kali Gandaki hydropower

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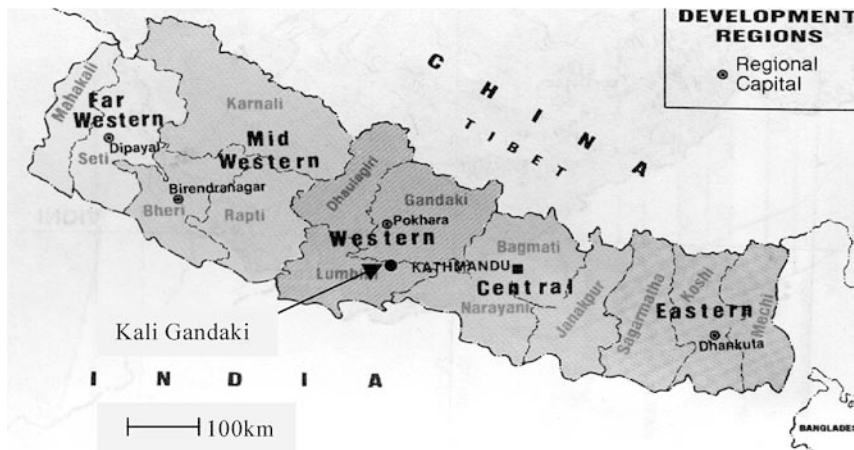


Fig. 1
Location of the project area

project of Nepal was considered as being representative of a common stability problem in Himalayan conditions. Due to the unstable geology along the hill slopes resulting from tectonic movement, dramatic variations in the topography and the intensive rainfall during every monsoon season, serious landslides have occurred frequently in Nepal. Slope failures have also been triggered by seismic activities. In addition to the importance of these landslides for infrastructures and properties, they have had a marked effect on the lives of local people and been a cause of many socio-economic problems including deforestation and intensive agricultural practices etc.

The Kali Gandaki hydropower project is a run-of river scheme located on the Kali Gandaki River in the Syangja district, the western development region of Nepal (Fig. 1). The installed capacity of the project is 144 MW and it generates about 842 GWh of electrical energy per year. The power from this project has been connected to the central grid. The available electrical energy has provided a greater operating flexibility to the system and reduced the country's dependence on imported fuels. The project has been in service since March 2002.

During the excavation of the Desander back slope in early 1998, a shallow failure occurred. A second failure, which was smaller, took place later the same year. These failures gave rise to concerns about the overall stability of the Desander back slope. The potential stability problem was caused by steep slope excavations in weak strata dominated by phyllite. Flattening of the slope and the installation of toe drains were chosen as remedial measures to stabilize this slope. Moreover, to control the surface erosion, which is very common in weathered phyllite during the monsoon period, shotcreting was undertaken. A view of the modified Desander back slope is shown in Fig. 2.

As mentioned above and shown in Fig. 2, the original cut slope was subsequently modified. However, the authors have decided to consider the original cut slope for this case study to quantify the variable input parameters. The profile of the original slope is shown in Fig. 3. Based on detailed field mapping, it was concluded that three discontinuity sets are predominant in the Desander area; see Table 1. The plane of the Desander back slope (SF) is

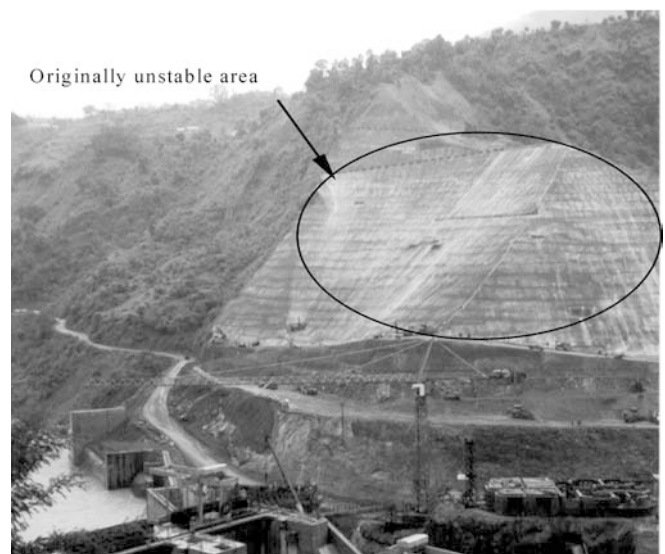


Fig. 2
View of the modified Desander backslope. Original unstable area is indicated

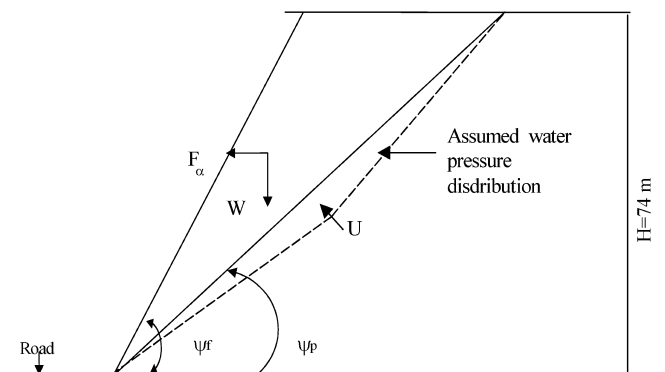


Fig. 3
Schematic sketch of potential stability problem (wedge failure) of the original Desander backslope

an average $60^{\circ}/322^{\circ}$ (dip/dip direction). The plotting of a stereographic projection (lower hemisphere) of these discontinuities is presented in Fig. 4. This shows that the

Table 1
Discontinuity sets for the Desander back slope area

Joint set number	Dip/dip direction (deg)	Joint spacing (cm)	Roughness
1 Foliation (J_1)	57/167	1-2	Planar to undulating
2 Joint (J_2)	51/342	18-40	Undulating
3 Joint (J_3)	58/276	8-30	Undulating

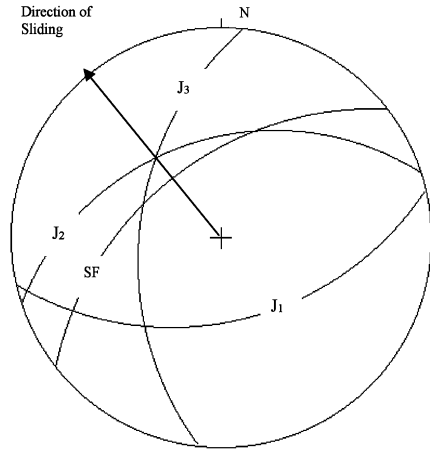


Fig. 4
Stereographic projection in the phyllites for the Desander back slope area

Desander back slope has a probability of wedge failure with a direction of sliding 320° and a plunge of the intersection line between J_2 and J_3 of 52° .

Characteristics of the input parameters

In Nepal there are basically two categories of landslides—the landslides inherent in the natural environment

Table 2
Input parameters and calculation results

Parameters	Deterministic				Probabilistic @RISK value
	Worst case (U_{max}/α_{max})	Best case ($U=0, \alpha=0$)	No water/ earthquake	No earthquake/ water	
Fixed					
$H(m)$	74	74	74	74	74
$\psi_i(deg)$	60	60	60	60	60
$\psi_i(deg)$	52	52	52	52	52
$W(kN/m)$	16027	16027	16027	16027	16027
Random					
$U(kN/m)$	3545	0	0	3545	996.09
α	0.3	0	0.3	0	0.084
$F_\alpha (kN/m)$	4808	0	4808	0	1350.77
$\sigma_n(kN/m^2)$	39.9	155.2	95.7	99.5	122.87
$\phi_a(deg)$	48.32	44	45.24	45.11	44

and the landslides initiated by public infrastructure built without making allowances for possible instabilities. Earthquakes are one of the main triggering agents of slope failure in the Nepal Himalayas. Moreover, the steep slopes, unstable geology (with weathered and crushed rocks) and intense monsoon rains, combine to make the young mountains one of the most hazard-prone areas in the world. In the light of the above, a detailed study of earthquake loading, groundwater pressures and shear strength parameters are particularly important for Himalayan conditions.

A schematic sketch of the potential stability problem of the original Desander back slope is given in Fig. 3. The calculated input parameters, which are based on Hoek and Bray (1981), Kovari and Fritz (1976) and Nilsen (2000) are given in Table 2. Values of variable input parameters for the probabilistic approach in this table are mean values of the truncation, as discussed below.

In the analysis, the following symbols/parameters were used. H =Slope height=74 m/ ψ_i =Slope angle= 60° / ψ_i =Plunge of line of intersection of two planes= 52° W =Weight of potentially sliding plane ($W=16,027$ kN/m) U =Water pressure resultant ($U_{max}=3,545$ kN/m) α =Seismic acceleration in fraction of g ($\alpha_{max}=0.3g$) $F_\alpha=m\alpha$ =Earthquake load ($F_\alpha_{max}=m \times 0.3g=0.3 W$).

The determination of the geometry is often a relatively simple task, because it can be easily defined by field mapping. The determination of groundwater pressure, active friction angle and seismic acceleration is relatively difficult in rock slope evaluation, because these parameters do not have a single fixed value.

Groundwater pressure

The distribution of groundwater in the hydro-geological regime varies with climate, topography and the nature and weathering condition of the bedrock. Due to the heavy rainfall during monsoon periods in the Himalayas and the loss by seepage, three levels of groundwater are considered: pre-monsoon, monsoon and post-monsoon. The frequency of precipitation ≥ 100 mm/24 h in a year for different regions of Nepal is shown in Fig. 5.

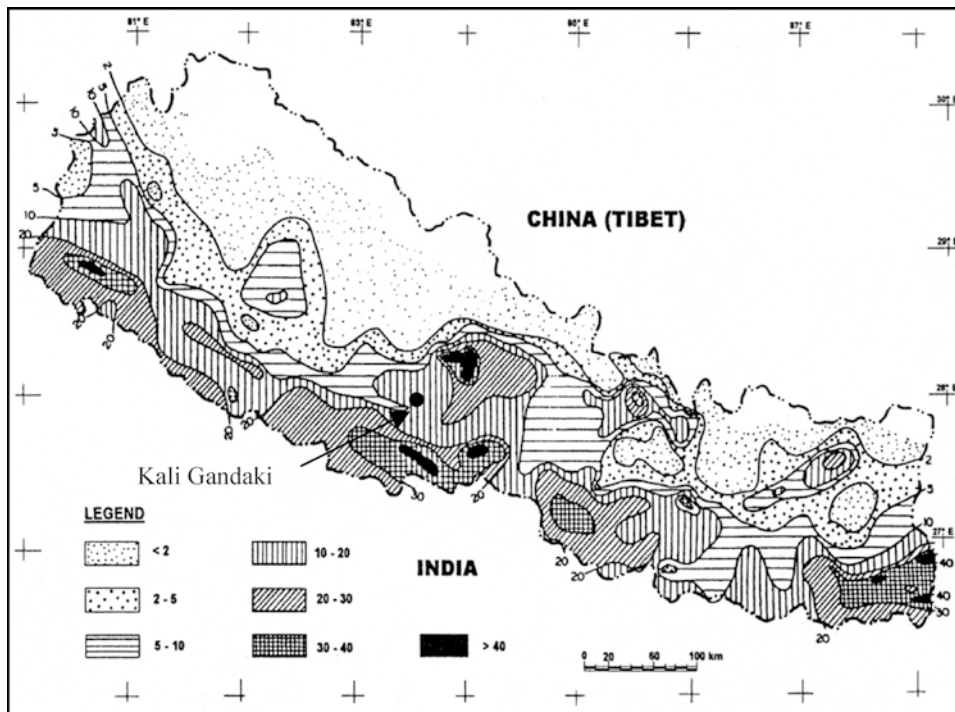


Fig. 5
Frequency of precipitation
>100 mm in 24 h between 1981 and
1990 for different regions of Nepal
(compiled by Upreti and Dhital
1996)

Many of the large and small landslides occur or reactivate during or after heavy monsoonal rainfall and hundreds of landslides occur in Nepal during every rainy season. Shallow landslides occur at the cumulative precipitation of 50–100 mm in 1 day and daily precipitation >50 mm in the area; the number of large landslides increases abruptly when there is >250 mm in 2 days with an average intensity of >80 mm/h in 1 day (Li 1990).

There are 25 precipitation/meteorological stations within the Kali Gandaki basin, but the precipitation station at Ridi Bazar is considered to be representative of the meteorological conditions at the project site (Morrison Knudsen Centennial et al. 1993). The station is located approximately 15 km from the project area. The available data for this station, which include mean monthly precipitation and maximum 24-h precipitation for the period of 1970–1990 are given in Table 3.

As precipitation is very high during the monsoon period in the Kali Gandaki project area (Table 3), the idealized triangular distribution of water pressure along the potential sliding plane as suggested by Hoek and Bray (1981) was considered to be the most appropriate for this study. This model represents a condition where water enters freely at the top of the slope but is fully drained at the toe after having reached a maximum pressure at a height corresponding to 50% of the slope height. The resultant water pressure (U_{max}) for the wedge failure case can be calculated as shown in Fig. 3. For the selected case, it is assumed that the maximum value of water pressure ($U_{max}=3,545 \text{ kN/m}^2$) would occur only very rarely within a 50-year period.

The technology and tools for groundwater pressure evaluations are well developed today, but there are always some constraints with the resources available to evaluate

Table 3
Monthly rainfall for Kali Gandaki area (from Morrison Knudsen Centennial et al. 1993)

Month	Mean (mm)	Lowest (mm)	Highest (mm)
January	28	0	117
February	22	0	79
March	27	0	126
April	40	0	134
May	96	15	210
June	240	81	517
July	416	221	678
August	288	75	613
September	196	19	532
October	63	0	430
November	6	0	60
December	16	0	72
Year	1436	411	2259

the conditions properly. Moreover, the suggested models seldom correspond perfectly with the real situation.

Active friction angle

As mentioned earlier, the Desander back slope is in highly weathered and crushed phyllite (Fig. 6).

The evaluation of shear strength parameters is generally a difficult task but is further complicated by the nature of the Himalayan geology and the difficulty of access. In this case study, the term active friction angle is used to define the shear strength of a discontinuity as discussed by Nilsen (1985):


Fig. 6

Weathered phyllites of the Desander backslope area. A Schmidt hammer was used for the rock strength test, as indicated in the figure

$$\tau = \sigma_n \times \tan \phi_a \quad (1)$$

where τ =Shear strength of rough joints (MPa) ϕ_a =Active friction angle of the sliding plane (degree) σ_n = Defined normal stress on the potential sliding planes (MPa)

To determine ϕ_a , the following empirical equation, proposed by Barton and Bandis (1990), is used here:

$$\tau = \sigma_n \times \tan \left(\phi_b + \text{JRC} \log_{10} \left(\frac{\sigma_j}{\sigma_n} \right) \right) \quad (2)$$

where JRC=Joint roughness coefficient σ_j =Joint compressive strength based on Schmidt hammer measurement (MPa) ϕ_b =Basic friction angle (degree) The other symbols in Eq. (2) are as in Eq. (1).

Based on the field study and laboratory testing and taking into account scale effects, the values of the friction parameters are: JRC=8, JCS=17 MPa, $\phi_b=27^\circ$. The calculated results of σ_n and ϕ_a for the different cases are given in Table 2.

The variation of rock properties is a major uncertainty in slope stability analysis. Several difficulties arise in the practical assessment of scatter and systematic error.

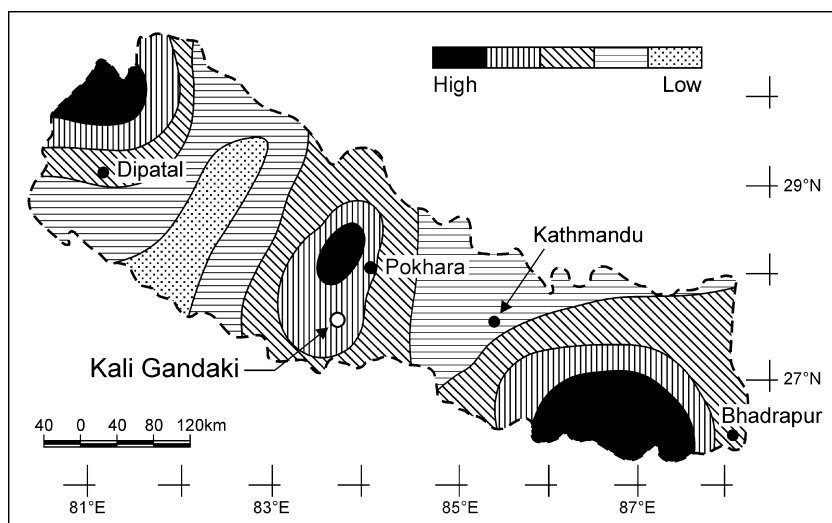
Seismic acceleration

Earthquakes are one of the natural hazards which occur in the Nepal Himalayas and take a heavy toll of life and property. Seismo-gravitational phenomena could generate serious slope instability after earthquakes with intensities >6 on the Richter scale in the mountain slopes of the area. A simplified seismic map of Nepal is given in Fig. 7. Table 4 shows the frequency of earthquakes instrumentally recorded for the period of 1911–1991 within 150 km of Nepal's border.

There are several major thrust and fault zones in the Himalayas, but only two are of major concern for the Kali Gandaki project: the Main Boundary Fault (MBF) and the Bari Gad Fault (BGF). The MBF is seismically active and many of the largest earthquakes of the region are believed to be associated with it. The BGF runs close to the project area and is believed to be active over much of its length. In addition to these major features, there are numerous minor faults. The earthquake magnitudes for the Kali Gandaki project area for the period 1978 to 1990 are given in Fig. 8.

In rock slope stability analysis, the so-called pseudo-static principle is commonly used, i.e., to consider the maximum earthquake load as an equivalent horizontal load (Nilsen and Palmstrom 2000; Aleotti and Chowdhury 1999). For this project, the maximum seismic acceleration for a 50-year period is assumed to be $\alpha_{\max}=0.3g$.

Nepal has not yet published any Earthquake Catalog. One of the main problems in studying the Nepalese projects is to obtain acceptable standard data on earthquakes. The Earthquake Catalog published for Continental Asia can be used to evaluate the seismic


Fig. 7

Simplified seismic map of Nepal (source Bajracharya, from Humagain 2000)

Table 4

Magnitude–frequency data on earthquakes in Nepal and the surrounding regions (from Geohazards International 2002)

Richter magnitude	No. of events	Approx. recurrence interval/year
4–6	41	2
6–7	17	5
7–7.5	10	8
7.5–8	2	40
>8	1	81

acceleration for particular cases, but requires some extrapolations. Quantification of seismic acceleration is therefore a relatively difficult task for Nepalese projects.

Variability of input parameters/ sensitivity study

The objective of a sensitivity study is to determine the basic statistical parameters (i.e. mean and variance) and the probability density function (PDF) in order to represent and predict the random property of the variable parameters. The PDF is used to model the relative likelihood of a random variable. The mean value of the PDF represents the best estimate of the random variable and the standard deviation of the PDF represents an assessment of the uncertainty. The Latin Hypercube technique—a stratified sampling technique where the random variable distributions are divided into equal probability intervals, is used for this study. A probability is randomly selected from within each interval for each basic event. The programs BestFit and @Risk, developed by the Palisade Corporation (1996, 1997) were used for this study.

Groundwater pressure

The probability distribution function (PDF) model of water pressure is assumed to be exponential with a truncation represented by the U_{\max} value and mean value defined as $U_{\max}/3$ as suggested by Nilsen (2000) and Hoek (1998). It is believed that this model will also be relevant for Himalayan conditions. The probabilistic model of water pressure, which is considered to be a truncated exponential function, represented by the $U_{\max}=3,545$ kN/m² and the mean value, which is equal to $U_{\max}/3=1,182$ kN/m² is presented in Fig. 9. This indicates that the maximum value of water pressure occurs very rarely during the 50-year lifetime of the slope while the minimum value of water pressure ($U=0$) occurs in most common situations.

Active friction angle

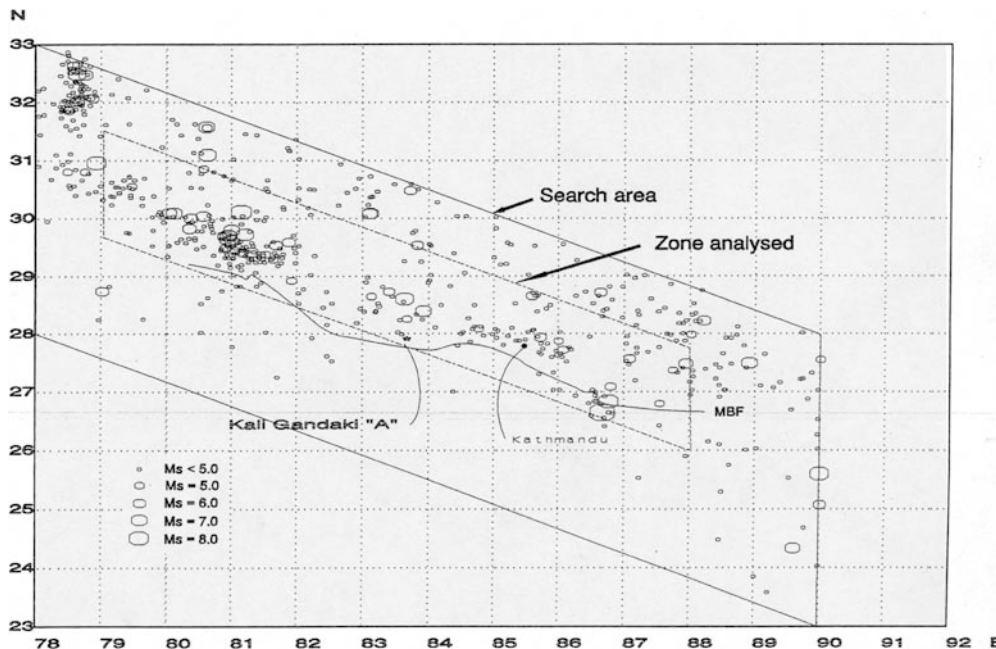
The active friction angle is modelled as a truncated normal distribution as suggested by Hoek (1998) and Nilsen (2000). The normal distribution is truncated by a minimum and maximum realistic value of the active friction angle. The probability density function for a normal distribution is defined by Hoek (1998):

$$f_x(x) = \exp\left[-0.5\left(\frac{x - \mu}{\sigma}\right)^2\right] / \sigma(2\pi)^{0.5} \quad (3)$$

For $-\infty \leq x \leq \infty$

where σ = true standard deviation, μ = true mean

For the selected case, the mean is 44° as indicated in Table 2 and is the approximate centre of the shear strength range illustrated in Fig. 10. The standard deviation of 4° implies that about 67% of the active friction angle values defined by the distribution will lie between 40° and 48°. The normal distribution is truncated by a minimum value of 29° and maximum value of 59°, which are believed to be the realistic upper limits for this project.

**Fig. 8**

Instrumental epicenters for the period 1978 to 1990 (Morrison Knudsen Centennial et al. 1993)

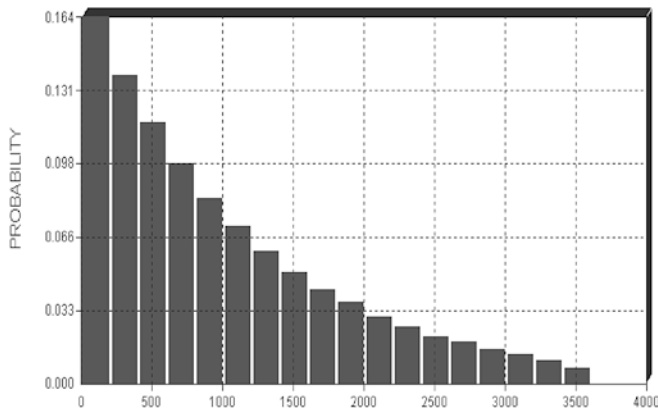


Fig. 9
Assumed probability distribution of water pressure (U)

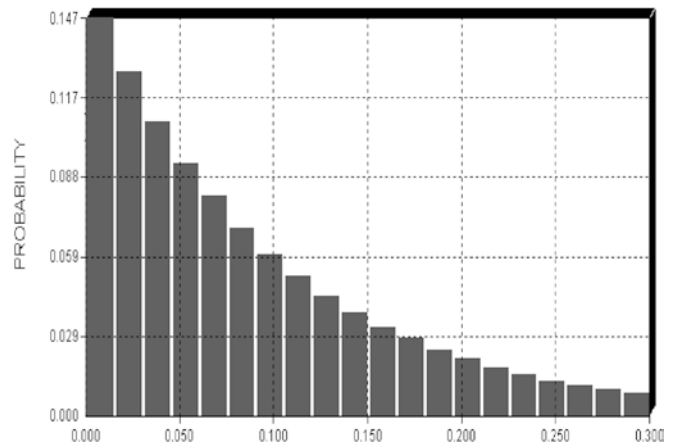


Fig. 11
Assumed probability distribution of seismic acceleration (α)

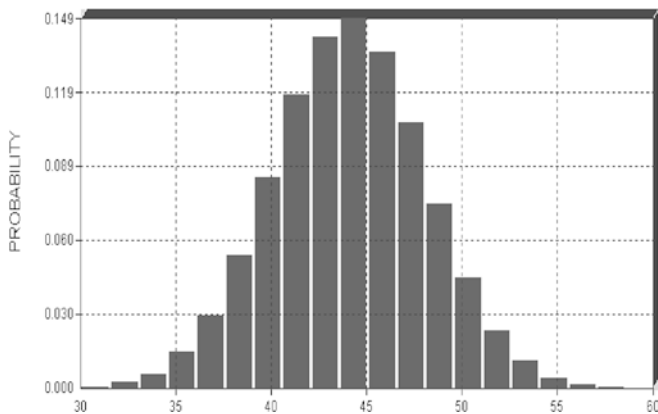


Fig. 10
Assumed probability distribution of active friction angle (ϕ_a)

Seismic acceleration

The probability distribution function (PDF) model of earthquake loading for the study is assumed as a truncated exponential function (Fig. 11), with a truncation represented by the α_{\max} value and mean value defined as $\alpha_{\max}/3$ as suggested by Nilsen (2000) and Hoek (1998). It is believed that this model can also be relevant for Himalayan conditions, because large earthquakes are very rare but small ones are very common in the Himalayas. For this case, the maximum seismic acceleration is assumed to be $\alpha_{\max}=0.3g$ and the mean value= $\alpha_{\max}/3=0.1g$.

Conclusion

The paper highlights the considerable difficulty in acquiring actual parameters for use in calculations for slope stability problems in the Himalayas. Attention is drawn to the problem of obtaining realistic rock strengths and the angle of friction in the phyllitic rocks in the study area. In addition, the water pressures related to the variable seasonal rainfall of the area change significantly such that most slope failures occur following the monsoon

rains, notably when the rainfall is higher than 100 mm in a 24-h period. The difficulty in obtaining a realistic ground water pressure is clearly immense in such an area where infiltration is also relatively rapid.

The paper demonstrates the value of a probabilistic approach in an area such as the Himalayas.

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