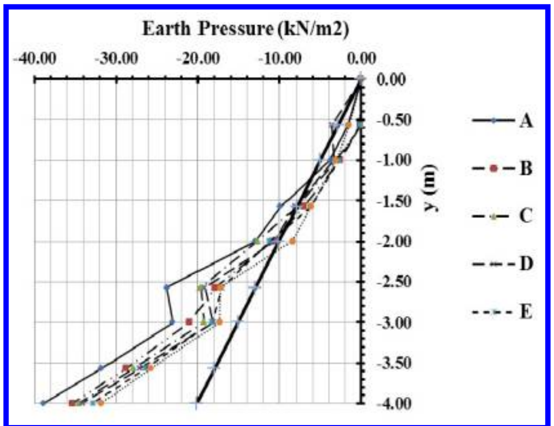

FIG. 7. Lateral EP dist. along wall height (t= 0.40 m and X/B= 0.71)

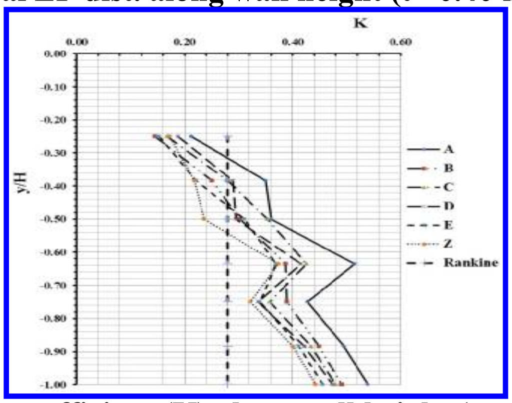

FIG. 8. Dist. of EP coefficient (K) along wall height (t = 0.40 m and X/B=0.71)

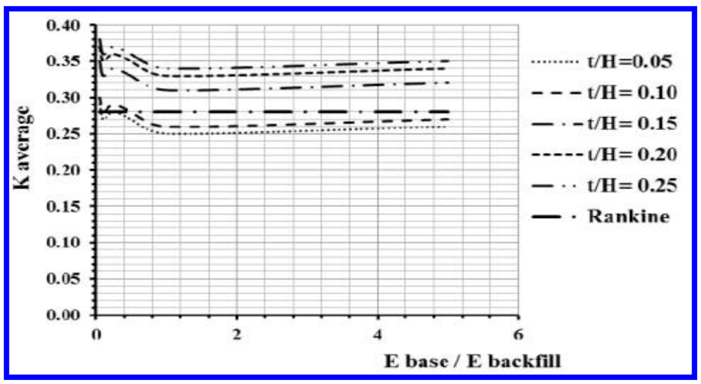

FIG. 9. Values of K_{av} vs. soil stiffness ratio for different t/H and X/B=0.71

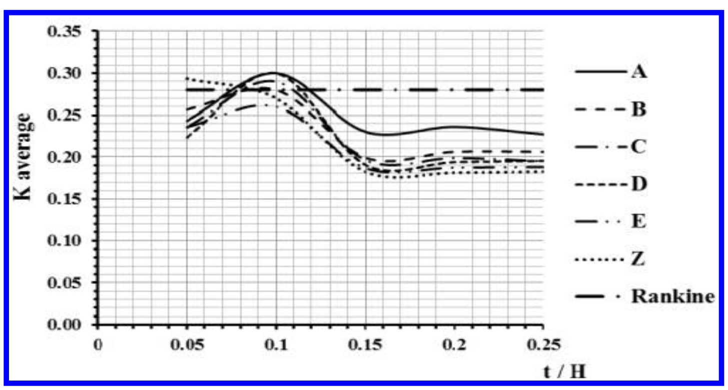

FIG. 10. Values of K_{av} vs. ratio (t/H) for different soil stiffness and X/B=0.71

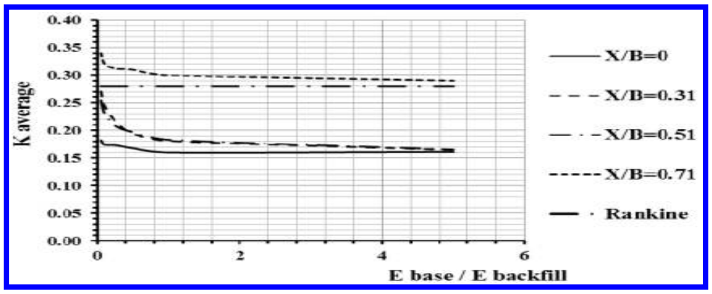

FIG. 11. Values of K_{av} vs. soil stiffness ratio for different X/B and t/H = 0.1

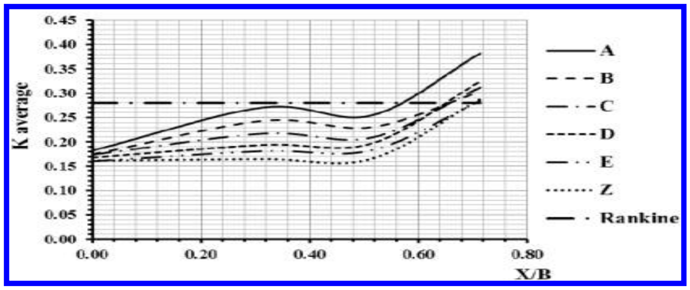

FIG. 12. Values of K_{av} vs. X/B for different soil stiffness and t/H = 0.1

The results showed that by increasing (X/B), the values of K_{av} are increased; this refers to the significant increment in the differential settlement and base rotation towards the backfill due to the backfilling weight. For the case of (X/B = 0), the backfilling weight has a slight effect on K_{av}. The effect is increased with the increase of (X). Now, the second objective of this research is studied with the following four Figures. The values of K are calculated with respect to the maximum bending moment that is resulted from the FEM and compared with Rankine's coefficient. Figure (13) present the relation between K vs. soil stiffness ratios for different thickness to height ratios for (X/B=0.71).

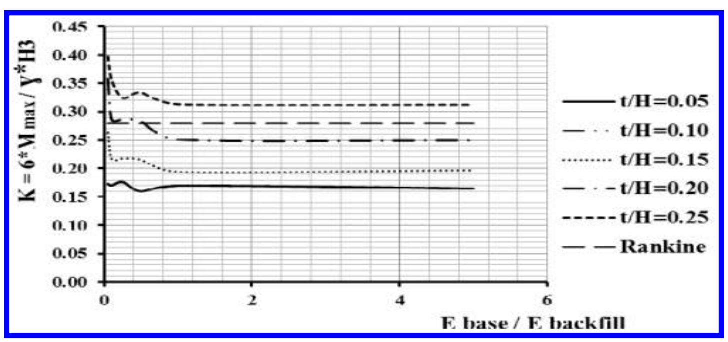

FIG. 13. The values of K vs. soil stiffness ratio for different t/H and X/B = 0.71

In addition, Figure (14) presents the relation between K and thickness to height ratios (t/H) for different stiffness ratios with (X/B = 0.71). The result showed that the maximum value of bending moment that is resulted from Rankine's theory is greater than those are resulted from the similar cases of FEM, except for the cases of higher rigid walls. These results are in good agreement with the previous presented results in this research. The increase of the embedded foundation width in the backfill (X) is decreasing the maximum bending moment resulting on the wall. In the other hand, it increases the maximum bending moment that is acting on the embedded footing width, but this effect is not studied in this research.

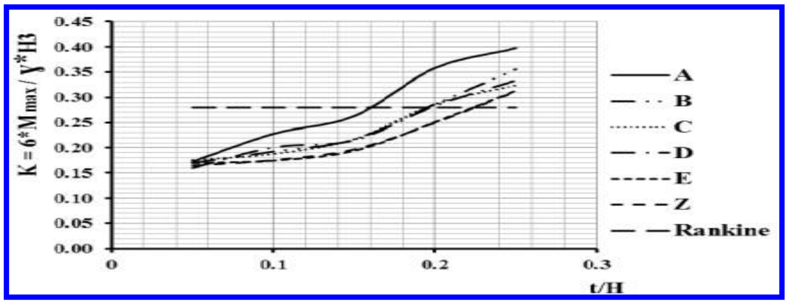

FIG. 14. The values of K vs. thickness ratio for different soil stiffness, X/B = 0.71

CONCLUSIONS

The research has proved the following:

a. The loose or soft base soils affect the lateral earth pressure distribution on the wall in a different behavior than the active pressure that is calculated using Rankine's theory.
b. Increasing the wall thickness more than about 0.10 of the wall height; the lateral earth pressure is increased significantly up to the at-rest pressure or more.
c. Increasing the wall rigidity is also producing an increase in the lateral pressure.
d. The increase of the embedded width inside the backfill decreases the resulted bending moment on the wall, but it increases the bending moment acting on the footing and increases the footing rotation.
e. In most cases, the Rankine's coefficient is having a sufficient safety factor for the cantilever retaining walls, except for the cases of rigid walls.

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Reliability Analysis of Strain-Softening Slopes Using the First Order Reliability Method (FORM)

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Abstract: The paper pertains to the slope reliability analysis under a probabilistic framework in strain-softening cohesive soils, using the first order reliability method (FORM). The performance function is based on the Bishop simplified method modified to take strain-softening into account in terms of the residual factor R_F over a potential slip surface, estimated based on a progressive failure model proposed in the literature. The reliability analysis is performed on the surface of minimum factor of safety determined by using the sequential quadratic programming (SQP). The random shear strength parameters are assumed to follow normal distribution while the residual factor has been considered both as a deterministic parameter and a beta-distributed random variable. The results obtained for an illustrative example shows substantial reduction (21%) in the value of reliability index when R_F is considered as a random variable with an assumed COV of 0.3. Results of FORM-based sensitivity analyses also reveal that R_F has the most dominating influence on reliability and thus justifies its inclusion as one of the random variables. A parametric study, varying the assumed correlation coefficient between the random shear strength parameters from 0 to 1, shows that there is a maximum reduction of 16% in reliability index.

INTRODUCTION

It is essential to understand the basic causes and mechanisms of slope failures which are often associated with decreased shear strength, increased pore water pressure and the progressive mechanisms of failure. Based on the availability of several case histories, it is now well appreciated that the state of stability of a slope falls somewhere between the two extremes i.e., the peak shear strength state and the residual shear strength state. A landslide may not have occurred or a slope may not have suffered a complete failure. Yet, as a consequence of slope formation, fluctuations of pore water pressure over time, seismic activity and other processes, strain-softening may have occurred to some unknown extent. Consequently it is necessary to consider the role of strain-softening in a more comprehensive manner when making slope stability assessments. In this context, apart from modeling the whole phenomenon of progressive failure, the residual factor (which is the ratio of the difference between peak shear strength to current shear strength to the difference between peak shear strength to residual shear strength) as defined by Skempton (1964, 1985), has been studied as a quantitative measure of the extent of progressive failure in a strain-softening soil.

Results of conventional assessments of stability based on traditional deterministic models of slope stability are subject to significant uncertainty. The sources of uncertainty include natural variability of geotechnical parameters, systematic errors and imperfect geotechnical models. Both spatial and temporal uncertainties play an important part in the assessments of long-term performance of slopes. Reliability analysis within a probabilistic framework offers a very powerful tool for taking into consideration the variability of key geotechnical parameters as well as other uncertainties.

In this paper, the progressive decrease in shear strength along potential slip surfaces is considered in terms of the Skempton's residual factor. The residual factor may be considered as one among several random variables in the slope reliability formulation for finite slope, which has been developed on the basis of a limit equilibrium model, specifically, the Bishop's simplified method. The First Order Reliability Method (FORM) (Haldar and Mahadevan, 2000) has been used for the purpose of reliability analysis. An assumption of suitable probability distribution (out of the generalized beta distribution) for residual factor has been made. Parametric analyses will prove to be very useful for understanding the change in reliability considering uncertainty, spatial and temporal, in the residual factor. A sensitivity analysis based on the FORM method shows the relative importance of residual factor as a random variable.

METHODOLOGY

Residual factor for a potential slip surface

In strain-softening soils, the processes of progressive failure are often associated with a decrease in the values of shear strength. The extent to which shear strength has decreased from its peak value to its residual value at a point in a soil mass can be expressed in terms of a 'residual factor' introduced by Skempton (1964, 1985). If no decrease has occurred, the residual factor is equal to 0; if the strength has decreased to the residual value, the residual factor is 1; and in all other cases this factor lies between 0 and 1. It is useful to consider an alternative definition of the residual factor which represents the whole of a potential slip surface. For a perfectly brittle soil, strain-softening will lead to one part of slip surface being at residual shear strength and the remaining part at peak shear strength. Skempton (1964) proposed that the average residual factor R_F over a slip surface could be represented as the proportion of slip surface length along which the shear strength has decreased to the residual, i.e., $R_F = L_r/L$ in which L is the total length of a slip surface of which the length L_r is at the residual shear strength, the remaining length ($L-L_r$) being still at the peak shear strength. The magnitude of the average residual factor represents the state of nature for a slope at a given point in time, being a consequence of the decrease in material strength parameters associated with processes of progressive failure.

Estimation of Residual Factor using an LEM based Progressive Failure Model (Chowdhury et al., 2010)

Chowdhury et al. (2010) proposed a simple model for progressive failure of slopes in strain-softening soils under the framework of the conventional limit equilibrium methods of slices (LEM). Assuming that the soil is perfectly brittle strain-softening, the shear strength parameters of overstressed slices will reduce to residual values c_r' and $\tan\phi_r'$, whereas the remaining segments of the slip surface will still be at the peak shear strength c_p' and $\tan\phi_p'$. An iterative process is required to identify the failed segments of slip surface and redistribute excess shear stress until no more segments are over-stressed. Once the overstressed or failed slices have been identified, the residual factor R_F, representing the entire slip surface can be estimated by the ratio of the summation of lengths of the failed slices to the overall length of the slip surface.

Performance function for a curved slip surface - Bishop Simplified Method

The expression for the factor of safety, F, associated with a curved slip surface of circular shape for a simple slope, based on the Bishop Simplified Method, has been modified for a strain-softening soil, by including the residual factor R_F. The modified expression is as follows:

$$F = \frac{\sum\left[\left\{c'_{rf}\, b + W(1-r_u)\times\tan\phi'_{rf}\right\}/\, m_{\alpha rf}\right]}{\sum W\sin\alpha} \tag{1}$$

where, b is the slice width, W is the slice weight, r_u is the non-dimensional pore water pressure ratio at slice base, and α is the inclination of slice base. Further,

$$c'_{rf} = R_F c'_r + (1-R_F)c'_p \tag{2}$$

$$\tan\phi'_{rf} = R_F \tan\phi'_r + (1-R_F)\tan\phi'_p \tag{3}$$

where, R_F is the overall or average residual factor for the entire length of the curved slip surface (assumed to be an arc of a circle in this case). These modified shear strength parameters follow directly from Skempton's definition of residual factor as shown by Chowdhury and Bhattacharya (2011).The factor $m_{\alpha rf}$ is given by

$$\mathrm{m}_{\alpha rf} = \left(1+\frac{\tan\alpha\tan\phi'_{rf}}{F}\right)\cos\alpha \tag{4}$$

The commonly used expression for factor of safety based on the Bishop Simplified Method (no strain-softening) is given by

$$F = \frac{\sum\left[\left\{c'b + W(1-r_u)\times\tan\phi'\right\}/\, m_{\alpha}\right]}{\sum W\sin\alpha} \tag{5a}$$

$$\text{where, } \mathrm{m}_{\alpha} = \left(1+\frac{\tan\alpha\tan\phi'}{F}\right)\cos\alpha \tag{5b}$$

It may be noted that Eq. (1) is analogous to Eq. (5a) except that c′ is replaced by c_{rf}' given by Eq. (2), $\tan\phi'$ is replaced by $\tan\phi_{rf}'$ given by Eq. (3), and m_α is replaced by $m_{\alpha rf}$ given by Eq. (4).

Residual Factor R_F as a Random Variable

For the residual factor R_F, a generalized beta distribution with the end points of 0 and 1 seems appropriate. Both symmetrical and skewed distributions can be included with the assumption of a beta system. For given values of mean and standard deviation of R_F, a corresponding beta distribution can be obtained. Therefore, it is feasible to vary independently the mean of R_F and the standard deviation of R_F.

The probability density function (PDF) for the generalized beta distribution representing a variable between given bounding values a and b is represented by the following equation (Harr 1977)

$$f(x) = \frac{1}{C}(x-a)^{q-1}(b-x)^{r-1} \tag{6a}$$

where, $$C = \frac{(q-1)!(r-1)!(b-a)^{q+r-1}}{(q+r-1)!} \tag{6b}$$

The expected value and variance of the beta distribution [a, b] are given by

$$E[x] = a + \frac{q}{q+r}(b-a) \tag{7}$$

and, $$V[x] = \frac{qr(b-a)^2}{(q+r)^2(q+r-1)} \tag{8}$$

ILLUSTRATIVE EXAMPLE

To elucidate the methodology presented in the preceding section, an example of a simple slope in a strain-softening soil has been selected from the literature (Chowdhury et al., 2010). Fig. 1 presents a section of the slope with height 25 m, inclination 22°, and unit weight of soil 20.8 kN/m^3. The statistical properties of the peak and the residual strength parameters are as given in Table 1.

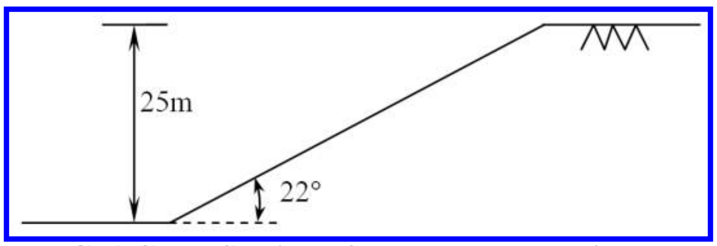

FIG. 1 Cross Section of a homogenous c-ϕ slope

Table 1. Statistical Properties of Strength Parameters

Parameter		Mean	Standard Deviation	Coefficient of Variation
Peak Strength Parameters	c_p'	30.0 kPa	6.0 kPa	0.20
	$\tan\phi_p'$	tan(20)	0.036	0.10
Residual Strength Parameters	c_r'	10.0 kPa	2.0 kPa	0.20
	$\tan\phi_r'$	tan(12)	0.021	0.10

RESULTS AND DISCUSSION

Deterministic Analysis and Estimation of Residual Factor

Initially, considering the shear strength parameters as deterministic with values equal to their respective mean values as given in Table 1, critical slip surfaces were determined based on the Bishop simplified method of slices coupled with the sequential quadratic programming (SQP) (Rao, 2009) technique of optimization. Specifically, two such deterministic critical slip surfaces were obtained for the two extreme cases, namely, Case I, when the entire slip surface is at peak strength, and Case II, when the entire slip surface is at residual strength. For the sake of convenience these surfaces are marked B_p and B_r and values of the associated minimum factor of safety (FS_{min}) are obtained as 1.652 and 0.819 respectively using a total of 48 slices. In addition to the above, a third critical slip surface considering strain softening (Case III) was also determined using the progressive failure model as proposed by Chowdhury et al. (2010). This surface is marked B_{prc} for which the associated minimum reduced factor safety was obtained as 1.331. After identifying the failed slices (out of 48 slices) in the surface B_{prc}, the residual factor R_F, being the ratio of the summation of lengths of the failed slices to the overall length of the slip surface, is estimated as 0.392.

The critical slip surfaces determined above are shown in Fig. 2 in which the strain-softened portions (failed slices) of the slip surfaces are highlighted in red. It is observed that the critical slip surfaces for case I and case III are very close to one another but substantially different from the critical slip surface for case II.

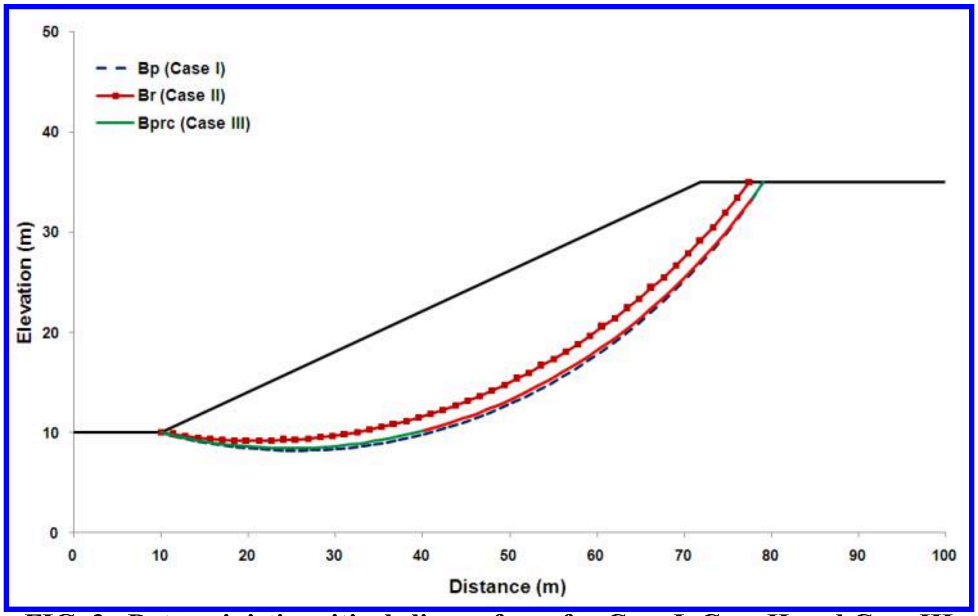

FIG. 2. Deterministic critical slip surfaces for Case I, Case II and Case III

Reliability Analyses on the Deterministic Critical Slip Surfaces considering Residual Factor as a Deterministic Parameter

Using FORM, reliability analyses have been carried out on all the three critical slip surfaces determined in the preceding section. For these analyses, the peak and residual shear strength parameters (Table 1) are treated as random variables and are assumed to be normally distributed and uncorrelated. The residual factor R_F is considered as a deterministic parameter which is estimated from the progressive failure model proposed by Chowdhury et al. (2010) as described in the preceding section. The performance function is based on the expression for the Bishop simplified method modified for strain-softening soils [Eq. (1)]. Table 2 presents a summary of the values of reliability index β of these slip surfaces along with the values of their factor of safety (FS_{min}) as detailed in the preceding section.

From Table 2 it is observed that F_{min} values for the strain softening case (case III) are in between the two extreme cases i.e., F_{min} value for all peak case (case I) and all residual case (case II), which is expected. From the results of the reliability analysis on all the critical slip surfaces for each of above cases, it is observed that nature of variation of β values are same as that of F_{min} values.

Table 2. Summary of results of deterministic analyses and reliability analyses on deterministic critical slip surfaces assuming random variables as uncorrelated

Cases Analysed	Deterministic Analysis			Reliability Analysis	
	Critical Slip Surface Chosen	FS_{min}	R_F	Slip Surface Chosen	β
Case I: Entire slip surface at peak strength	B_p	1.652	0.000	B_p	4.198
Case II: Entire slip surface at residual strength	B_r	0.819	1.000	B_r	-2.439
Case III: Part of slip surface strain softened	B_{prc}	1.331	0.392	B_{prc}	3.308

Influence of Residual factor R_F as a random variable

In view of the uncertainties associated with the residual factor R_F, it would be of real interest to study the influence of the residual factor as a random variable on the results of reliability analysis. Thus, in this case, reliability analysis will involve five random variables as against four random variables in the earlier analysis. As stated before, the residual factor is assumed to follow a beta-distribution while the remaining four random variables are assumed to follow normal distribution, as before. The mean of R_F for a slip surface is determined based on the progressive failure model proposed by Chowdhury et al. (2010), while the COV of R_F is assumed here as 0.3. The parameters q and r defining the specific shape of beta-distribution are then calculated using Eqs. (7) and (8). The values of the reliability indices are calculated for the critical slip surface for the strain softening case B_{prc}. Results are presented in Table 3. The values of the reliability indices when R_F is deterministic as obtained from the proposed procedure based on the limit equilibrium method are also tabulated for the sake of comparison.

Effect of Correlation

It would be of interest to study the effect of correlation among the random variables on the results of reliability analysis presented in Table 2. In absence of published data on correlation coefficients, a parametric study has been carried out with assumed values of the correlation coefficients between c_p' and c_r' and between $\tan\phi_p'$ and $\tan\phi_r'$. For simplicity, these two correlation coefficients are assumed to be of equal value and denoted by ρ. A parametric study has been conducted considering values of ρ as 0.25, 0.5, 0.75 and 1.0. The cross correlation coefficients between the different strength parameters are, however, assumed to be zero. These results are