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ORIGINAL PAPER

Analysis of Overall Reliability of Embankment Dam for Steady-State Seepage

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Abstract The reliability method of slope stability analysis, unlike the deterministic approach, received a series of attention to evaluating the performance of the slope, this method considered uncertainties of the random variables of the soil parameters. This study considered steady-state seepage conditions and the soil variability resulting from the inevitable uncertainties. Uncertainties were managed by Monte Carlo simulation (MCS) for 1000 iterations integrated into Slide 6 software. Both normal and lognormal probability distributions were considered for the most likely value of the soil parameters and the standard deviation of each soil parameter. The standard deviation for each soil was expressed with the soil's coefficient of variation (COV). For the random variable of each of the soil parameters, the stability analysis of the dam by the Morgenstern-price method gave a mean factor of safety (FS) of 1.202, probability of failure (PF) of 0.217% or reliability (R) of 99.783%, reliability index (RI) of 2.608 and 2.827 respectively for a normal and lognormal distribution. Sensitivity analysis showed that FS is more sensitive to the shell material's friction angle (ϕ) than other soil parameters. Moreover, the effect of the surcharge on the probabilistic stability of the dam showed that PF increased and R decreased simultaneously with an increased surcharge load.

Keywords Embankment · FS · MCS · Reliability · Sensitivity · Steady-state

1 Introduction

The structural safety of the embankment dam depends on the slope of the dam, which requires serious attention to possible failure. Much research has been done to check the slope performance by using the deterministic approach for evaluating the slope performance for the case of cut slope and embankment dam; thus, conventional slope practice based on the factor of safety (FS) cannot explicitly address uncertainty (Abdulai and Sharifzadeh 2019; Cala and Flisiak 2020; Cheng and He 2020; Chowdhury 2017; Deliveris et al. 2020; Jaber et al. 2022; Kaur and Sharma 2016; Yu et al. 2005; Zheng et al. 2006).

Abramson (2002) concluded that two slopes with the same FS may experience different levels of safety since they experience different levels of uncertainty. Uncertainties are categorized as natural variability (randomness) and systematic (model) uncertainties (Stamatelatos 2002; Verma et al. 2016). Probabilistic techniques are rational means

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to quantify and incorporate uncertainty into slope analysis and design (Burgess et al. 2019; Chen et al. 2005; Chowdhury and Xu 1992, 1995; Duncan 2000; Hassan El-Ramly et al. 2002; Ge et al. 2019; Husein Malkawi et al. 2000; Li et al. 2016; Metya and Bhattacharya 2016; Myers 2005; Reale et al. 2015; Vanmarcke 1977; Villavicencio et al. 2011; Wang et al. 2021). Recently, many researchers investigated the slope performance by the reliability methods; Chowdhury (2017), Siacara (2020), Zhu et al. (2021), and Kar and Roy (2022) evaluated the slope performance by FS and showed the reliability of the slope.

Reliability-based slope stability received much attention for the analysis of slope, which gives information about the slope in more elaborative expression to evaluate the slope performance from the random variable input parameter considering uncertainty. Reliability is the probability of an object (item or system) performing its required function adequately for a specific time under stated conditions(Basha and Babu 2011; Chen et al. 2019; Chowdhury 1978; Li et al. 2016; 2020; Luo et al. 2016; Wang et al. 2019). Many research outputs analyzed the stability of embankment dams using a deterministic approach by ignoring uncertainties of the soil parameters and a few considered uncertainties to analyze cut slopes. However, considering uncertainty, few researchers have analyzed the dam's stability under steady-state seepage conditions.

This paper evaluated the overall slope reliability of an existing embankment dam under steady-state seepage conditions. Monte Carlo simulation (MCS) from the random variables was used for iterations; many researchers applied MCS (Aladejare and Akeju 2020; El-Ramly et al. 2003; Griffiths and Fenton 1997; Guo and Dias 2020; Kar and Roy 2022; Li et al. 2020; Misra et al. 2007; Tobutt 1982). MCS is integrated into Slide 6 software, which is the most comprehensive slope stability analysis software, coupling finite element seepage analysis and limit equilibrium slope stability analysis, complete with probabilistic capabilities. In this study, soil parameters from representative soil samples were the input parameters of the study. The reliability of the slope was determined for normal and lognormal distribution for the random variables of the input parameters for steady-state seepage conditions. The present paper figured out the slope statistically and was also used as an output for future research on the study area.

2 Materials and Methods

This paper aimed to determine the overall reliability of existing embankment dams from the random variables of soil parameters. In this paper, the reliability and probability of failure of the embankment dam were determined from the random variables of soil parameters by MCS for steady-state seepage conditions. Many researchers utilized MCS methods to manage uncertainties of the soil variability for evaluating slope performance (Aladejare and Akeju 2020; Griffiths and Fenton 1997; Guo and Dias 2020; Tobutt 1982).

2.1 Location of the Study Area

The project area in Rift Valley Lakes Basin is situated in the southern part of Ethiopia (Fig. 1). The project area lies approximately between 6° 20′ and 6° 25′ N and 38° 05' and 38° 10′ E, at an average elevation of 1190 m a.s.l.

2.2 Seepage Analysis

Seepage analysis is essential for the stability of embankment dams, which determines the pore water pressure that affects the dam's long-term stability. The pore pressure was determined from finite element analysis (FEA) of groundwater flow from Slide 6 software for steady-state and transient analysis conditions.

2.3 Reliability of the Slope

Reliability calculations evaluate the combined effects of uncertainties and distinguish between conditions where uncertainties are exceptionally high or low (Varde and Pecht 2018).

$$R(t) = P(T \geq t) \tag{1}$$

Reliability (R) denotes failure-free operation, which can be termed success probability (Eq. 1).

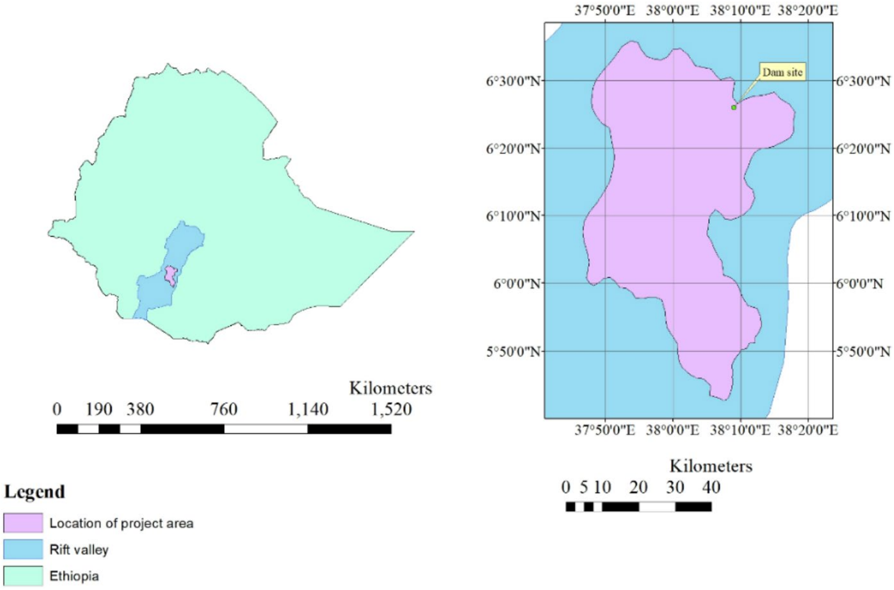


Fig. 1 Location of the study area

Conversely, the probability that failure occurs before the time t is called probability of failure (PF). Failure probability can be mathematically expressed as the probability that time to failure occurs before a specified time t expressed by Eq. (2).

$$R(t) = P(T \leq t) \tag{2}$$

Reliability Index (RI) often denoted by β, a ratio of the mean of safety margin (mean of FS-1) and the standard deviation of safety margin (SD of F), first defined by Cornell (1969) and expressed by Eq. (3).

$$RI = \beta = \frac{(mean\ of\ FS - 1)}{SD\ of\ FS} \tag{3}$$

Given the Probability Density Function (PDF), the failure probability or cumulative density function (CDF) and probability of success or reliability are given by Eqs. (4), (5).

$$F(t) = \int_{0}^{t} f(t)dt \tag{4}$$

$$R(t) = \int_{t}^{\infty} f(t)dt \tag{5}$$

Variability of the soil was expressed by the coefficient of variation (COV), the ratio of standard deviation to the most likely parameter value, which may be used as an indicator of parameter variability (Eq. 6).

$$\mathrm{COV_t} = \frac{\sigma_t}{\mu t} \tag{6}$$

Many researchers have shown COV for soil parameters to indicate variability: (Akbas and Kulhawy 2010; Pham et al. 2001) suggested COV of 3–8% for a unit weight of soil: Einstein and Baecher (1983); Akbas and Kulhawy (2010), and Kulhawy et al. (2006) showed COV of 2–21% for Effective ϕ.

2.4 Input Data for Analysis of the Dam

In this paper, the soil parameters taken were the same as the soil for the existing embankment dam. The study area's detailed laboratory testing results showed the most average occurrence of unit weight, shear strength parameters, internal friction angle, cohesion, and permeability for each parameter. The variability of the soil parameters: COV = 5% for γ, 5% for ϕ, and 20% for c) were taken as per the COV suggested by Einstein and Baecher (1983) and Akbas and Kulhawy

Table 1 Input parameters for reliability analysis

Material zone	γ_μ(kN/m^3)	$\varnothing_\mu$(^{0})	c_μ(kPa)	Permeability K(m/sec)	σ_γ	$\sigma_\varnothing$	σ_c
Impervious core	16	20	10	5.48×10^{-8}	0.8	1	2
Gravel shell	19	32	0	1.17×10^{-5}	0.95	1.6	0
Fine filter	18	34	0	1.0×10^{-4}	0.9	1.7	0
Coarse filter	18	35	0	5×10^{-3}	0.9	1.75	0
Rip rap	22	40	0	5×10^{-2}	1.1	2	0
Rock toe	22	40	0	5×10^{-2}	1.1	2	0

(2010). Input data for the reliability assessment of the dam is given in Table 1.

MCS is used for uncertainty propagation generating a random sample of the input parameters and determining the system measure from each set of inputs in the sample. MCS gives an excellent approximation of the system model distribution with many iterations for natural variability and model uncertainty (Verma et al. 2016).

In this study, random variables were defined by a probability density function (PDF) by the associated parameters such as the mean value (μ) and the standard deviation (σ). Normal PDF and lognormal PDF distribution were used to evaluate the reliability of the slope.

2.5 Normal (Gaussian) Distribution

The normal distribution is the most important and widely used field of statistics and probability. They are used in stress-strength interference models in reliability studies.

The PDF of normal distributions for the random variables with mean, μ, and standard deviation σ is given by Eq. (7).

$$f(t,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}, \quad -\infty \le t \le \infty \tag{7}$$

Equations 8 and 9 give the normal reliability function and cumulative density function (CDF)

$$R(t) = \int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} dt, \tag{8}$$

$$F(t) = \int_{-\infty}^{t} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} dt, \tag{9}$$

For insufficient data suggested by Dai and Wang (1992), most data will be normally distributed, so 99.73 percent of all values will lie within plus or minus three standard deviations from the mean value. Therefore, a geotechnical engineer may estimate the highest possible value of a particular parameter (Xmax) and its lowest possible value (Xmin) and then estimate the standard deviation by Eq. (10).

$$\boldsymbol{\sigma}_{\mathbf{X}} = \frac{\mathbf{X}_{\mathbf{max}} - \mathbf{X}_{\mathbf{min}}}{6} \tag{10}$$

2.6 Lognormal Distribution

A continuous positive random variable T is lognormal distribution if its natural logarithm is normally distributed. The lognormal PDF is given by Eq. (11).

$$f(t) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln t-\mu}{\sigma}\right)^2}, \ t > 0 \tag{11}$$

Equations 12 and 13 give the lognormal reliability function and CDF.

$$R(t) = 1 - \phi\left[\frac{\ln t - \mu}{\sigma}\right] \tag{12}$$

$$F(t) = \phi\left[\frac{\ln t - \mu}{\sigma}\right] \tag{13}$$

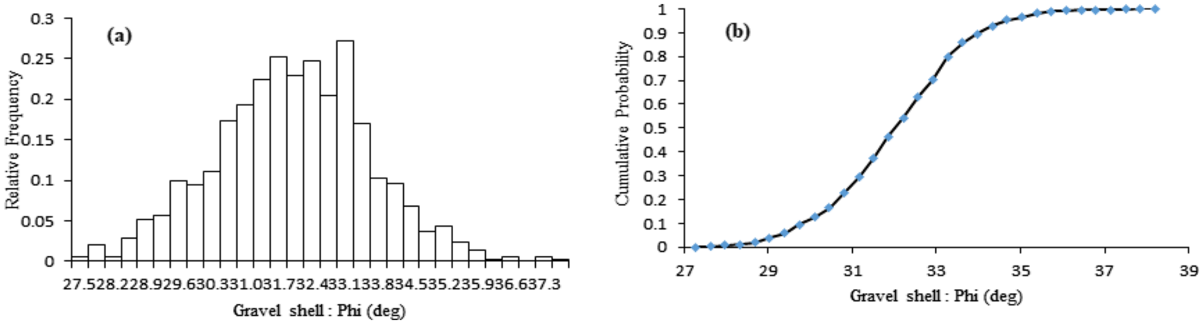


Fig. 2 The probability density function of the shell (**a**) and cumulative density function (**b**)

3 Results and Discussion

As discussed in the previous section, this paper aims to determine the overall slope reliability of the existing slope for the embankment dam in the case of steady-state seepage. For the random variable of soil parameters, the probability density function and cumulative density function took the shape of normal distribution and cumulative distribution function. The normal PDF and CDF for the random variable of internal friction angle for shell material are depicted in Fig. 2(a) and Fig. 2(b), respectively. Moreover, the PDF and CDF for other parameters have the same shape.

Similarly, the PDF and CDF of FS have the same shape with soil parameters. Figure 3(a) and Fig. 3(b), respectively, depicted PDF and CDF for FS of the embankment dam for steady-state seepage conditions.

The reliability of the dam for the steady-state condition was evaluated when there is a constant phreatic line established; in this condition, the most critical slope is the downstream part of the dam. The upstream part of the dam is more stable than the downstream slope since the hydrostatic pressure gives additional lateral support for the slope. For analysis of the embankment dam using Slide 6, the cross sections of the embankment dam profile were taken from the proposed dimensions of the embankment dam, which is safe from the possible cause of failures. From the analysis of the dam for steady-state seepage, the Porewater pressure distribution and the overall reliability of the slope of 1000 iterations for the GLE/Morgenstern method is depicted in Fig. 4. From the analysis, the overall mean FS = 1.202, the probability of failure (PF) = 0.217%, which implied the reliability of 99.783%, and the reliability index (RI) for normal PDF and lognormal PDF is 2.608 and 2.827 respectively. Probabilistic analysis of the slope for 1000 iterations for different limit equilibrium methods (LEM) is shown in Table 2. PF for ordinary methods of slices and Bishop simplified methods were the same, whereas for the case of Janbu simplified, Spencer, and GLE/Morgenstern methods gave similar results.

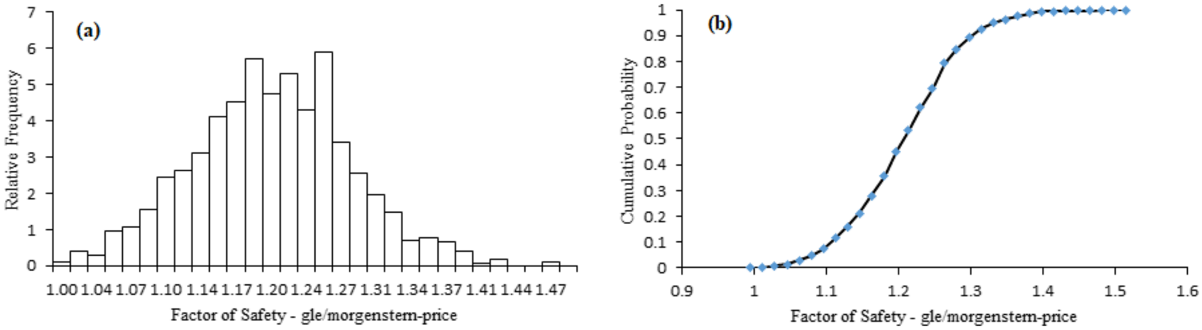


Fig. 3 The probability density function of the shell (**a**) and cumulative density function (**b**)

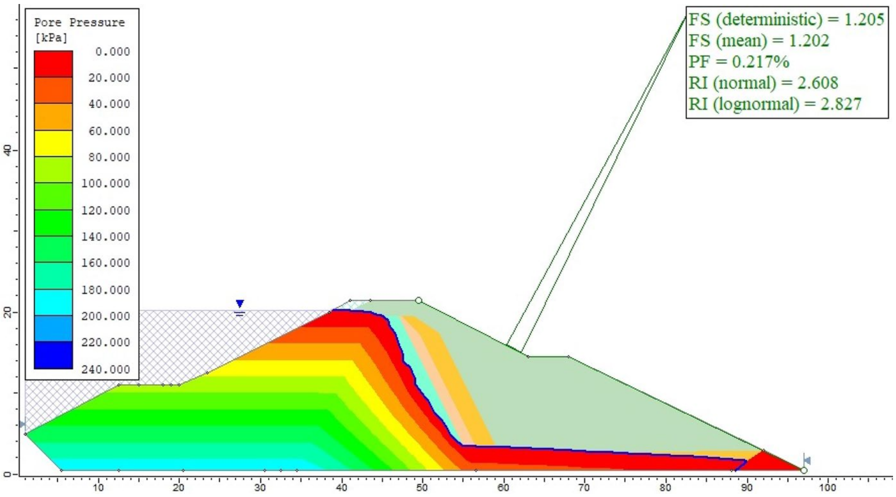


Fig. 4 Seepage and slope stability of the dam: Morgenstern-price

Table 2 Analysis of slope for different slope stability methods

Analysis method	FS (deterministic)	FS (mean)	PF (%)	R (%)	RI(normal)	RI(lognormal)
Ordinary/fellenius	1.205	1.205	0.200	99.8	2.657	2.883
Bishop simplified	1.206	1.205	0.200	99.8	2.656	2.883
Janbu simplified	1.205	1.202	0.217	99.783	2.607	2.825
Spencer	1.205	1.202	0.217	99.783	2.608	2.826
GLE/morgenstern-price	1.205	1.202	0.217	99.783	2.608	2.827

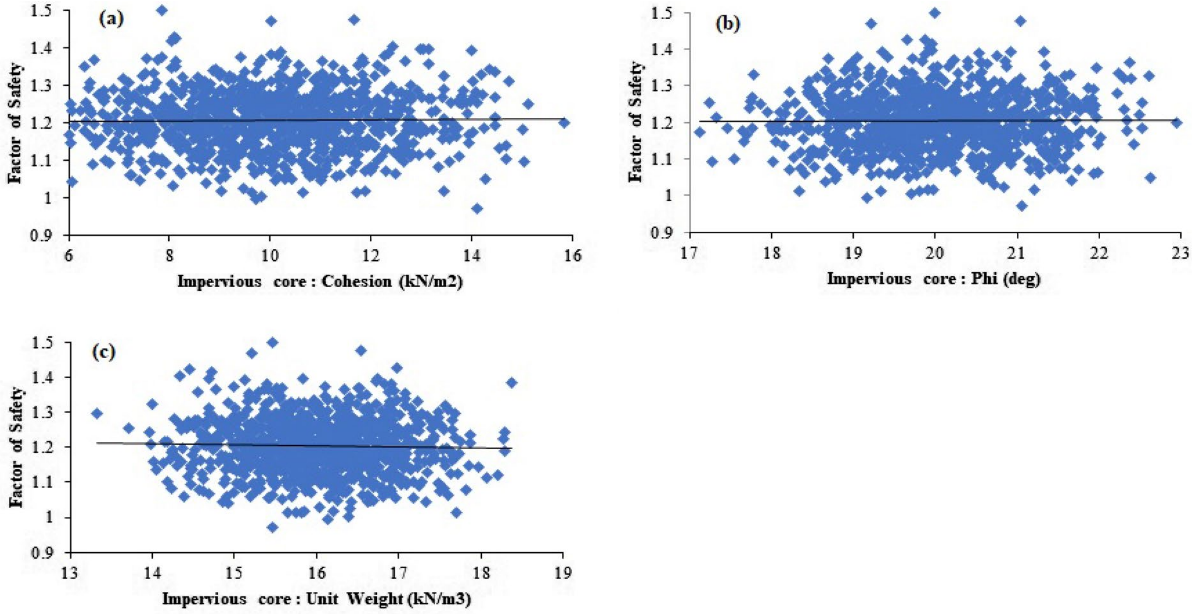


Fig. 5 Scatter plot of FS for the impervious core with cohesion (**a**), friction angle (**b**), unit weight (**c**)

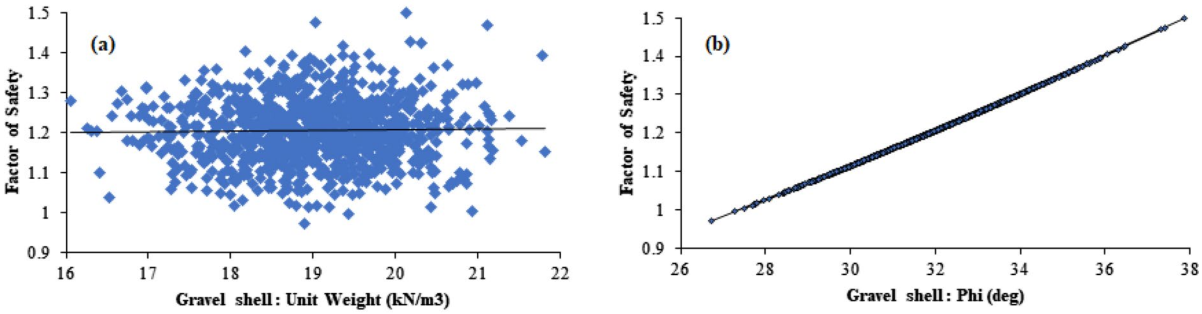


Fig. 6 Scatter plot of FS for the gravel shell with unit weight (**a**), friction angle (**b**)

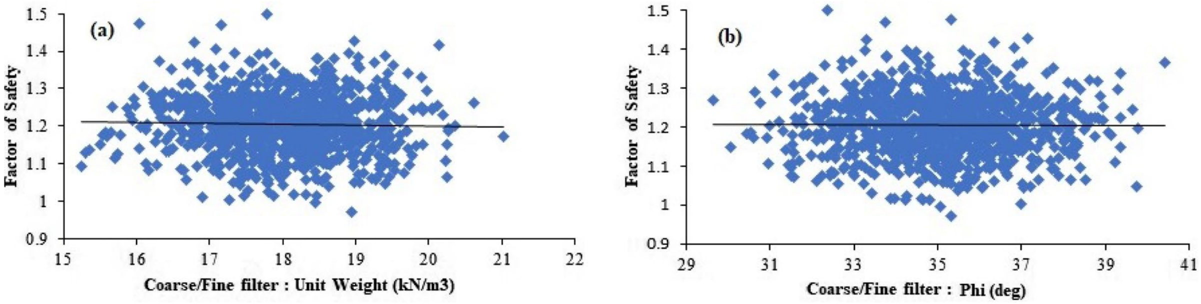


Fig. 7 Scatter plot of FS for the coarse/Fine filter with unit weight (**a**), friction angle (**b**)

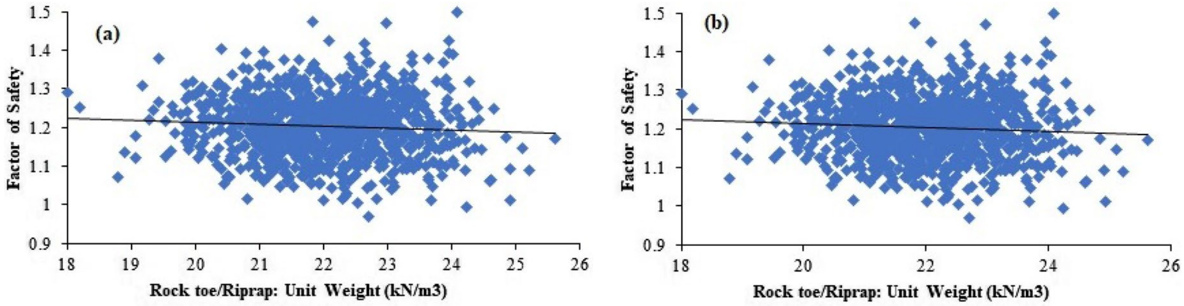


Fig. 8 Scatter plot of FS for the rock toe/riprap with unit weight (**a**), friction angle (**b**)

The effects of each of the soil properties on the FS of the slope are depicted in Fig. 5(a–c), Fig. 6(a, b), Fig. 7(a, b), & Fig. 8(a, b). From the scatter plot of the figures, it is clear that FS is only dependent on soil friction angle (ϕ) of gravel shell materials than unit weight (γ) and cohesion (C) of the soils, which implies R of the dam is dependent on friction angle of the shell materials (Fig. 6b).

In addition, the scatter plot of FS with soil properties of the dam and the sensitivity of FS with each soil parameter (50% of the mean) are depicted in Fig. 9. From the sensitive chart, FS is sensitive to the friction of the gravel shell material than other soil parameters.

Additionally, the effects of each soil parameter on the probabilistic slope stability for a 50% value of each soil parameter were examined. According to the investigation, FS, PF, and R are more sensitive

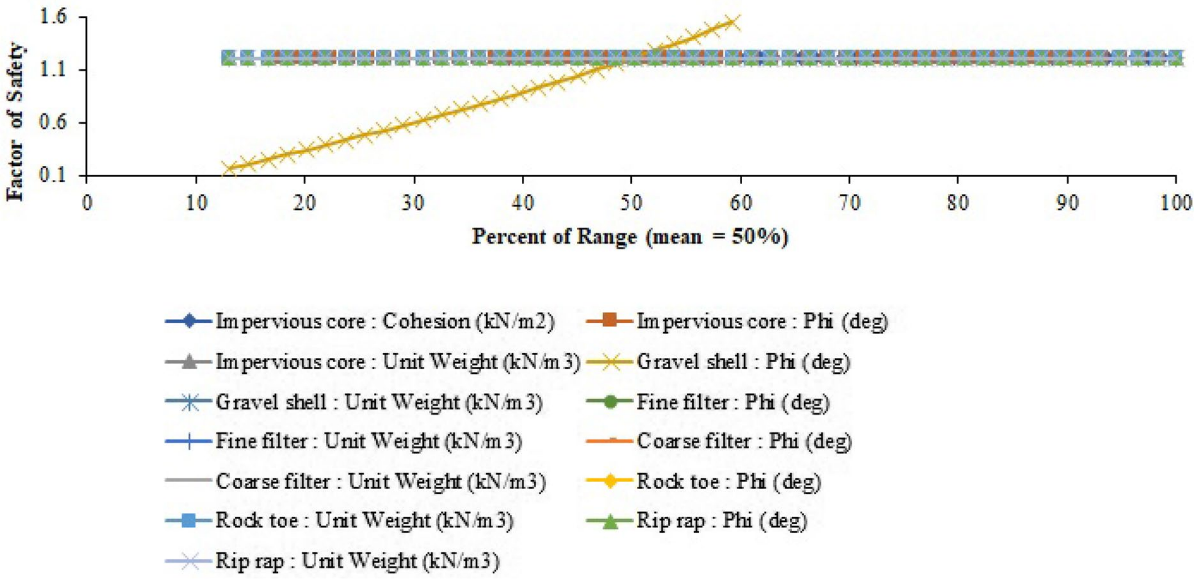


Fig. 9 Sensitivity of FS with each soil parameter of the dam

Table 3 Effects of FS, PF, and R on 50% of soil parameters

Soil parameter value	FS (mean)	PF (%)	R
50% Of the unit weight	1.208	0.2	99.8%
50% Of the cohesion	1.202	0.22	98.78%
50% Of the friction	0.552	100	0

to the friction angle than unit weight and soil cohesiveness (Table 3).

The probabilistic slope stability of the dam produced a PF of 100% for 50% soil friction is depicted in Fig. 10.

3.1 Effect of Surcharge on the Stability of the Slope

In many cases, Embankment dams are subjected to loads that are not free from overburden pressure. In this study, the effects of the vertical surcharge loads were considered to determine the embankment's deterministic and probabilistic slope stability. The

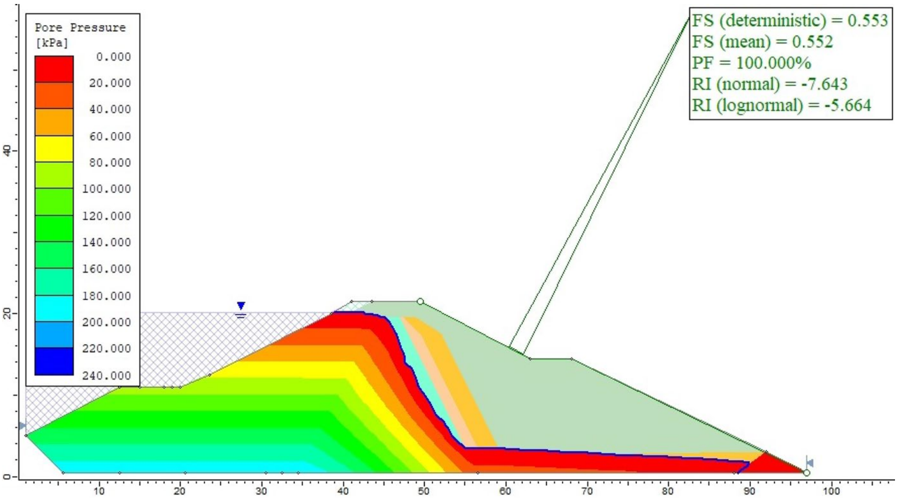


Fig. 10 Pore pressure and Probabilistic analysis of the dam for 50% friction angle

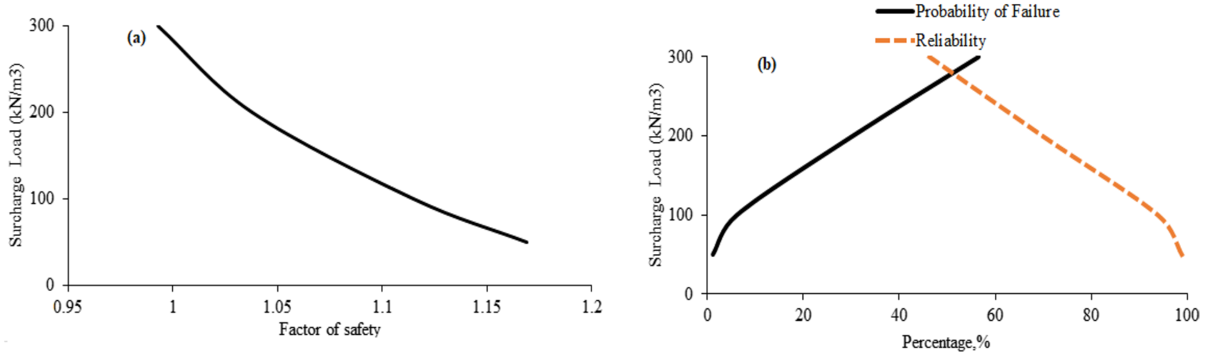
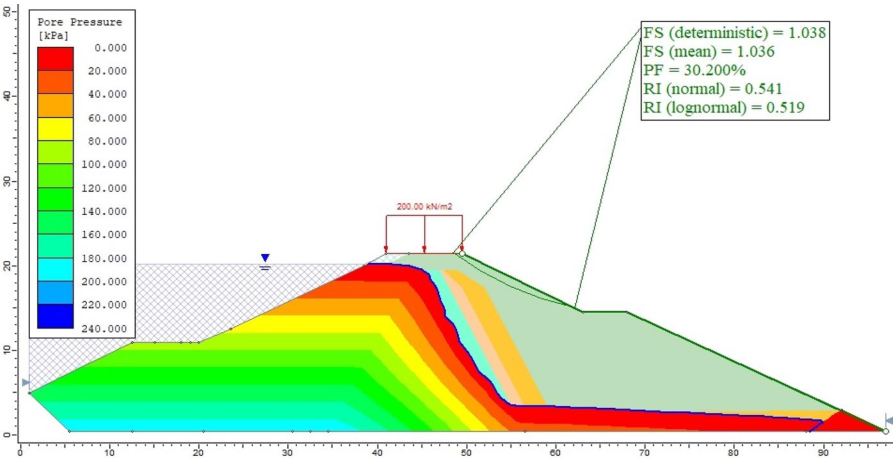


Fig. 11 Effect of FS, PF, and R with surcharge load

Fig. 12 Reliability of the dam for a surcharge of 200 kN/m2



Morgenstern-price slope stability analysis showed that FS decreases with increases in surcharge load (Fig. 11a). Moreover, probabilistic slope stability analysis showed that PF increases with surcharge load while R increases with the decrease of surcharge loads (Fig. 11b). The probabilistic slope stability analysis for the vertical surcharge of 200 kN/m^2 is depicted in Fig. 12.

4 Conclusions

The reliability of the embankment dam is a better representation of the slope performance for the random distribution of the soil parameters for the inherent uncertainties of the soil parameters, which were taken as a random variable. From reliability methods of slope stability analysis, two slopes having different deterministic FS, the performance of the slope with the lower FS could be safer due to uncertainties and random variables of the soil parameters.

In this paper, the reliability of the dam was determined from the probability distribution of the random variables for different slope stability methods for 1000 MCS iterations using Slide 6 software. The probability of failure (PF) for a Morgenstern-price method was 0.217%, reliability (R) of the dam was 99.783%. The reliability index of the dam (RI) for the normal distribution was 2.608, and for the lognormal distribution, 2.827. From the scatter plot of FS with soil parameters, the reliability (R) of the slope is more sensitive to the friction angle of the gravel shell materials than other soil parameters. For the 50% friction angle of the soil parameters, the probabilistic slope stability analysis gave PF of 100%; therefore, selecting appropriate gravel shell materials plays a significant role in the probabilistic analysis of the slope. Moreover, from the probabilistic slope stability analysis of the dam for surcharge load, PF increased with an increase in surcharge loads. In contrast, the reliability of the dam decreased with an increase in the surcharge load.

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Data Availability The data used to support the study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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