

RS2

Seepage Analysis

Examples

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1. From Classical to Cutting-Edge: A Comparative Examination of Seepage Analysis Techniques

1.1. Introduction

Seepage analysis plays a pivotal role in various engineering applications, such as ensuring the safety, stability, and sustainability of slopes, infrastructure and natural ecosystems. Accurate analysis results can help prevent potential seepage-induced disasters such as dam failures and landslides. As such, the usage of a seepage analysis software that can reliably predict groundwater flow patterns in the most complex situations is paramount. However, often users will first verify the results from a software with analytical solutions before accounting for more complicated conditions.

In this article, two case studies are examined in RS2 to highlight the effects of anisotropic conditions and saturated-unsaturated regimes on seepage analysis compared to ones that use a traditional approach.

1.2. Case I: Effect of Anisotropy on Flow Net Shape

Flow nets are essential tools for analyzing the movement of groundwater through soil structures, as they provide insight to seepage patterns and aid in design and stability assessment. A flow net consists of 2 families of lines: streamlines which represent the direction of water particle flow, and equipotential lines which represent lines of constant total head.

In soils that exhibit isotropic permeability, streamlines are always perpendicular to equipotential lines for every point in the flow net. However, in most engineering applications soil permeability is anisotropic due to factors such as compaction and loading, which often results in the horizontal permeability being much greater than the vertical. In these cases, streamlines are no longer orthogonal to the equipotential lines, resulting in a skewed mesh. For the case Kx > Ky, the flow net will have a stretched appearance.

1.2.1. Model Geometry

In RS2, we can compare the flow nets for isotropic and anisotropic soils by adjusting the ratio for the horizontal and vertical permeabilities in the hydraulic properties tab.

In this study we will be examining a problem which consists of uniform fluid flow around a 1m radius cylinder as shown in Figure 1.1. Due to its symmetry about the x-axis, only the upper half of the domain is modelled in RS2. The hydraulic boundary condition is set to total head of 1m on the left and 0m on the right. The dimensions of the tunnel are also shown in Figure 1.2.



Figure 1.1: Fluid flow around cylinder



Figure 1.2: RS2 model of tunnel

We can define the ratio for the horizontal and vertical permeability with the K2 / K1 parameter. K2 is the vertical permeability while K1 is the horizontal. In Table 1.1, the ratio is set to 0.1, meaning the horizontal permeability is greater than the vertical by a factor of 10.

Parameter	Value
Model	User Defined
Material Behavior	Drained
K2/K1	0.1
K1 Definition	Angle
K1 Angle (degrees)	0
Permeability and Water Content	
Permeability - 0 kPa Suction (m/s)	1e-5
Permeability - 100 kPa Suction (m/s)	1e-5

1.2.2. Results

In this analysis, permeability ratios of 1, 0.5, 0.1, and 0.01 were used. Flow nets can be constructed in the interpreter by turning the contour mode to "Filled (with lines)" to show equipotential lines and using the "Add Multiple Flow Lines" tool to show equidistant streamlines. The results are shown below.







Figure 1.4: K2 = 0.5 K1







Figure 1.6: K2 = 0.01 K1

From Figure 1.3 to Figure 1.6 above, we can notice that as the K2 / K1 ratio decreases, or as horizontal permeability becomes even greater than the vertical, the skew of the flow lines to the equipotential lines becomes more pronounced, especially around the tunnel area. For reference, angle markings have been included in each figure to illustrate how the line intersection at a particular point increases from 90 degrees for isotropic soil to 150 degrees for the most extreme anisotropic case.

1.3. Case II: Modelling Saturated vs. Saturated-Unsaturated Flow in RS2

Seepage plays a critical role in the failure of dams because of its potential to cause slope instability, erosion, and saturation-induced strength reduction. As such, accurate analysis of flow through a dam is important for determining its safety.

Traditional models for groundwater seepage consider flow only in the saturated zone, such as the unconfined flow net technique proposed by Casagrande (1937). This technique treats the upper surface of the flow net (the phreatic surface) as the upper boundary on seepage and ignores all flow occurring in the unsaturated region. However, it is well known that flow also exists in the unsaturated zone, and the use of traditional methods in these situations typically overestimates the elevation of the water table.

1.3.1. Model Geometry

We can model both flow methods in RS2 by setting different hydraulic models in the hydraulic properties tab.

In this study we will be examining an earth dam with a chimney drain example from Cedergren (1989) as shown in Figure 1.7, which uses the traditional saturated flow method. The dam consists of two soil layers, with the bottom layer having permeability 100 times that of the top layer. Both soil layers are

assumed to be anisotropic with the horizontal permeability nine times the vertical. A total head of 176m is applied to the submerged section of the left side of the dam and 120m is applied to the water surface at the right side of the dam as shown in Figure 1.8.



Figure 1.7: Earth dam with chimney drain



Figure 1.8: Earth dam in RS2

2 models were created, one using the saturated-unsaturated flow method and the other using the saturated flow method.

Hydraulic models included in RS2 automatically account for the unsaturated flow above the phreatic surface. For this particular model, we use the "Simple" model for all the material. In the hydraulic properties tab, set the horizontal permeability Ks to 1000 ft/s for the earth dam, 1e6 ft/s for the drain, and 1e5 ft/s for the foundation material. For all materials set the K2/K1 ratio to 0.111111 to simulate anisotropy. Leave all other properties as their default values. Hydraulic properties are shown in Table 1.2 below.

Parameter	Earth Dam	Drain	Foundation
Model		Simple	
Material Behavior		Drained	
K2/K1	0.111111		
K1 Definition	Angle		
K1 Angle (degrees)	0		
Ks (ft/s)	1000	1e+6	100000

Table 1.2: Hydraulic properties – saturated-unsaturated model

In order to model the traditional approach where no flow is allowed in the unsaturated zone, we can use the "User defined" hydraulic model to specify a permeability function for each material. Click "Define" to input a table of matric suction vs. permeability data in the permeability and water content dialog. For 0 matric suction (for regions below the phreatic surface), the permeability values are 1000, 1e+6, and 1e+5 for earth dam, drain, and foundation materials respectively. Then for 0.001 matric suction, the permeability is set to the smallest possible value for all materials, which in RS2 is 1e-12. This essentially reduces all flow above the phreatic surface to zero, which is required for the traditional saturated flow method. Hydraulic properties are shown in Table 1.3 below.

lable	1.3:	Hydraulic	properties	- traditional	model

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Parameter	Earth Dam	Drain	Foundation
Model	U	ser Defir	ed
Material Behavior		Drained	
K2/K1		0.11111	1
K1 Definition		Angle	
K1 Angle (degrees)		0	
Permeability and Water Content			
Permeability – 0 psf Suction (ft/s)	1000	1e+6	100000
Permeability – 0.001 psf Suction (ft/s)		1e-12	

1.3.2. Results

The results of both models are shown below, with Figure 1.9 using the traditional saturated flow method and Figure 1.10 using the saturated-unsaturated method. In the saturated flow case, the phreatic surface intersects the drain near the top of the vertical section, matching the flow net from the example in Cedergren (1989). For the saturated-unsaturated case, the phreatic surface intersects lower at the horizontal section of the drain.



Figure 1.9: Phreatic surface with saturated flow method



Figure 1.10: Phreatic surface with saturated-unsaturated flow method

The difference in phreatic surface elevation is due to conservation of mass flow. In the saturatedunsaturated case, seepage occurs above and below the phreatic surface. In the pure saturated flow case, the seepage occurring above the phreatic surface is ignored. By conservation of mass that flow must therefore occur below the phreatic surface, which increases the elevation of the water table.

1.4. Conclusion

Modern software tools have significantly advanced the capability to carry out realistic seepage analysis. These software solutions can also yield results comparable to those obtained through traditional methods, when employing the same assumptions – for instance, the omission of flow within the unsaturated zone. This technological evolution not only enhances the precision of seepage analysis but also simplifies the integration of established techniques into workflows, contributing to more efficient and accurate assessments of seepage-related problems in various engineering and environmental applications.

1.5. References

Casagrande, A. (1937). Seepage through dams. New England Water Works. 51(2), pp. 295-336.

Cedergren, H.R. (1989). Seepage, drainage, and flow nets. *Wiley-InterScience, John Wiley & Sons, New York.*

2. Permeability Variation on Rock Tunneling Analysis

2.1. Introduction

It is well recognized that the effect of stress on permeability of geomaterials is significant. As studied by many researchers (e.g., Meng et al., 2019, Davies and Davies, 2001, Zhang et al., 2013), changes in permeability occur due to closure, dilation, and further development of pores and cracks within the material. Over a complete stress-strain process, the permeability variation can be broken down into four distinct phases. Initially, permeability decreases during volumetric compression, followed by a gradual increase when the first structural damage occurs and the rock begins to dilate, then it increases rapidly at the yield period until the peak value is reached, and lastly it decreases slightly with fluctuations in the post-peak period. In this example, we demonstrate the effect of permeability changes in tunneling analysis with RS2.

2.2. Background

The model is derived from a case study by Hoek et al. (2008) that investigates methods of reinforcement and support to enhance tunneling stability. For the model, the tunnel was excavated using the top heading and bench approach (see Figure 2.1 and Figure 2.2). The approach involves the following sequence: temporary support and excavation of the top heading; temporary support and excavation of the bench; the placement of permanent concrete lining. Note that the temporary support here refers to shotcrete lining and invert. Rock bolts were also installed to the top heading. Additionally, an open cut to the slope toe was operated (see Table 2.2).

In this example, two tunnel design models are evaluated: a base model and a permeability variation model, differing only in their permeability inputs. The base model uses a constant permeability value, while the permeability variation model employs a volumetric strain-permeability function (see Figure 2.3) from Zhao et al. (2016).

Zhao et al. (2016) examined the permeability characteristics of fractured rock throughout a complete strainstrain curve. By applying this function in the permeability variation model, the effect of stress on permeability is accounted for in the tunneling analysis.

2.3. Model Geometry

Both models share identical geometry. It consists of a 120 m span highway tunnel and the rock mass is composed of parallel interbedded jointed sandstone, bedded sandstone, and shear zones (see Figure 2.1 and Figure 2.2).



Figure 2.1: Original geometry, rock layers, and tunnel and slope excavations. (From Integration of geotechnical and structural design in tunneling, by Hoek et al, 2008, Presented at University of Minnesota 56th Annual Geotechnical Engineering Conference. Minneapolis.)





The material solid properties are provided in Table 2.1 below.

Туре	Jointed Sandstone	Bedded Sandstone	Fault Material (Shear zone)	Softened inclusion 100 MPa	Softened inclusion 75 MPa
Young's Modulus (MPa)	9500	4000	650	100	75
Poisson's Ratio	0.25	0.25	0.3	0.3	0.2
Material Type	Plastic	Plastic	Plastic	Elastic	Elastic
Peak Tensile Strength (MPa)	0.2	0.14	0.08	0	0
Peak Friction Angle (degrees)	52	50	40	35	30
Peak Cohesion (MPa)	2	1.4	0.8	10.5	10.5
Residual Tensile Strength (MPa)	0	0	0	N/A	N/A
Residual Friction Angle (degrees)	50	47	40	N/A	N/A
Residual Cohesion (MPa)	1.5	1.2	0.8	N/A	N/A
Dilation Angle (degrees)	0	0	0	N/A	N/A
Unsaturated Behavior	None	None	None	None	None

Table 2.1: Material solid properties

Table 2.2: Model stages

#	Name
1	Initial
2	Core Softening 1
3	Core Softening 2- Initial Supports
4	Heading Excavation-Temp Invert
5	Core Softening Invert 1
6	Core Softening Invert 2 - Initial Support
7	Full Excavation
8	Finalize Support-Slope Excavation
9	Final Lining-no Drainage

The model uses the gravity method for field stress, with an effective stress ratio of 1.5 for in-plane and 2.0 for out-of-plane, and no locked-in horizontal stress. Total head values of 46.56 m and 69.7 m are set at the left and right boundaries, respectively, while unknown boundary conditions are assigned to the slope and tunnel boundaries. The groundwater analysis is conducted in a steady state, with the groundwater discharge rate monitored during tunneling.

2.3.1. Base Model vs. Permeability Variation Model

For the base model, constant permeability properties are applied as shown in Table 2.3. In contrast, for the permeability variation model, instead of a constant value of Ks = 1e-06 m/s, the permeability of jointed sandstone and bedded sandstone is distributed spatially based on volumetric strain, as shown in Figure 2.3 below, following Zhao, et al. (2016). All other properties stayed the same.

Туре	Jointed Sandstone	Bedded Sandstone	Fault Material (Shear zone)	Softened inclusion 100 MPa	Softened inclusion 75 MPa
Ks Distribution	Constant	Constant	Constant	Constant	Constant
Ks (m/s)	1e-06	1e-06	1e-07	1e-06	1e-06
K2/K1 Distribution	Constant	Constant	Constant	Constant	Constant
K2/K1	1	1	1	1	1
K1 Angle Distribution	Constant	Constant	Constant	Constant	Constant
K1 Angle Degrees	0	0	0	0	0
DoS sat Distribution	Constant	Constant	Constant	Constant	Constant
DoS sat	0.8	0.8	0.8	0.8	0.8
Dos res Distribution	Constant	Constant	Constant	Constant	Constant
Dos res	0.1	0.1	0.1	0.1	0.1

Table 2.3. Explanatic propertie	e 2.3: Hydraulic properties	Table 2	Т
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Figure 2.3: Volumetric strain versus permeability (m/s)

2.4. Results

The results for both models at the final stage are compared. The permeability variation in rock leads to an increase in the permeability, water table, discharge velocity, and support strengths, including liner bending moment and bolt axial force, as described below.

The permeability distributions are displayed in Figure 2.4 below. For the permeability variation model, the permeability of jointed sandstone and bedded sandstone depends on the volumetric strain, resulting almost 10 times increase (1.02e-05 m/s) compared to the base model (1.00e-06 m/s). The permeability of the shear zones remains constant in both models.



Figure 2.4: Permeability distribution for the base model (left) and the permeability variation model (right) at Stage 9

The degree of saturation is shown in Figure 2.5 below. The water table, indicated by the pink line, rises in the permeability variation model.



Figure 2.5: Degree of saturation for the base model (left) and the permeability variation model (right) at Stage 9

The maximum total discharge velocity increased tenfold, from 7.00e-07 m/s to 7.61e-06 m/s (see Figure 2.6 below).



Figure 2.6: Total discharge velocity for the base model (left) and the permeability variation model (right) at Stage 9

In terms of support strength, the maximum bending moment in liners increased from 0.034 MNm to 0.042 MNm, representing a 24% increase, as plotted in Figure 2.7 below. Additionally, the axial forces in the bolts nearly doubled, rising from 0.007 MN to 0.013 MN, as illustrated in Figure 2.8.



Figure 2.7: Bending moment in liners



Figure 2.8: Axial force in bolts

2.5. Reference

Davies, J.P., & Davies, D.K. (2001). Stress-dependent permeability: Characterization and modeling. *SPE Journal*, 6(2), 224-235.

Hoek, E., Carranza-Torres, C., Diederichs, M., & Corkum, B. (2008). The 2008 Kersten lecture -Integration of geotechnical and structural design in tunneling. Presented at University of Minnesota 56th Annual Geotechnical Engineering Conference. Minneapolis.

Meng, F., Baud, P., Ge, H., and Wong, T-F. (2019). The effect of stress on limestone permeability and effective stress behavior of damaged samples. Journal of Geophysical Research: Solid Earth, 124, 376-399.

Zhang, R., Jiang, Z., Sun, Q., and Zhu, S. (2013). The relationship between the deformation mechanism and permeability on brittle rock. *Natural Hazards*, 66, 1179–1187.

Zhao, Y., Tang, J., Chen, Y., Zhang, L., Wang, W., Wan, W., & Liao, J. (2016). Hydromechanical coupling tests for mechanical and permeability characteristic of fractured limestone in complete stress-strain process. *Environmental Earth Sciences.* doi:10.1007/s12665-016-6322-x

3. Spatial Permeability for Drawdown Slope Analysis

3.1. Introduction

Spatial variability of soil properties plays a crucial role in geotechnical engineering. The natural variation in soil properties across a region results from the complex soil formation process and other underlying factors. Permeability, in particular, can vary widely even within the same soil type. In seepage analyses, the spatial permeability has a profound impact on groundwater flow, as well as slope stability regarding the size and location of slope failure. Incorporating spatial variation of permeability into analyses assist with more realistic drainage system and structural designs.

Given the complexity of varying properties, obtaining a complete set of spatial soil data from the field or through formulas is challenging. Statistical analysis can help address the uncertainty of these properties. In this case study, a spatial variability analysis was previously conducted in Slide2 to generate the spatial distributed permeability data. The primary focus of the study is on examining the effect of spatial permeability on drawdown slope analysis.

3.2. Background

Drawdown is a common geotechnical problem that occurs when the water level in a reservoir, river or other water body surrounding a slope or embankment drops. The consequent reduction in external hydrostatic pressure on the soil or rock face may lead to an unbalanced internal pressure distribution to the slope materials, especially for materials such as clay, which have low permeability and a slow response to change in pore water pressure. The pressure imbalance can cause slope instability or even failure.

3.3. Model Description

In RS2, we can evaluate the effect of spatial permeability on drawdown slope analysis by comparing constant to spatial permeability models. The spatial permeability data were collected from a Slide2 spatial variability analysis.

3.3.1. Data Collection

Many approaches were found feasible to manage the risk of uncertainty in soil properties. In this case study, probabilistic analysis was conducted in Slide2 to model the spatial variability of permeability across the geometry. A random field is generated for permeability based on the overall slope analysis type. A total of 100 samples were produced using Latin Hypercube technique. For the spatial variable analysis, a correlation length of 15 m was defined for both horizontal and vertical directions, with permeability following a normal distribution (mean: 1e-07 m/s, standard deviation: 6e-08 m/s, covariance function: Markovian). The Slide2 model is included in the data files as *hydraulic statistics - drawdown analysis for slope.slmd*.

This Slide2 analysis produced 100 sets of spatial permeability data, stored as *.dat* files (in the folder named *samples*), each containing permeability values in terms of x and y coordinates. These data sets are used as inputs for further analysis in the study.

See the <u>topic</u> for more about spatial variability analysis in Slide2. Alternatively, users can adopt other approaches to estimate spatial variability in permeability. Note that the data collection was completed beforehand and is not the primary focus of this study.

3.3.2. Constant Model

A model with constant permeability was established. The constant model is included in data files as *Drawdown Analysis for Slope_Constant.fez*.

Additional note that, this model is equivalent to the model in RS2 Drawdown Analysis for Slope (FEA) tutorial. See the <u>tutorial</u> for further information.

3.3.3. Variation Models

100 variation models were created, each with a unique spatial permeability function distributed across the geometry.

To achieve this, a Python script drafted in RS2Scripting was utilized. The script processes the 100 data files generated by Slide2, replacing the constant permeability in a copy of the constant model with each dataset, resulting in 100 distinct variation models. The variation models will be saved in the *samples* folder.

Note that, in order to minimize storage space, only the variation model using the first dataset, *1.fez*, will be included in the example. The other 99 variation models can be retrieved by running the script *slope_spatial_variability_hydraulics.py*.

3.4. Model Geometry and Properties

The model consists of a soil slope with two stages. The geometry and boundary conditions of the homogeneous slope are shown in Figure 3.1 and Figure 3.2.

In stage 1 (Figure 3.1), the total head is 40 m along the left boundary, the slope base, and the bottom section of the slope face. The groundwater boundary condition for the middle section of the slope above the water table is undefined. The total head along the right boundary is 47 m. In stage 2 (Figure 3.2), the ground water table drops from a height of 10 m to 5 m during drawdown.



Figure 3.1: Model geometry at stage 1



Figure 3.2: Model geometry at stage 2

The solid and hydraulic properties of the soil are provided in Table 3.1 and Table 3.2 below.

Table 3.1: Solid material properties

Туре	Data
Initial Element Loading	Field Stress and Body Force
Unit Weight (kN/m³)	19

Porosity Value	0.5
Poisson's Ratio	0.4
Young's Modulus (kPa)	50000
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Tensile Strength (kPa)	10
Friction Angle (degrees)	35
Cohesion (kPa)	10
Dilation Angle (degrees)	0
Apply SSR (Shear Strength Reduction)	True

Table 3.2: Hydraulic properties

Туре	Data
Ks Distribution (constant model)	Constant
Ks (m/s) (constant model)	1e-07
K2/K1 Distribution	Constant
K2/K1	1
K1 Angle Distribution	Constant
K1 Angle	0
WC Input Type	By Water Content
WC sat Distribution	Constant
WC sat (m³/m³)	0.4
WC res Distribution	Constant
WC res (m³/m³)	0

The constant model and variation models share the same geometry and properties, differing only in the hydraulic permeability (Ks) input. In the constant model, a constant permeability of 1e-07 m/s is applied (see Table 3.2), while the variation models incorporate a spatial permeability function defined with respect to x and y coordinates (see Figure 3.3).

Permeability vs. Coo	ordinate				>
Soil 1	Name:	Soil 1			
		XDB	- ite 🛼 💈	1	
		X (m)	Y (m)	Permeability (m/s)	
	1	0	0	0.014153	
	2	0.95588	0	0.016119	
	3	1.9118	0	0.015357	
	4	2.8676	0	0.01279	
	5	3.8235	0	0.015422	
	6	4.7794	0	0.014233	
	7	5.7353	0	0.014789	
	8	6.6912	0	0.014645	
	9	7.6471	0	0.016088	
	10	8.6029	0	0.012115	
	11	9.5588	0	0.010877	
🕂 🗇 🗘	🚰 In	nport	Export	OK Cancel)

Figure 3.3: Permeability spatial distribution

3.5. Results

The SSR (shear strength reduction) analysis was performed to evaluate slope stability at the last stage. The results are compared between the constant model and the first variation model: *1.fez* (or any of the 100 variation models).

Figure 3.4 below illustrates the permeability distribution across the geometry. The maximum pore pressure rises from 441.45 kPa to 461.07 kPa with spatial permeability, as shown in Figure 3.5.



Figure 3.4: Permeability distribution for constant model (left) and first variation model (right)



Figure 3.5: Pore pressure for constant model (left) and first variation model (right)

Figure 3.6 and Figure 3.7 below show the maximum shear strain and total displacement contours at SRF of 1.3 for both models respectively. With spatial permeability, the critical SRF value at the last stage increases from 1.25 to 1.29, while the maximum total displacement reduces from 0.727 m to 0.148 m, indicating a more stable slope.



Figure 3.6: maximum shear strain at SRF of 1.3 for constant model (left) and first variation model (right)



Figure 3.7: Total displacement at SRF of 1.3 for constant model (left) and first variation model (right)

Figure 3.8 below displays a histogram for the factor of safety across the 100 variation models. This histogram is launched automatically by the Python script: *slope_spatial_variability_hydraulics.py*. It demonstrates that, when considering spatial permeability, the factor of safety is consistently greater than 1, indicating a safe slope.



Figure 3.8: Factor of Safety Histogram for 100 variation models in RS2

It is worth mentioning that, after the spatial variability analysis in Slide2, the slope stability analysis can be further conducted within Slide2 (*hydraulic statistic – drawdown analysis for slope.slmd*). Unlike RS2, which uses finite element methods, Slide2 employs the limit equilibrium method. A histogram displaying the factor of safety results can be plotted in Slide2 (see Figure 3.9 below). It can be seen that Figure 3.8 and Figure 3.9 patterns resemble each other, indicating that the from Slide2 and RS2 are in agreement.



SAMPLED: mean=1.275 s.d.=0.0623 min=1.063 max=1.388 (PF=0.000% RI=4.40715, best fit=Beta distribution)

Figure 3.9: Factor of Safety Histogram for 100 samples in Slide2

3.6. Data Files

The input files include:

- 1. A python script: slope_spatial_variability_hydraulics.py
- 2. A *samples* folder containing the first variation model *1.fez* and 100 spatial permeability datasets as *.dat* files
- 3. Constant model: Drawdown Analysis for Slope_Constant.fez
- 4. Slide2 model for reference: hydraulic statistics drawdown analysis for slope.slmd

4. Staging Spatial Permeability in Seepage Analysis

4.1. Introduction

The hydraulic properties of materials can vary by stage in a multi-stage model. For finite element groundwater analysis in RS2, the hydraulic properties can be either constant or spatially distributed as a function of stress, strain, or coordinates. This example simply showcases how to stage permeability distributions for seepage analysis and examines their impact on the results.

4.2. Model Geometry

This example utilizes a two-stage model consisting of a soil slope. The geometry and boundary conditions of the homogeneous slope are shown in Figure 4.1. The total head is 40 m along the left boundary, the slope base, and the bottom section of the slope face. The groundwater boundary condition for the middle section of the slope above the water table is undefined. The total head along the right boundary is 47 m.



Figure 4.1: Model geometry in RS2

The solid and hydraulic properties of the soil are provided in Table 4.1 and Table 4.2 below.

Table	4.1:	Soil	material	properties
i ubic	T . I.	001	material	properties

Туре	Data
Initial Element Loading	Field Stress and Body Force
Unit Weight (kN/m ³)	19
Porosity Value	0.5

Geotechnical tools, inspired by you.

Poisson's Ratio	0.4
Young's Modulus (kPa)	50000
Failure Criterion	Mohr-Coulomb
Material Type	Plastic
Tensile Strength (kPa)	10
Friction Angle (degrees)	35
Cohesion (kPa)	10
Dilation Angle (degrees)	0

Table	4.2:	Hydraulic	properties
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Туре	Data
Ks Distribution (stage 1)	Constant
Ks (m/s) (stage 1)	1e-07
K2/K1 Distribution	Constant
K2/K1	1
K1 Angle Distribution	Constant
K1 Angle	0
WC Input Type	By Water Content
WC sat Distribution	Constant
WC sat (m³/m³)	0.4
WC res Distribution	Constant
WC res (m³/m³)	0

Stage 1 and 2 share the same geometry and properties, differing only in the hydraulic permeability (Ks) input. In stage 1, a constant permeability of 1e-07 m/s is applied (see Table 4.2), while stage 2 incorporates a spatial permeability function defined with respect to x and y coordinates (see Figure 4.2).

To assign different permeability distributions by stage, use the Stage Factors tab in the Define Material Properties dialog, by following these steps.

- 1. Navigate to the Hydraulic Properties tab,
- 2. Set the Ks distribution to Coordinate and input a Ks function with the permeability vs. coordinates data. Name this function as "Function 1" to store it for later use.
- 3. Change the Ks distribution to Constant and input a Ks value of 1e-07 m/s.
- 4. Navigate to the Stage Factors tab and toggle both the Stage Hydraulic Properties and Stage Hydraulic Distributions options.

5. Select "Add Stage" and, for stage 2, select Coordinate > Function 1 from the Ks Function dropdown list.

After these steps, the Stage Factors tab should look the same as in Figure 4.3 below. This successfully stages permeability, with constant for stage 1 and a permeability vs. coordinate function for stage 2.

unction 1	Name:	Function 1		
		X 🗅 🛍	3+ = s	+
		X (m)	Y (m)	Permeability (m/s)
	1	0	0	0.0078435
	2	0.95588	0	0.0069509
	3	1.9118	0	0.0064278
	4	2.8676	0	0.0069539
	5	3.8235	0	0.011048
	6	4.7794	0	0.011196
	7	5.7353	0	0.0059944
	8	6.6912	0	0.0074207
	9	7.6471	0	0.0069411
	10	8.6029	0	0.007271
	11	9.5588	0	0.0074852

Figure 4.2: Spatial permeability function for Stage 2

Define Material Properties							? ×
Soil 1 Material 2	Soil 1						
Material 3 Material 4	Name:	Soil 1	Fill:		Mate	:h:	~
Material 5	Initial Co	nditions Stiffness Stre	ength Hydraulic Properties	Datur	n Dependency Sta	ge Factor	s
	Stage	Strength/Stiffness Prop	erties 🔽 Stage Hydraulic Pro	opertie	5		
			🗹 Stage Hydraulic Dis	stributio	ons		
	Stage	Material Behaviour	Ks Function	Ks	K2 / K1 Function	K2 / K1	K1 Angle Function
	1	Drained	Constant	1	Constant	1	Constant
	2	Drained	Coordinate - Function 1	N/A	Constant	1	Constant
	Add S	Delete Stage	Rese	et Elem	ent Stress When Ma	terial Cha	nges To This Material
₽ • 🔟 🗅 • 🍸						ОК	Cancel



4.3. Results

The seepage analysis results for stage 1 and 2 are compared. Figure 4.4 and Figure 4.5 display the permeability distribution over the geometry for both stages respectively. It can be seen that the water table (pink line in Figure 4.4 and Figure 4.5), total discharge velocity (Figure 4.6 and Figure 4.7), and pore pressure (Figure 4.8 and Figure 4.9) are all affected by the spatial distribution of permeability.



Figure 4.4: Permeability distribution for Stage 1



Figure 4.5: Permeability distribution for Stage 2



Figure 4.6: Total discharge velocity for Stage 1



Figure 4.7: Total discharge velocity for Stage 2



Figure 4.8: Pore pressure for Stage 1



