Integration of Asset Management Systems with Load and Resistance Factor Design (LRFD)

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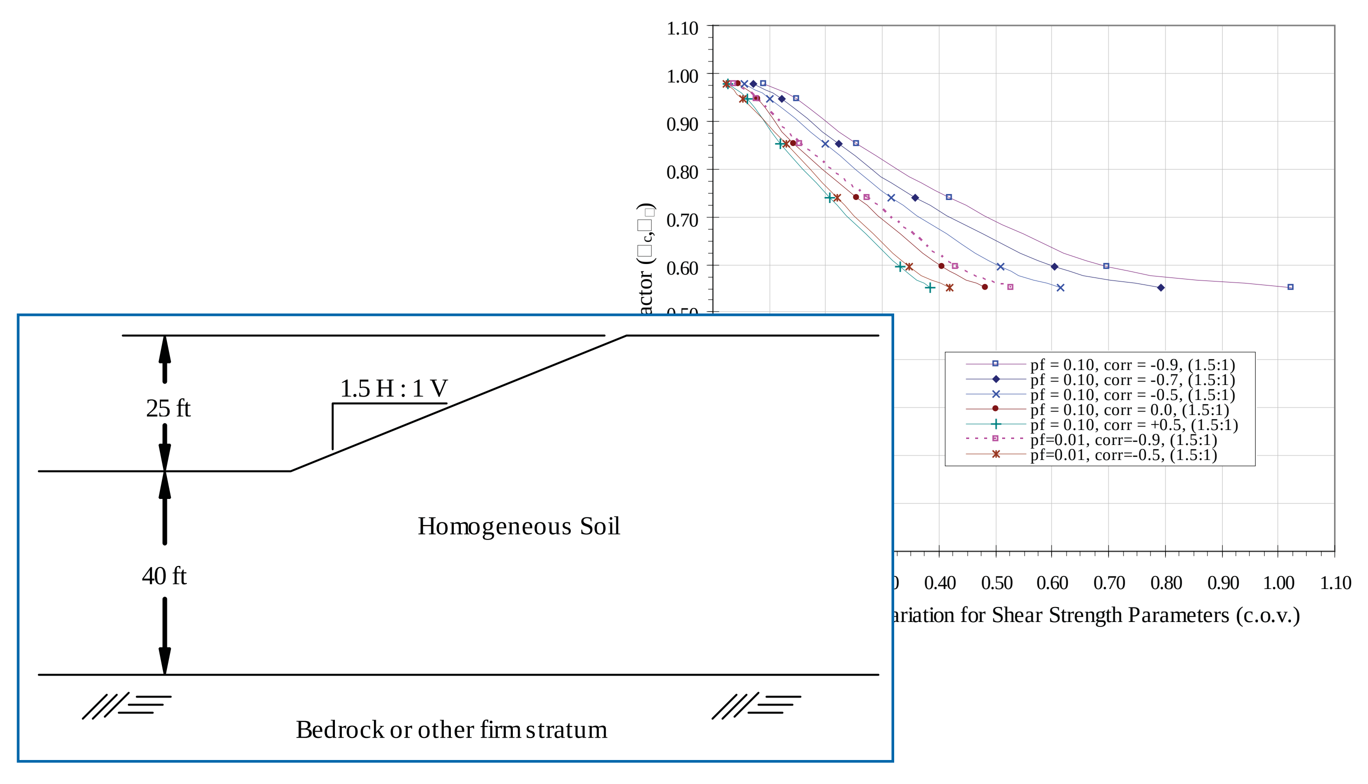
Final Report
November 2008



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16. Abstract

In 2005, researchers from the University of Missouri developed general procedures for designing earth slopes using Load and Resistance Factor Design techniques (Loehr et al. 2005). The work produced curves that linked the resistance factors with the uncertainty of the design input parameters and a selected level of reliability. Unfortunately, the charts developed presented resistance factor values that would produce designs too conservative for a selected level of reliability. The sources of conservatism identified included the existing correlation between soil strength parameters cohesion and friction angle and the inherent bias produced mostly by investigation techniques.

This report describes the considerations and procedures used to recalibrate the resistance factor curves for a target probability of failure of 10%. The completed recalibrated curves including parameter correlations and biases are shown and discussed in this report. Finally, this progress report includes the description of the ongoing research.

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INTEGRATION OF ASSET MANAGEMENT SYSTEMS WITH LOAD AND RESISTANCE FACTOR DESIGN (LRFD)

Final Report
November 2008

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EXECUTIVE SUMMARY

In 2005, researchers from the University of Missouri developed general procedures for designing earth slopes using Load and Resistance Factor Design (LRFD) techniques (Loehr et al. 2005). The work produced curves that linked the resistance factors with the uncertainty of the design input parameters and a selected level of reliability. Unfortunately, the charts developed presented resistance factor values that would produce designs too conservative for a selected level of reliability. The sources of conservatism identified included the existing correlation between soil strength parameters cohesion and friction angle and the inherent bias produced mostly by investigation techniques.

This report describes the considerations and procedures used to recalibrate the resistance factor curves for a target probability of failure of 10%. The completed recalibrated curves including parameter correlations and biases are shown and discussed in this report. Finally, this progress report includes the description of the ongoing research.

1. INTRODUCTION

In 2005, researchers from the University of Missouri worked to develop general procedures for designing earth slopes using Load and Resistance Factor Design (LRFD) techniques (Loehr et al. 2005). From this work, a series of graphs, similar to the one shown in Figure 1 were developed, establishing values of resistance factors that were dependent on the variability of the soil parameters, and would produce a select level of reliability.

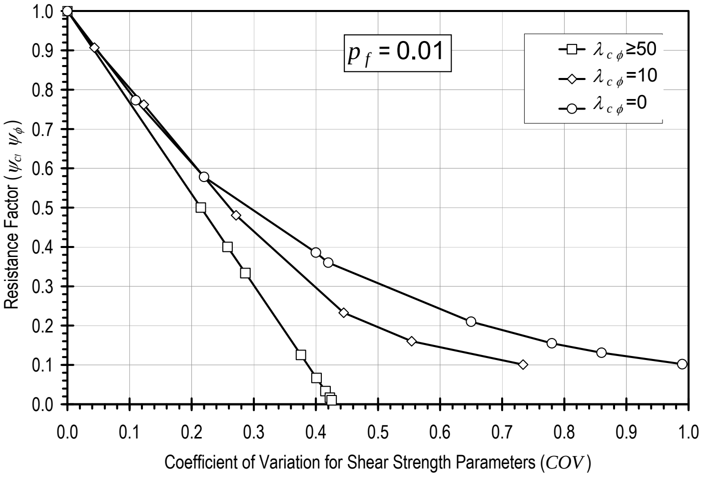

Figure 1. Example of a LRFD chart with a probability of failure of 1 in 100

The charts developed presented resistance factor values that would produce designs too conservative for a selected level of reliability. During the research it was identified that in order to produce designs similar to the conventional Allowable Stress Design (ASD) procedure, it was necessary to consider the existing correlation between soil parameters and parameter bias produced by site investigation and laboratory practice.

This report describes the work performed to recalibrate the resistance factor curves related to parameter correlations and biases.

2. OBJECTIVE

The principal objective of this work was to incorporate soil parameter bias and correlation in order to recalibrate the resistance factors curves of the LRFD design charts in order to produce more consistent levels of safety.

3. RECALIBRATION OF RESISTANCE FACTORS CURVES

The general procedure adopted to incorporate parameter correlations and biases consisted of performing probabilistic and analytical analysis. The following sections describe the work and results obtained for the recalibration of the resistance factors curves, taking into account the existing soil parameter correlation and the bias between site and laboratory soil values.

3.1 Setup Considerations and Procedure

The resistance factors presented in 2005 for earth slope stability analyses using the LRFD technique were established by probabilistic calibrations. The level of safety (reliability) of these factors was observed to be inadequate or too conservative. For the reduction in the level of conservatism that these resistance factors would produce for slope stability designs, it was required to perform both probabilistic and analytical analysis. The general procedures used to accomplish this are described in this section.

3.2 Selection of Slope Geometry

According to previous work by (Loehr et al. 2005), probabilistically calibrated resistance factors were demonstrated to be insensitive to slope inclination and slope height. An example graph showing the sensitivity of the resistance factors to slope inclination is presented in Figure 2. The curves shown in this figure were developed for slope inclinations of 1.5(H):1(V), 2.5(H):1(V), 3.5(H):1(V), and for Janbu (1954) soil parameter, $\lambda_{c\phi}$= 10 and a probability of failure of 1%, (p_f = 0.01).

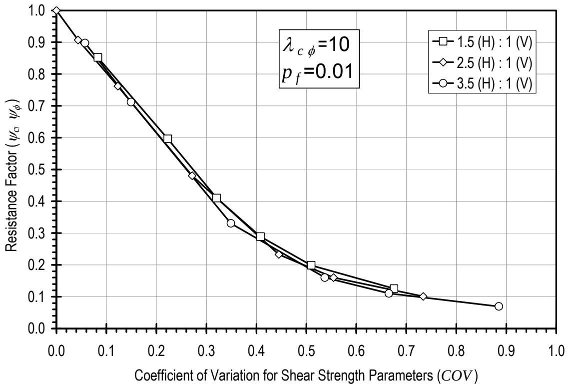

Figure 2. Resistance factor curves for different slope inclinations, $\lambda_{c\phi}$ =10 and p_f =0.01

An example graph showing the influence of slope height in the calibration of the resistance factors is shown in Figure 3. The resistance curves shown in this figure were developed for heights of 12.5, 25 and 50 ft again for Janbu soil parameter, $\lambda_{c\phi}$= 10 and p_f= 0.01 (selected level of reliability of 99%).

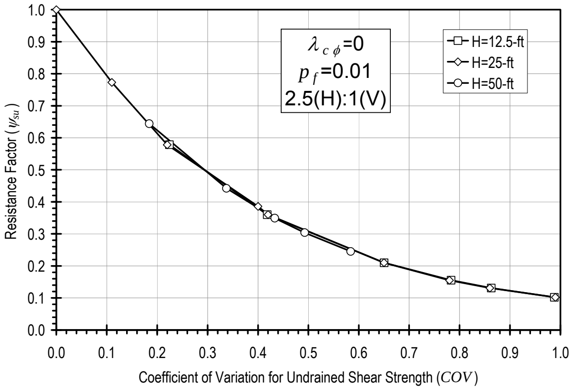

Figure 3. Resistance factor curves for different slope heights for $\lambda_{c\phi}$=10 and p_f=0.01

Based on these geometrical considerations, the slope geometry displayed in Figure 4 was used to recalibrate the resistance factors. The slope inclination considered was 1.5:1 (H:V) and the slope height was 25 ft.

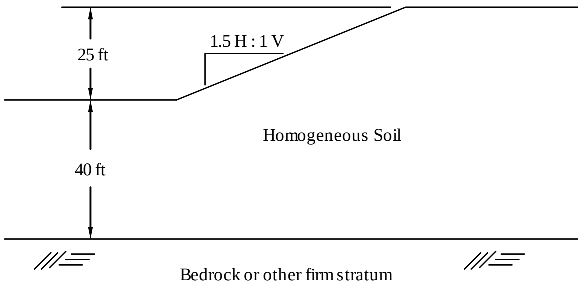

Figure 4. Slope geometry used to calibrate resistance factors

The geometry of the slope used in for the recalibration of the resistance factors was considered adequate and within the range of routine dimensions used by the state department of transportation.

3.3 Computer Settings

The probabilistic calibration of the resistance factors was executed with the commercial slope stability analysis software package Slide^{TM} version 5.034 from Rocscience. The software includes the option of performing probabilistic analysis through Monte-Carlo and Latin Hypercube sampling methods for simulations.

Factors of safety were computed using Spencer’s Method. Pore pressures were not included in the computations at this stage. Probabilistic analysis was performed using the *Latin-Hypercube* method of sampling. The advantage of this method over the Monte-Carlo method is that it results in a smoother probability distribution. In addition, analysis using 1000 samples with the Latin

Hypercube technique produces comparable results to the analysis of 5000 samples using the Monte Carlo method. The left graph displayed in Figure 5 shows the accuracy Latin Hypercube sampling method while the graph at the right shows the sampling accuracy of the Monte Carlo sampling method for 1000 samples. Sampling methods were complemented with the Park and Miller v.3 algorithm to generate random numbers.

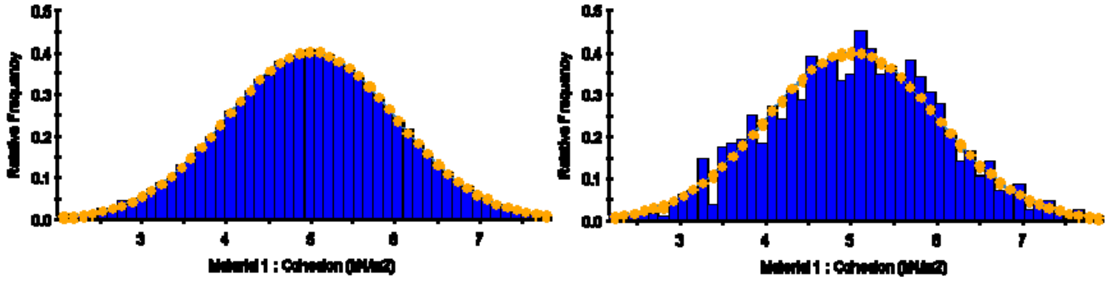

Figure 5. Comparison of Latin Hypercube and Monte Carlo sampling methods for 1000 samples

Probabilistic analysis was carried out using the overall method of Slide^{TM}. This method assumes that the probability of failure is defined as the number of analyses that result in factors of safety less than one, divided by the total number of samples. Unfortunately, this method requires substantial computation time, taking several hours to complete.

Finally, resistance factor recalibrations were performed based on a target probability of failure of 10%. This rather large target probability required less simulations and therefore less computation time. The convergence of the probability of failure result was clearly achieved in under 10,000 simulations, as shown in Figure 6.

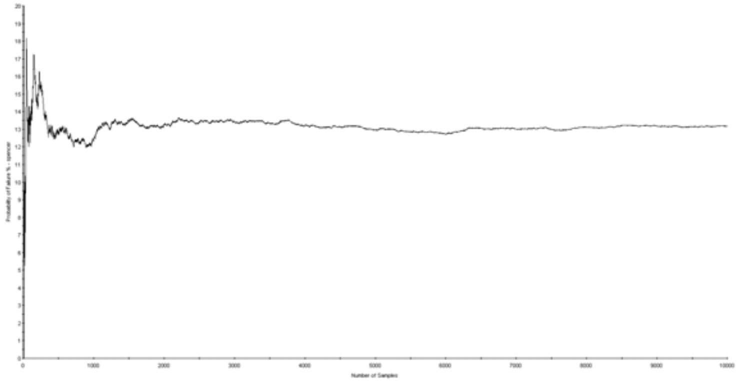

Figure 6. Probability of failure versus number of simulations convergence plot

However, targeting a smaller probability of failure (e.g., 1 in 1000), will require simulations and therefore more computational time. Modifications in settings or analysis approaches would need to be considered when targeting these probabilities of failure.

3.4 Probabilistic Analysis Considerations

The purpose behind the establishment of the resistance factors was to link the uncertainty of the design input parameters with a selected level of reliability. The uncertainty of design input parameters is known to depend on the variability of the soil and/or the site investigation. The selection of the level of reliability depends on the potential consequences of failure that could be expressed in terms of cost or human risk. To address the inherent soil property variation and uncertainty in measurement, random variables were assigned for each soil property.

In 2005 the Missouri Department of Transportation provided soil testing results from the site investigation of the New I-70 Interchange for the new Mississippi River Bridge project in Saint Louis. The results of direct shear testing performed to obtain effective stress strength parameters showed that a normal distribution was the best fit for the friction angle and unit weight of the soil while a lognormal distribution was the best fit for the cohesion intercept. The 2005 study based the soil parameter variability on these distributions. The recalibration progress described in this study also considered the same distributions for the soil input parameters.

Probabilistic analysis was performed to identify the influence of the type of soil cohesion distribution on the resistance factor curve. The overlapping curves displayed in Figure 7 show that the distribution type has very little effect on the resistance factor curves.

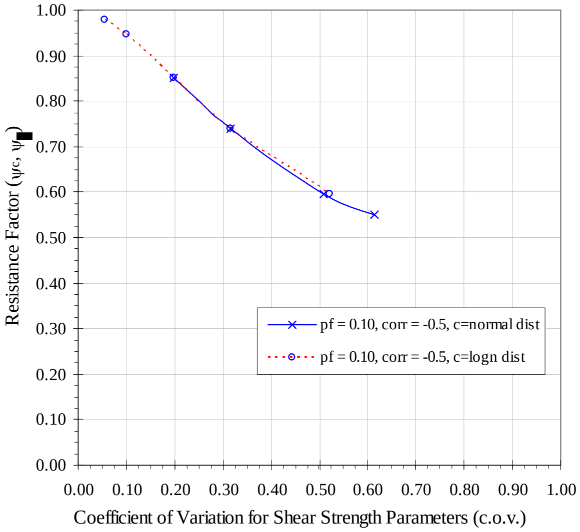

Figure 7. Resistance factor curve developed for normal and lognormal cohesion distributions

At least seven soil parameters are included in slope stability analysis. In order to reduce the number of variables, these were normalized using Janbu's 1954 dimensionless parameter $\lambda_{c\phi}$ as shown below.

$$\lambda_{c\phi} = \frac{\gamma \cdot H \cdot \tan\phi}{c}$$

where,

γ, represents the soil unit weight
H, represents the slope height,
ϕ, represents the soil internal friction angle, and
c is the soil cohesion intercept.

The slope height H, as mentioned before, had no influence on resistance factor values. Therefore the height of the slope was set as a constant at 25 ft. From the St. Louis data, the soil unit weight was observed to have, for practical purposes, no variability. Therefore in the study, the soil unit weight was assumed constant at 125 pcf. For a selected value of $\lambda_{c\phi}$, only variables c and ϕ were considered for the recalibration of the resistance factors. An example of the normalization of soil parameters for the study is shown in Table 1.

Table 1. Normalization of soil parameters for $\lambda_{c\phi}$=10

$\lambda_{c\phi}$	γ	H	c	ϕ
10.0	125	25	**107.6**	**19**
10.0	125	25	110.0	19.4
10.0	125	25	113.7	20
10.0	125	25	126.3	22
10.0	125	25	145.7	25
10.0	125	25	180.4	30
10.0	125	25	195.3	32

The general procedure to recalibrate the resistance factor curves through probabilistic analysis consisted of first selecting a level of reliability. Depending on the location of a slope, the cost of consequence may vary substantially. Reasonable risks or probabilities of failure for these structures may range from 10% (10 in 100) to 0.1% (1 in 1000). To identify the behavior of the curves with less computational effort, the recalibrations were performed at this stage of progress considering a 10% probability of failure.

Considering that the coefficient of variation (c.o.v.) is defined as the ratio of the standard deviation of a variable to its mean value, the next step consists of identifying, through iterations, a friction angle and cohesion c.o.v. that would produce the selected probability of failure. The iterations are executed with the slope stability software. Simultaneously, as the required c.o.v. is identified with the software, the resistance factor is computed in a spreadsheet according to the following formula:

$$\psi(c.o.v.) = \frac{x_{ref}}{\mu_x(c.o.v.)}$$

where,

$\psi(c.o.v.)$ is the resistance factor which is a function of the coefficient of variation of both friction angle and cohesion,
x_{ref} is a reference friction angle or cohesion value that produces a factor of safety

of unity (F=1.0), and
$\mu_x(c.o.v.)$ is any selected mean value of friction angle or cohesion.

When identifying the c.o.v. to produce a selected probability of failure, only the standard deviation varies. The mean values of friction and cohesion are selected by the researcher, with the only requirement being selection of values to achieve the previously selected value of the dimensionless parameter $\lambda_{c\phi}$.

Considering that the computation of the probability of failure is executed through a probabilistic analysis where the value of ϕ and c vary within their distribution range, the values of these parameters do not necessarily meet the requirement of $\lambda_{c\phi}$ at slope failure surfaces.

3.5 Recalibrated Resistance Factor Results

The slope stability resistance factors curves presented by Loehr et al. (2005) were observed to be conservative for a selected reliability level. One of the sources of conservatism identified was the lack of correlation considered between c and ϕ values when calibrating the 2005 resistance factors. According to the literature, soil parameters cohesion and internal friction angle are normally inversely correlated (negative correlation). The average correlation between these parameters is -0.5. If correlating c and ϕ inversely, then both parameters can not be at their lowest distribution value simultaneously when being selected through the Monte Carlo method.

To illustrate the effect of correlation in the study, several resistance factor curves were developed for different correlation values. Figure 8 shows recalibrated resistance factor curves considering correlations of -0.9, -0.7, -0.5, 0.0, +0.5. Notice in the same figure that as the correlation increases negatively, the resistance factors increase. However as the correlation increases positively, the resistance factor is less sensitive to the uncertainty of the variable value which is expressed through the c.o.v.

Resistance factor curves were developed by plotting resistance factor values versus their corresponding c.o.v.s As an example, Table 2 shows the values used to plot the curve $\lambda_{c\phi}$=10, p_f=10 and a correlation =-0.9 which is shown in Figure 8. The table shows that as the mean values of parameters c and ϕ increase, the resistance factors decrease. Figure 8 shows that as the resistance factors decrease for all correlation curves, they become less sensitive to the c.o.v.

Table 2. Calculation of *c* and ϕ resistance factors for $\lambda_{c\phi}$=10 and p_f=10

Statistic: **corr = -0.9** **Bias: 0%**

$\lambda_{c\phi}$ = 10.0			pf = 10%			c.o.v.
μ_c	σ_c	ψ_c	μ_ϕ	σ_ϕ	$\psi_{\tan(\phi)}$	
110.0	10	0.98	19	1.76	0.98	0.091
113.7	17	0.95	20	2.99	0.95	0.149
126.3	32	0.85	22	5.58	0.85	0.253
145.7	61	0.74	25	10.47	0.74	0.419
180.4	126	0.60	30	20.95	0.60	0.698
195.3	200	0.55	32	32.77	0.55	1.024

The increase of sensitivity to the c.o.v. at small resistance factors is explained by considering that as the mean values of *c* and ϕ increase, the slope becomes more stable. Furthermore, Monte Carlo selection of *c* and ϕ values will be weighted towards the large values of the *c* and ϕ distribution because at large standard deviations, the distribution curves are truncated on the lower values of the distribution at $c=\phi=0$.

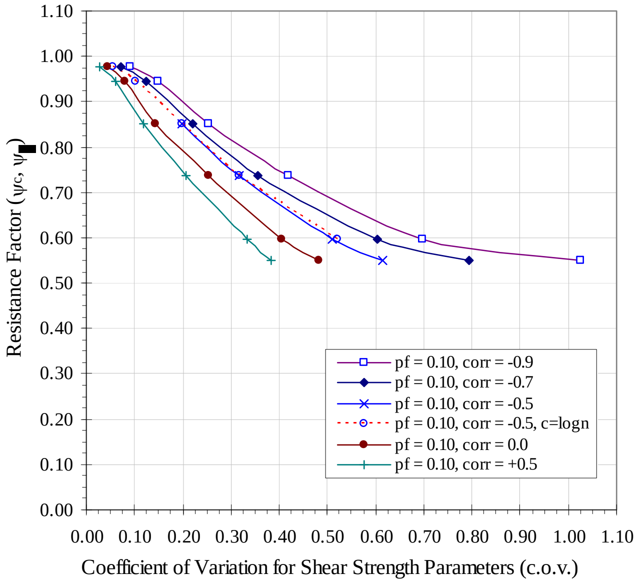

Figure 8. Resistance factor curves developed for different correlations between *c* and ϕ

Soil strength parameter bias is inherent in site investigation procedures, in testing methods, and in the empirical conservatism used when averaging values. The methodology adopted to incorporate the bias to calibrate the resistance factor curves was based mainly on the performance of analytical analysis. The equation used for the recalibration of the factors was the following:

$$\psi = \frac{x_{ref}}{\mu_x \cdot (1 + bias)}$$

The bias in the equation is expressed as a percentage. The equation recalibrates the resistance factor by modifying the parameter mean value by an equivalent of a bias. An example of resistance factor correction for bias is observed by comparing the factors of Table 2 with Table 3.

Table 3. Calculation of reduction factors and c.o.v. for 30% bias

Statistic: **corr = -0.9** **Bias: -30%**

$\lambda_{c\phi}$ = 10.0			pf =			c.o.v.
μ_c	σ_c	ψ_c	μ_ϕ	σ_ϕ	$\psi_{tan(\phi)}$	
110.0	10	1.40	19	1.76	1.40	0.091
113.7	17	1.35	20	2.99	1.35	0.149
126.3	32	1.22	22	5.58	1.22	0.253
145.7	61	1.05	25	10.47	1.05	0.419
180.4	126	0.85	30	20.95	0.85	0.698
195.3	200	0.79	32	32.77	0.79	1.024

Several resistance factor curves were developed to illustrate the effect of bias. Figure 9 shows recalibrated resistance factor curves considering bias values of 0%, 10%, 20%, 30%, 40%, and 50% for $\lambda_{c\phi}$=10, p_f=10 and a correlation =-0.9.

The curves shown in Figure 9 were developed to illustrate the effect of bias on the resistance factor curves.

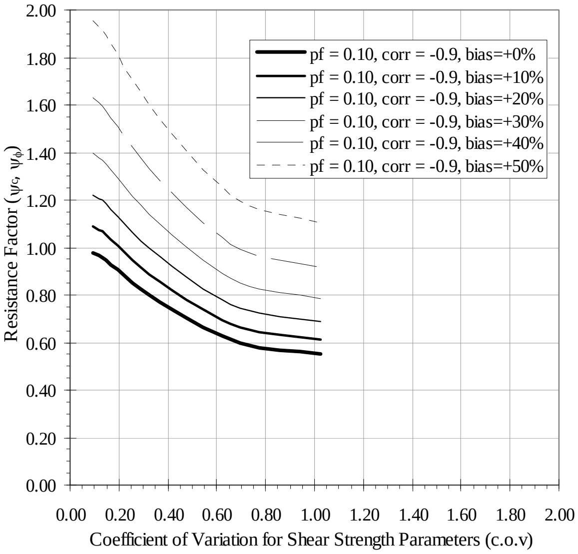

Figure 9. Reduction factor curves considering mean increase to account for bias

4. ONGOING ANALYSIS

Currently resistance factor curves for probability of failure of 1% are being recalibrated, as shown in Figure 10. Considering the early convergence shown in Figure 6 for the 10% probability of failure, the 1% probability of failure curves are also being generated satisfactorily with 10,000 simulations. Target probability of failure of less that 1% will require modifications in software settings or the use of an alternative analytical method such as Taylor's series approximation.

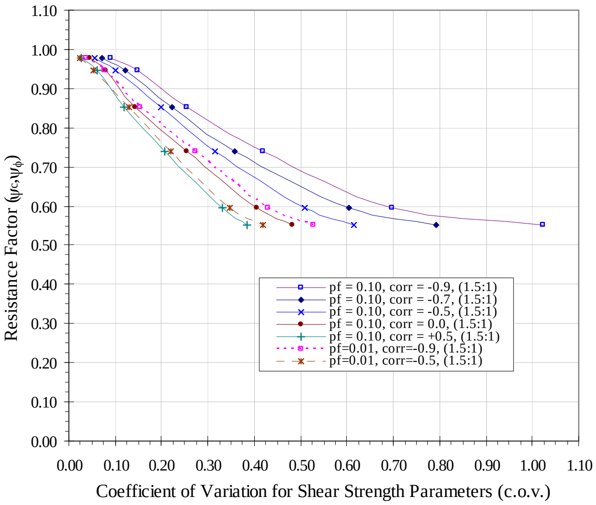

Figure 10. Ongoing recalibrated resistance factor curves including curves for p_f=10%

5. CONCLUSIONS

The following conclusions can be drawn from this project:

1. Changing the cohesion distribution type from normal to lognormal had no significant influence on resistance factor curves.
2. Resistance factor curves were able to be recalibrated by including correlation magnitudes between strength parameters cohesion and friction angle.
3. Resistance factor curves showed that low resistance factor values are not sensitive to soil parameter uncertainty or variability.
4. The inclusion of parameter bias allowed recalibration of the resistance factor curves that produce less conservative slope designs.
5. The Latin Hypercube technique allowed good convergence with a probability of failure of 10% with 10,000 simulations. Because of the computational effort and time, lower probabilities of failure may require the consideration of fewer simulations by using a different slope searching technique or to apply an analytical method such as Taylor's series approximation.

6. REFERENCES

Loehr, J. Erik, C. Finley, D. Huaco, (2005). Procedures for Design of Earth Slopes Using LRFD, Technical Report. University of Missouri-Columbia. Presented to the Missouri Department of Transportation. RI03-030.

Loehr, J. Erik, (2007). Integration of Asset Management Systems with Load and Resistance Factor Design (LRFD). University of Missouri-Columbia. Presented to the Missouri Department of Transportation

Slide-Rocscience Tutorial, (2008). Rocscience Inc. software Version 5.034.