rocscience

RS3

Application of DFN for Open Pit Stability Analysis

Examples

Table of Contents

1. Application of DFN for Open Pit Stability Analysis

1.1. Problem Description

The slope stability of open pit excavations is of great importance to the safety of mining operations. In open pit mines, the primary objective is to ensure the structural integrity of the slope surface and prevent undesired structurally driven or stress induced failure. In order to design a cost-effective, yet stable open pit mine, robust understanding in lithology, rock mass properties, and structural geology is crucial.

Numerical analysis is a widely favored approach in the field of slope stability analysis. The effective utilization of numerical analysis relies upon the comprehensive geological information gathered. This analysis technique allows engineers to assess the potential failure mechanisms and critical stability factors of the pit walls, enabling the optimization of slope angles while ensuring safety and minimizing excavation costs. Additionally, numerical analysis is a useful tool to simulate complex interactions between rock structures, discontinuities, and excavation processes, facilitating the precise prediction of ground behavior. The consideration of joints is imperative in geomechanical modeling process to gain accurate prediction of rock mass behaviour. Joints, as natural fractures or weaknesses within rock masses, play a pivotal role in controlling the driving failure mechanism to slope instability and hence impacting critical stability factors.

This example demonstrates the numerical experiments of explicit modeling of joint sets using Discrete Fracture Network (DFN) in sloped surface using 3D Finite Element Model (FEM) to investigate their impact on mechanical behaviour of rock mass. The objective is to both capture the control failure mechanism of the slope with different joint configurations and evaluate validity of different modeling techniques to represent joint sets. The investigation involves conducting a series of Shear Strength Reduction (SSR) analysis of a sector of an open pit mine with varying structural conditions. Furthermore, comparison studies are performed with simulated cases of no joint (base), single joint set, and double joint set.

1.2. Model Setup

Characteristics of jointed rock mass behaviour can be introduced in numerical analysis in two different forms, such as adding DFN or adopting anisotropic material model. DFN approach for modeling fractured rock masses refers to explicit representation of fractures forming a network. In RS3, this feature stochastically generates network of joint boundaries based on user-defined spacing, orientation, joint length etc. Jointed rock mass behaviour can also be simulated using anisotropic material properties, which captures the directional dependence of material properties due to the presence of the joint network. For this example, anisotropic plastic properties are assigned using one of RS3's inherent material strength formulations, Generalized Anisotropic failure criterion. This failure criterion allows defining anisotropic strength properties for a material using any combination of failure criteria applied over user defined orientations. For more information on Generalized Anisotropic failure criterion, see [Generalized Anisotropic] section in RS3 manual.

This example constitutes several FE models that share the same geometry. A sector of an open pit is used as the main external geometry, which has an Overall Slope Angle (OSA) of approximately 22 degrees towards East and consists of four different rock types (Figure 1-1). This exercise focuses on the deformation of Shale unit and hence jointed material model is applied to this unit only.

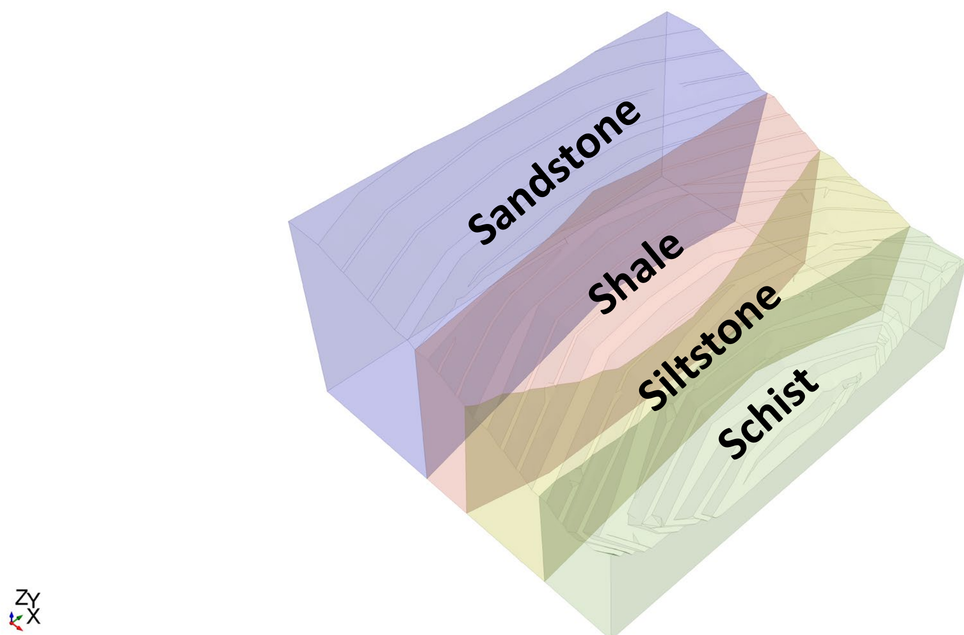


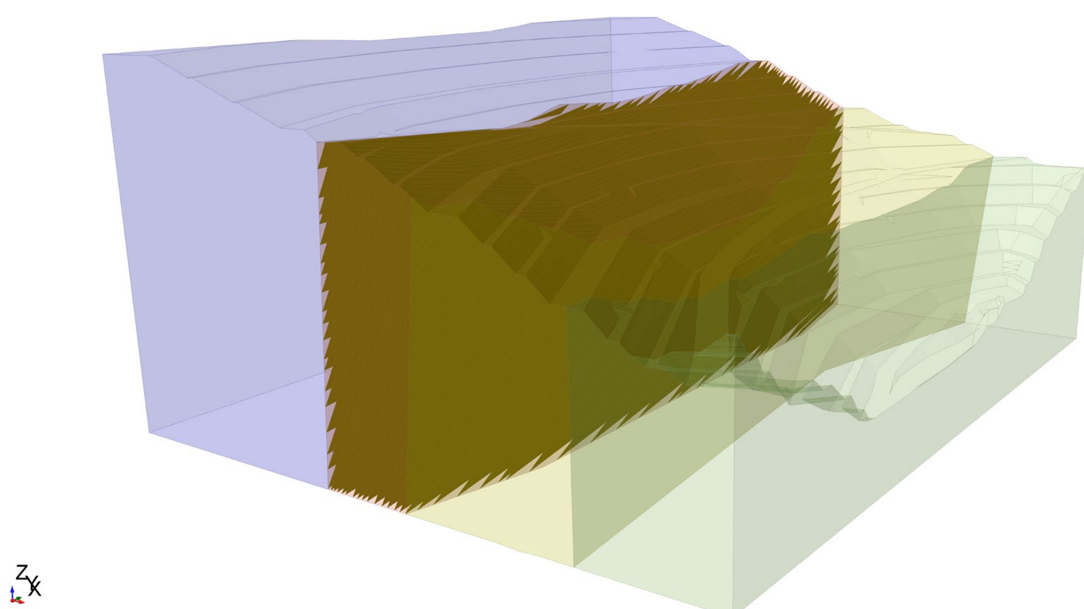
Figure 1-1. Model geometry

Modeling cases are described in **Error! Reference source not found.**. Base case has the simplest model, where anisotropic material behaviour is not included in any form. The rest of the cases have DFN or anisotropic material properties applied to Shale unit to simulate jointed rock mass behaviour.

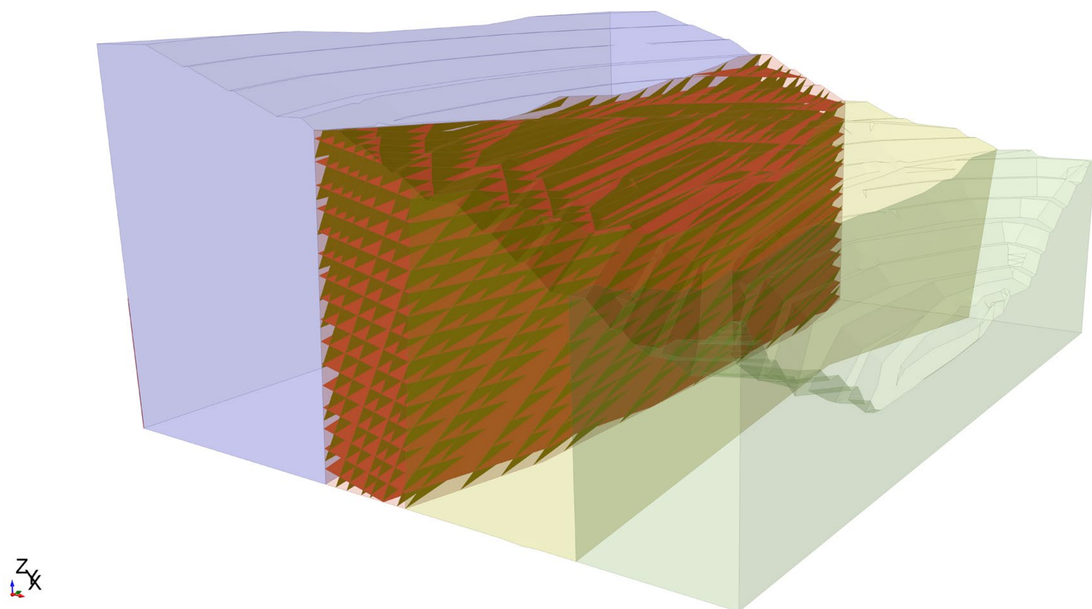
Table 1-1 Modeling Case Descriptions

Case	Anisotropic Material	DFN	Joint Set 1 Orientation		Joint Set 2 Orientation	
			Dip (°)	Dip Direction (°)	Dip (°)	Dip Direction (°)
Base	No	No	63	259	12	100
Single Joint Set- DFN	No	Joint Set 1				
Single Joint Set- Anisotropic	Joint Set 1	No				
Double Joint Set- DFN	No	Joint Set 1 & Joint Set 2				
Double Joint Set- Anisotropic	Joint Set 1 & Joint Set 2	No				

The modeling geometry for Single Joint Set-DFN case and Double Joint Set-DFN case are presented in Figure 1-2. As DFN is not included in Base case, Single Joint Set-Anisotropic case, and Double Joint Set-Anisotropic case, their modeling geometries are as shown in Figure 1-1.



Single Joint Set DFN



Double Joint Set DFN

Figure 1-2 Model Geometry with DFN included in Shale Unit

1.3. Material Properties

Material properties for all rock types used for the models are presented in Table 1-2. A widely-used empirical failure criterion, Generalized Hoek-Brown parameters were used to define the strength of rock mass. Also, to enforce an elastic-perfectly plastic material behaviour, the peak strength properties are equal to the residual properties. However, this is not the case for joints. The residual strength of joints is assigned with lower value than of peak to ensue strain softening material behaviour from constituent joint sets (Table 1-3).

Table 1-2. Rock Mass Properties

Rock Mass		Sandstone	Shale	Siltstone	Schist
Unit Weight (MN/m^3)		0.028	0.026	0.02	0.027
Stiffness	Poisson's ratio	0.19	0.25	0.3	0.3
	Young's modulus (Erm) (MPa)	9000	6500	7000	12000
Strength	Intact UCS (MPa)	46	22	25	29
	GSI	41.3	29.6	33.5	41.3
	mi	6.2	6.1	5.2	5.5
	d	0	0	0	0

Table 1-3. Joint Properties

		Joint Set 1	Joint Set 2
Stiffness	**Normal Stiffness (MPa/m)**	65000	65000
	Shear Stiffness (MPa/m)	6500	6500
Strength	**Tensile Strength (MPa)**	0.001	0.001
	Peak Cohesion (MPa)	0.025	0.01
	Peak Friction Angle (°)	20	22
	Dilation Angle (°)	0	0
	Residual Tensile Strength (MPa)	0	0
	Residual Cohesion (MPa)	0	0
	Residual Friction Angle (°)	10	12

1.4. Modeling Results

Conducting SSR analysis iteratively computes stress analysis with updated strength properties to determine at which Strength Reduction Factor (SRF) the slope becomes unstable, which is referred as Critical SRF. Numerically, this is equivalent to the state of which energy balance in the system fails to reach equilibrium or convergence failure. SSR analysis is computed for all cases to find out the overall stability of the modeled sector, the critical region of failure, and to compare between cases quantitatively. Moreover, the rock mass deformation and failure mechanisms are investigated.

1.4.1. Base Case

Base case model does not take into account any anisotropic rock mass behaviour. The sliding surface is primarily formed by the development of shear failure of rock mass. In this case, the critical SRF is determined to be 2.04 with the deformation concentrated at Southern region in Shale unit (Figure 1-3). Displacement contour is plotted on a cutting plane trending parallel to the orientation of which major deformation occurs on Figure 1-4. This plot better shows the deformation trend with depth and demonstrates that it is primarily controlled by Shale unit. Moreover, with the aid of isosurface interpolating the critical value of maximum shear strain of 0.002, the overall volume the sliding material can be predicted as shown in the figure.

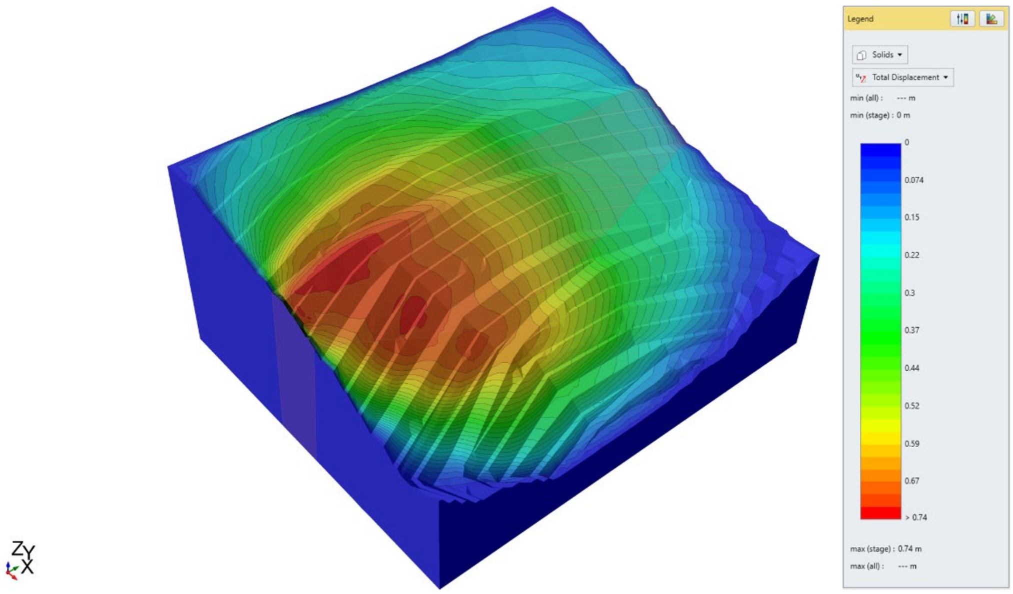


Figure 1-3 Displacement Contour Plot of Total Displacement of the Exterior

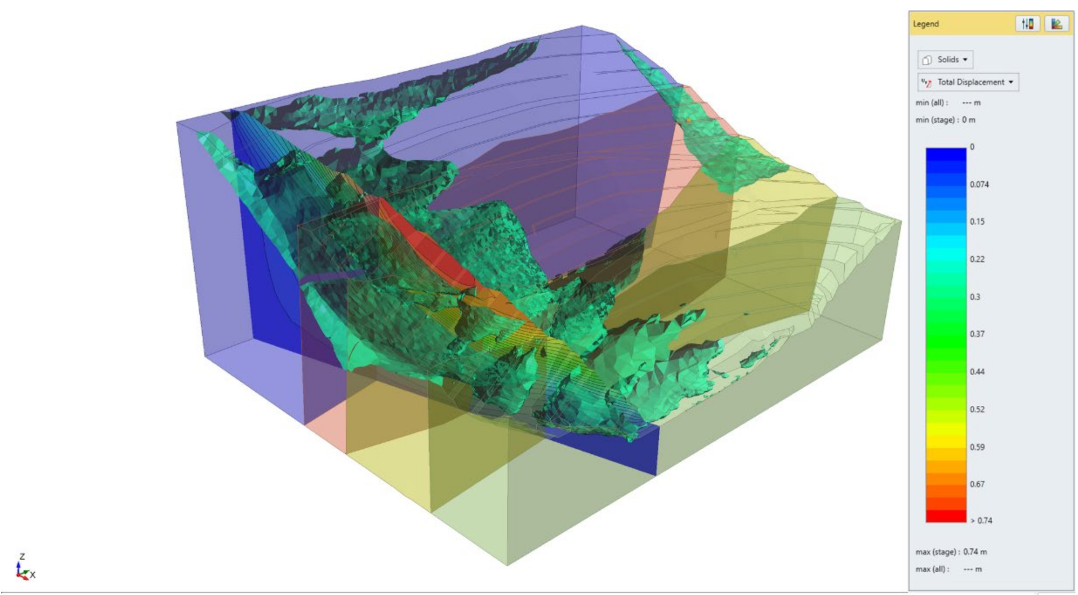


Figure 1-4 Displacement Contour Plot on Sampled Plane Intersecting High Deformation Region and Isosurface of Maximum Shear Strain of 0.002

1.4.2. Single Joint Set

The analyzed case comprises a sloped surface bearing a single joint set trending in the opposite direction to the slope. Two modeling methodologies were applied to capture the unique characteristics of the jointed rock mass. The first model employed a Discrete Fracture Network (DFN) approach, providing a detailed representation of the joint network's geometry and connectivity. In contrast, the second model incorporated anisotropic material properties to simulate the directional dependence of material properties due to the presence of the joint network. For the context of this article, this model is referred to as anisotropic material model.

Of particular interest is the correct capture of mechanical behavior for anisotropic material with respect to the applied material anisotropy parallel to Joint Set 1 (Dip/Dip Direction of 63/259) within the model. A shear strain contour diagram plotted on planes trending parallel to the orientation of major deformation are shown in Figure 1-5. This diagram shows a shear strain anomaly parallel to the orientation of Joint Set 1, demonstrating the preferential shearing behaviour representing the slipping of joints.

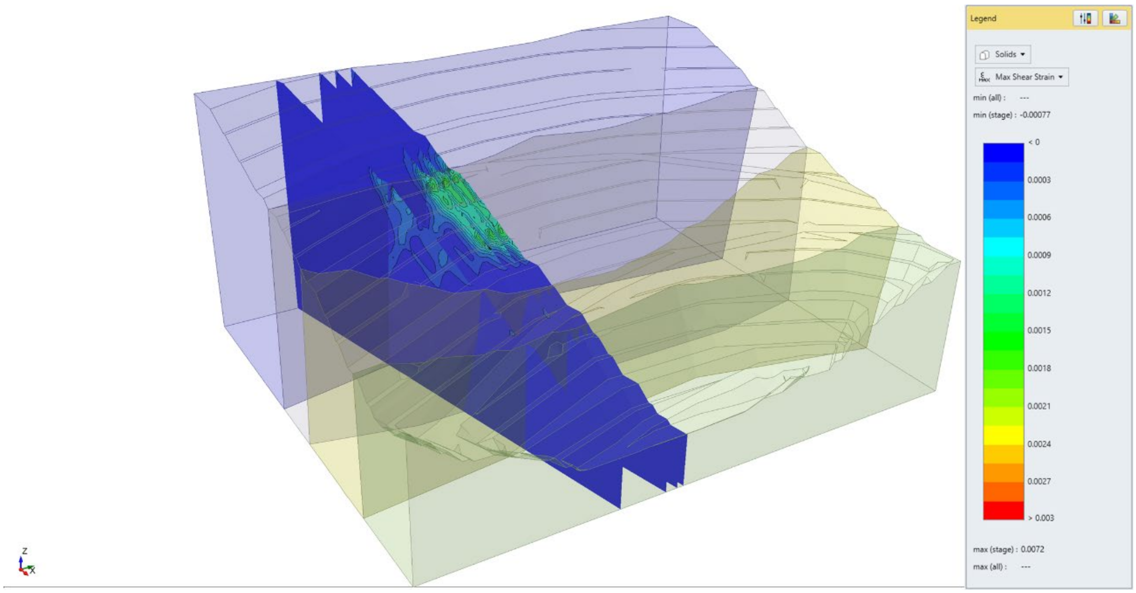
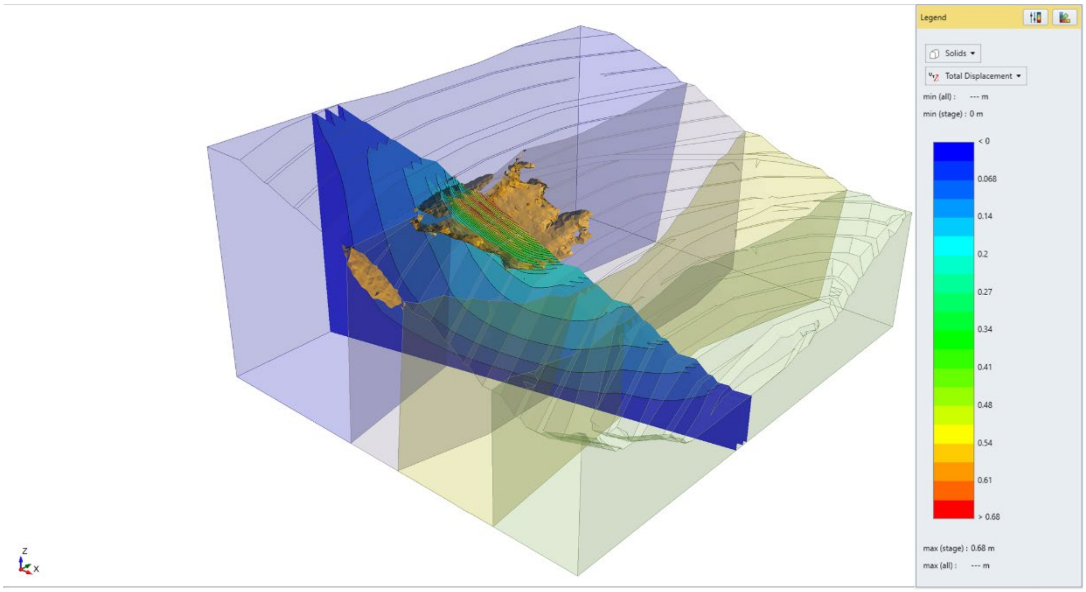
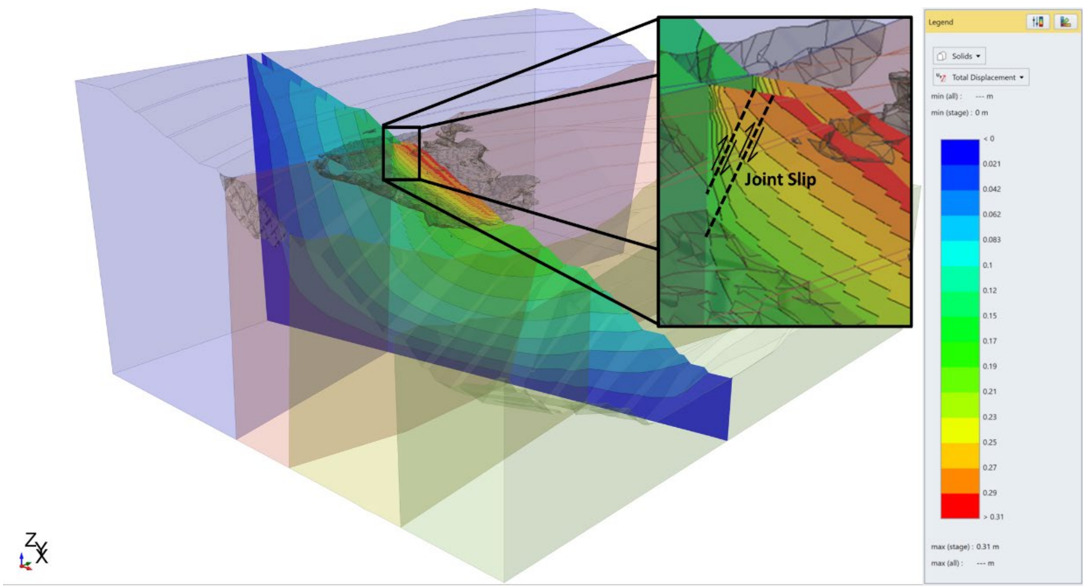


Figure 1-5 Shear Strain Contour Diagram of Anisotropic Material Model at SRF = 1.24

Between the two models, the critical Strength Reduction Factor (SRF) values for the anisotropic material and DFN models were notably similar, measuring 1.31 and 1.30, respectively. Furthermore, obtaining matching failure mechanism is crucial to affirm the alignment between the two modeling approaches. The displacement contour plots of the two models in Figure 1-6 show a typical late stage large-scale (flexural) toppling failure, where the sliding surface is developed propagated by tensile bending failure at base. The sliding surface, represented by the isosurface generated by interpolating the critical shear strain value of 0.0035, is obtained from the anisotropic material model (Figure 1-6 a). This surface is laid on the DFN model, which shows a close compliance with its potential failure surface (Figure 1-6 b).



(a)



(b)

Figure 1-6 Displacement Contour Plot on Sampled Planes Crossing High Deformation Region with Projected Sliding Plane for (a) Anisotropic Material Model and (b) DFN Model

1.4.3. Double Joint Set

The investigation was extended to encompass a comparative study involving double joint set models, each represented using anisotropic material properties and the Discrete Fracture Network (DFN) methodology. As observed in the previous single joint set analysis, this study sought to evaluate the behavior of the rock mass under the influence of the existing joint, Joint Set 1 with the addition of joint set dipping at 12 ° towards 100° each trending in near opposing directions.

The shear strain diagram from material anisotropic material model reveals the deformation patterns influenced by both joint sets represented by material anisotropy (Figure 1-7). The diagram shows a near vertical shear strain concentration at the boundary between Sandstone and Shale units and sporadic anomaly trending near-opposite direction to the slope incurred by the representation of Joint Set 1. At the same time, the diagram shows the shearing at shallow angle due to the representation of Joint Set 2, which is also manifest in displacement plot (Figure 1-8 a). This is of great importance to capture when incorporating the anisotropic nature to the material properties implicitly, to make sure the directional dependencies of mechanical properties is appropriately taken into account.

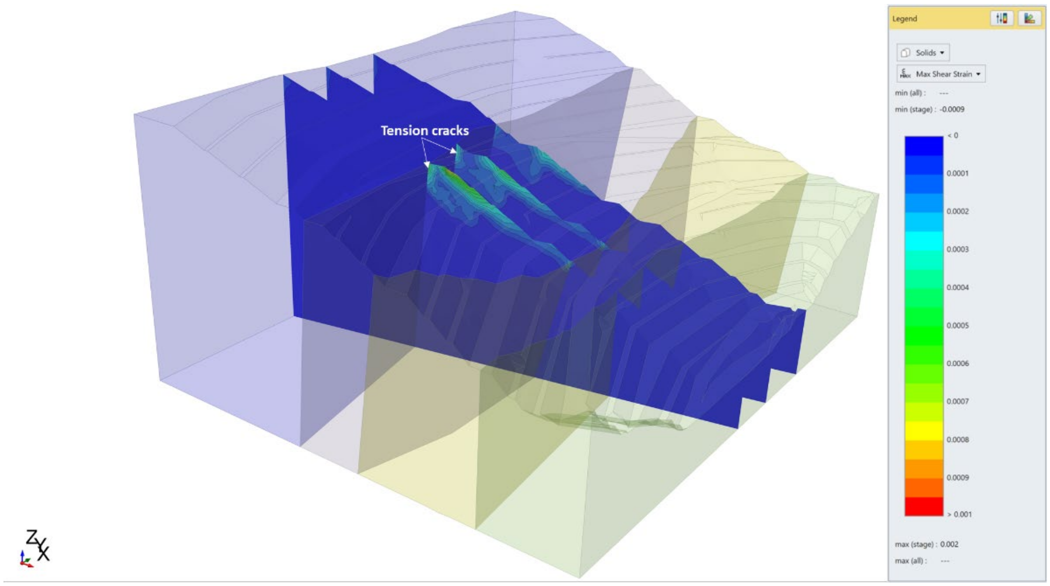
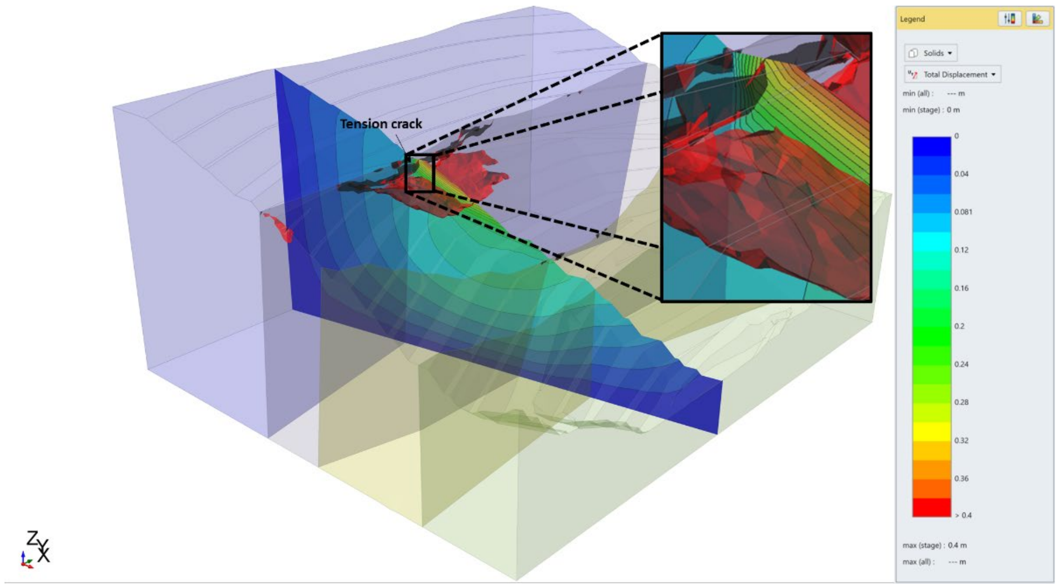
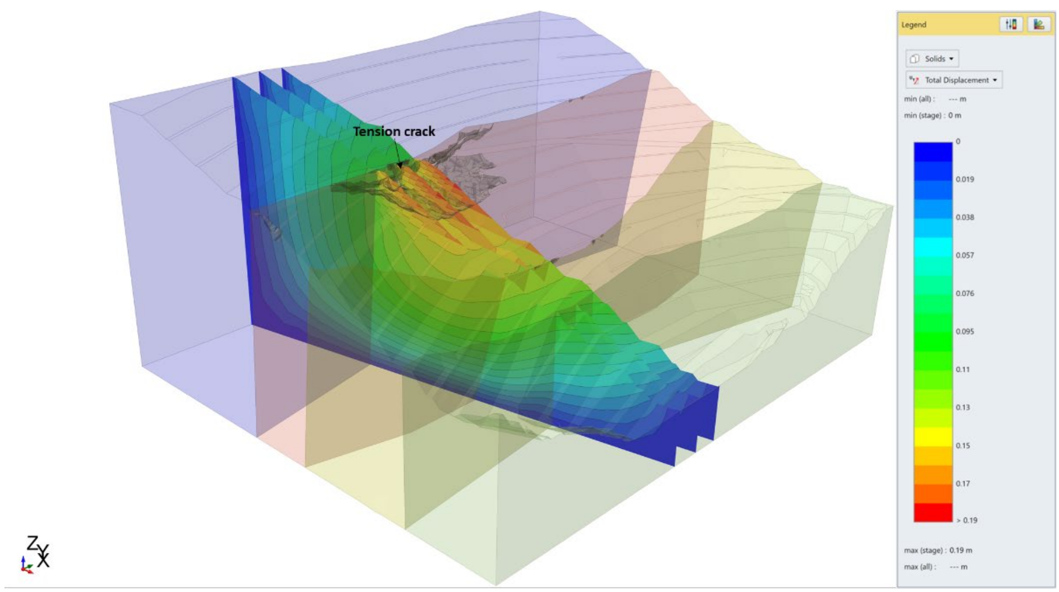


Figure 1-7 Shear Strain Contour Diagram of Anisotropic Material Model at SRF = 0.45

Critical SRF values computed from the anisotropic material- and DFN models are in close agreement with 0.62 and 0.63, respectively. The slope failure surface for the anisotropic material model is projected with isosurface interpolating critical shear strain value of 0.0035 (Figure 1-8 a). This surface is imported into the DFN model, which shows a close projection of potential failure surface of DFN model as well (Figure 1-8 b). The isosurface representing tension crack and sliding plane are near-parallel to Joint Set 1 and Joint Set 2, respectively. Due to the combination of two joint sets, the failure occurs at shallow depth near the surface level. The alignments in various aspects, including stability, failure location and failure mechanism provide that the two models created with different modeling techniques are in overall agreement.



(a)



(b)

Figure 1-8 Displacement Contour Plot on Sampled Planes Crossing High Deformation Region with Projected Sliding Plane for (a) Anisotropic Material Model and (b) DFN Model

1.5. Discussion

In the course of this study, both single joint set and double joint set configurations are considered, and the presence of joints was addressed through two distinct approaches. Joints are explicitly represented using the Discrete Fracture Network (DFN) method or generalized anisotropic material property was employed to account for the joint presence. The comparison of results for both cases result in a concordance in the outcomes between the two modeling approaches (Table 1-4).

The congruence in both the slope stability, represented by critical SRF, and the failure mechanism provides compelling evidence supporting the consistency and accuracy of the used modeling techniques. Moreover, the results underscore the effectiveness of both approaches in simulating the jointed rock mass behaviour under surface excavation.

Table 1-4 Critical SRF Determined for Single and Double Joint Set Cases

Case	Critical SRF	
	DFN	Anisotropic Material
Single Joint Set	1.30	1.31
Double Joint Set	0.62	0.63

For the purpose of this study, there are no alterations made to the base material properties of Shale other than introduction of different number of joint sets across the three modeling scenarios: the base case, single joint set case, and double joint set case. Joints act as geological structure of weak planes that allow slipping/opening along the surface, providing rock mass a preferential plane of deformation. Their presence attributes to a substantial impact on the mechanical behaviour of rock mass. As a result, the modeling results show different control failure mechanism for each case, manifesting sliding failure, flexural toppling failure, and block sliding failure for Base, Single joint, and Double joint set cases, respectively. Moreover, the modeling outcomes indicate a shallower depth of failure and a reduction in safety factor as the number of joint sets increases.

A fundamental expectation with representation of jointed rock mass behavior in FEM through the incorporation of anisotropic material properties within a continuous medium (instead of explicitly modeling the joints), is that it accounts for anisotropic behavior at the mesh scale. Moreover, the utilization of a fine mesh to enhance modeling accuracy renders modeling joints using DFN with an equivalent density unfeasible. Thus, in sole purpose of accurate reproduction of joint distribution, particularly when considering the scale of an open pit relative to the joint spacing, employing anisotropic material properties may sought to be the more pragmatic choice in comparison to modeling DFNs. However, it is vital to acknowledge that, as borne out by the modeling results, use of DFN offers a more distinct interaction between rock and joints and, most significantly, an explicit simulation of failure mechanism. Nonetheless, the calibration process substantiated that, with the concurrent increase in both mesh and joint density, a closer agreement could be reached in result between anisotropic material models and DFN models. At a certain spacing, this convergence effectively reduced the difference in critical Strength Reduction Factors (SRF) to less than 2 percent, underscoring the value of incorporating DFN for gaining detailed insights into the precise failure mechanisms within the rock mass. Moreover, considering that the DFN model, in effect, simulates the same case with wider joint spacing, renders a lower critical SRF than anisotropic material model indicating that it does not necessarily result in a less conservative design.