Why consider SPATIAL VARIABILITY

The role of spatial variability: ***Slide* 2018**

Traditional slope stability analysis is based on the assumption that each material in the cross section of a slope has homogeneous properties spatially. That is, the cohesion, for example, at the far left end of a material is the same as that at the far right end, even if the material spans 20 m. **The concept of spatial variability considers the question - what if a parameter, such as cohesion, varies throughout the same material?** 1) How much of a difference does it make on the results? And 2) how can it be considered in the absence of meticulous data on the soil? This document will address these questions in the form of an example, along with details about how spatial variability works in the upcoming *Slide* 2018.

Mount Polley tailings dam, BC, Canada

This example will compare three different types of LEM analyses: 1) deterministic analysis, 2) probabilistic analysis, and 3) probabilistic analysis considering spatial variability.

The Mount Polley tailings dam was selected to provide baseline geometry and soil properties for this example (Province of British Columbia, 2015). Some soil properties were adjusted from the Mount Polley case study so that detectable values of probability of failure (PF) could be computed for the purpose of comparison. The geometry and properties used are found in Figure 1.

Deterministic Analysis

A simple deterministic analysis was first computed, using the GLE/Morgenstern-Price method and a non-circular search method. The results of the analysis are shown in Figure 2 - a factor of safety (FS) of 1.27 was computed.

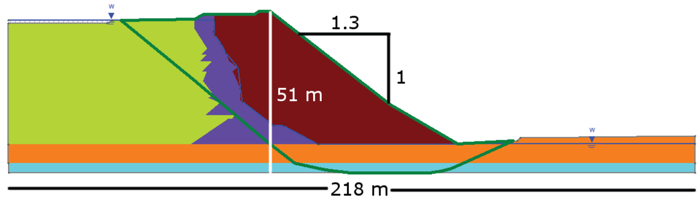
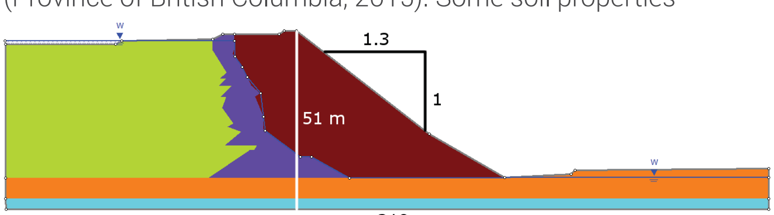


Figure 2. Non-circular surface located in deterministic analysis.

A deterministic shear strength reduction (SSR) analysis was also computed with RS^2 in order to verify the LEM results. Figure 3 shows the maximum shear strain contours of the model, which resulted in a shear strength factor (SRF) of 1.26. The surface in Figure 3 is in agreement with the non-circular slip surface, as are the SRF and FS



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface
Core		20.5	Mohr-Coulomb	0	35	Water Surface
Rock		22	Mohr-Coulomb	100000	0	None
Tailings		18	Mohr-Coulomb	0	30	Water Surface
Upper Till		21	Mohr-Coulomb	0	35	Water Surface
Upper Glaciolacustrine		20	Mohr-Coulomb	25	15	Water Surface

Figure 1. The Mount Polley tailings dam model and the material properties used in this example.

values.

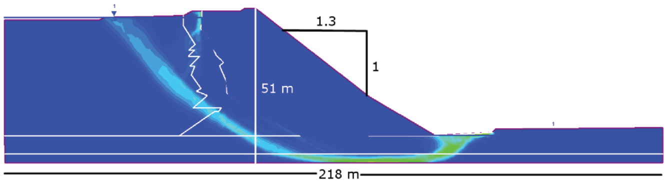


Figure 3. Maximum shear strain contours from SSR analysis in *RS*^{2}.

Probabilistic Analysis

A probabilistic analysis considers soil variability by defining a distribution for each soil parameter and carrying out Monte Carlo simulations. Each realization uses a single set of sampled soil property values to compute the corresponding factor of safety in each simulation. The PF is calculated as the ratio of the number of simulations resulting in FS<1 to the total number of simulations. This is shown schematically in Figure 4. In this example 10,000 simulations were used in all probabilistic analyses.

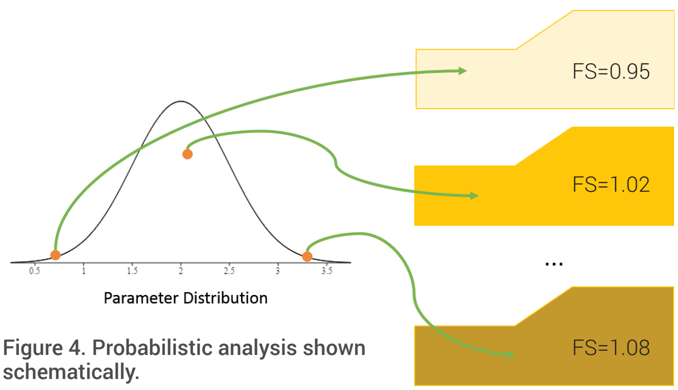


Figure 4. Probabilistic analysis shown schematically.

The random material parameters used in this example are shown in Table 1. Lognormal distributions are assumed for all random variables. The core and rock materials were assumed to have the constant material properties defined in Figure 1.

Table 1. Random variable parameters used in this example.

Material	Property	Mean	Std. Dev.
Tailings	Unit Weight	18 kN/m^3	1.8 kN/m^3
Tailings	Friction Angle	30 deg.	6.0 deg.
Upper Till	Unit Weight	21 kN/m^3	2.1 kN/m^3
Upper Till	Friction Angle	35 deg.	7.0 deg.
Upper Glaciolacustrine	Unit Weight	20 kN/m^3	2.0 kN/m^3
Upper Glaciolacustrine	Friction Angle	20 deg.	4.0 deg.
Upper Glaciolacustrine	Cohesion	25 kPa	7.5 kPa

The probability of failure computed was 11%, and the mean FS was 1.195.

Probabilistic Analysis Considering Spatial Variability

Two additional input parameters are required to move from a probabilistic analysis, to one that considers spatial variability: horizontal and vertical correlation length.

What is correlation length? Correlation length represents the distance over which soil parameters are similar, or correlated. There are various ways of obtaining correlation length values. In this example the correlation length was measured from available CPT data. Correlation lengths can also be estimated from data recorded in literature. *Slide* 2018 will include a table of compiled literature data estimating correlation lengths for several materials. Typically correlation length ranges from 1 - 6 m in the vertical direction and 20 - 60 m in the horizontal direction.

In this example, a vertical correlation length of 1 m was used. The effect of horizontal correlation length was considered negligible by letting it be 1000 m.

A schematic of a probabilistic analysis with spatial variability is shown in Figure 5. This is a more realistic model that takes into account the variability of the material *within* each simulation, such that each of the 10,000 realizations used considers a different arrangement of weak and strong areas.

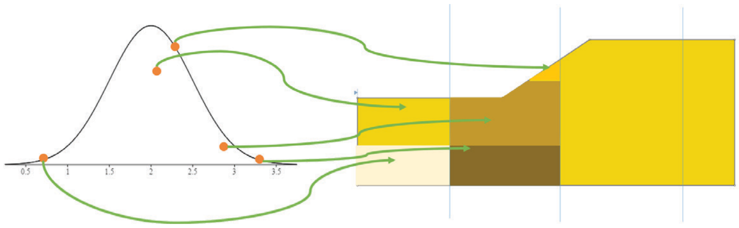


Figure 5. Considering spatial variability shown schematically.

Figure 6 shows a dialog from *Slide* 2018 with the random properties and correlation length of Upper Glaciolacustrine.

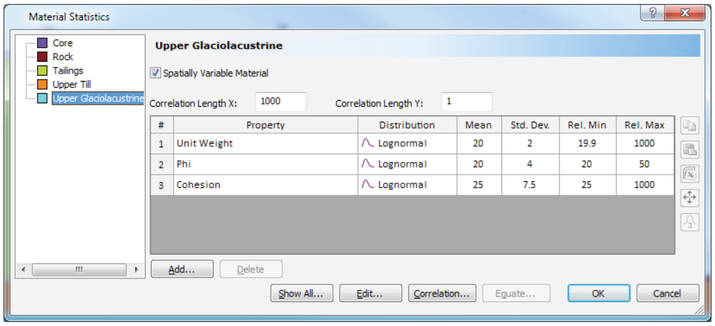


Figure 6. Random properties for Upper Glaciolacustrine in *Slide* 2018.

The probability of failure computed from the probabilistic analysis considering spatial variability was 0.15% and the mean FS was 1.189. Figure 7 shows a preview of the unit weight random fields generated in three of the 10,000 samples, illustrating some of the different arrangements of weak and strong areas considered. Figure 7 also helps visualize the meaning of correlation length - it can be seen that the unit weight values are correlated about 1 m vertically and "infinitely" horizontally, creating the bands seen in the figure.

Conclusion

The concept of spatial variability considers the question - what if a parameter, such as cohesion, varies throughout the same material? 1) How much of a difference does it make on the results? And 2) how can it be considered in the absence of meticulous data on the soil?

1) How much of a difference does it make on the results?

The different results obtained from the three methods in this example are summarized in Table 2.

Table 2. Results obtained from the three LEM methods.

Deterministic	FS = 1.27
Probabilistic	PF = 11.0%, mean FS = 1.195
Probabilistic Considering Spatial Variability	PF = 0.15%, mean FS = 1.189

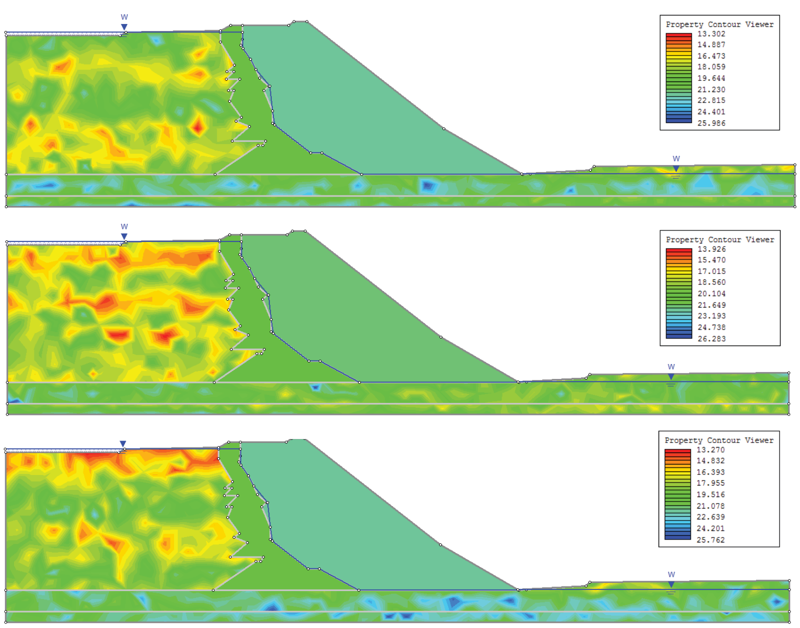


Figure 7. Unit weight contours at three different simulations.

By considering spatial variability, the third approach is judged to give more realistic results when compared to the other two methods for the tailings dam case used here. In most cases, this means a less conservative PF value. As seen in Table 2, the probability of failure using a simple probabilistic analysis is extremely conservative, resulting in a different appreciation of the margin of safety against collapse when compared to the other two results. The effect of considering spatial variability in a project is extensive - by obtaining a more accurate probability of failure, a more cost-effective project can be designed.

2) How can it be considered in the absence of meticulous data on the soil?

For users who are already comfortable running probabilistic analyses, considering spatial variability will be a straightforward transition, needing only two additional parameters: horizontal and vertical correlation length. *Slide* 2018 will then generate random samples considering different arrangements of the weak and strong areas on the slope in each simulation.

In short, spatial variability accounts for the "what-if" scenarios. It's not possible to obtain the soil properties at every location. By inputting correlation length, spatial variability is accounted for by considering different arrangements of weak and strong areas in each simulation. It is an additional step in obtaining a more accurate probability of failure.

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References

For a more detailed version of this study, see: Cami, B., Javankhoshdel, S., Lam, J., Bathurst, R.B., Yacoub, T. 2017. Probabilistic Analysis of a Tailings Dam using 2D Composite Circular and Non-Circular Deterministic Analysis, SRV Approach, and RLEM. Proceedings of GeoOttawa 2017 conference, Ottawa, Ontario, Canada.

Province of British Columbia 2015. Independent Expert Engineering Investigation and Review Panel. Report on Mount Polley Tailings Storage Facility Breach.