RS2

2D finite element program for stress analysis and support design around excavations in soil and rock

XFEM Verification Manual

Table of Contents

1 JOINT NETWORK 1

1.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example is compared with the forward toppling example given in:

Lorig, L., & Varona, P. (2004). Toppling Failure - Block and Flexural. In D. C. Wyllie, & C. W. Mah, Rock Slope Engineering Civil and Mining 4th Edition (pp. 234-238). New York: Spon Press Taylor & Francis Group.

1.2 PROBLEM DESCRIPTION

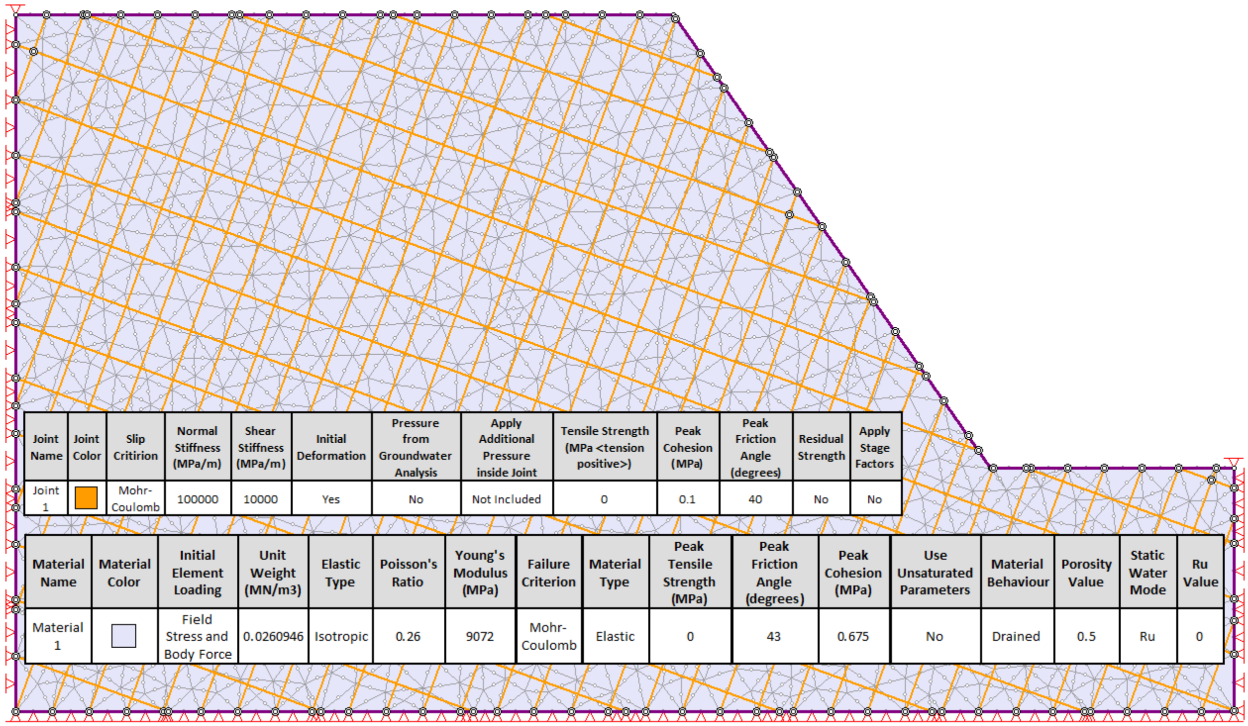
This model is from verification problem #3 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model is analyzed for forward block toppling.

The model has a slope height of 260 m, slope angle of 55 degrees, and joint angles of 70 & 160 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

1.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
43	9,072	26.0946	0.26	0.675	0	Mohr Coulomb Elastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0.1	40	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.0260946	Isotropic	0.26	9072	Mohr-Coulomb	Elastic	0	43	0.675	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

1.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 1.14, lower than the common critical SRF of 1.16. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

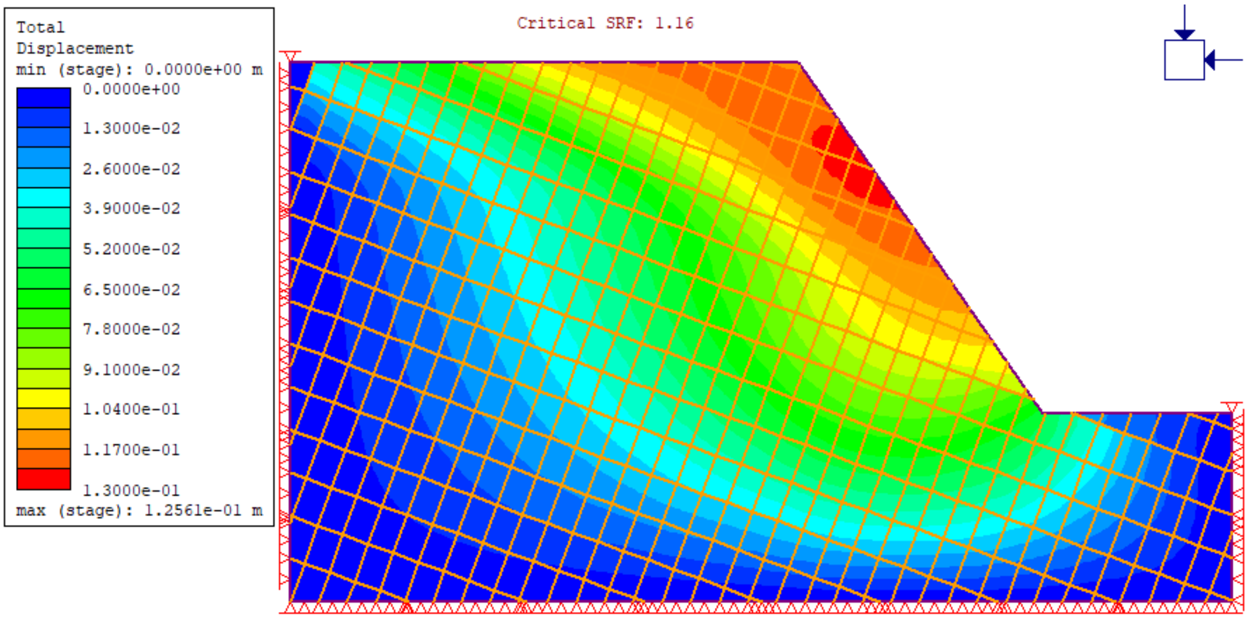


Figure 2: Solid Displacement at Initial Stage: FEM Joints

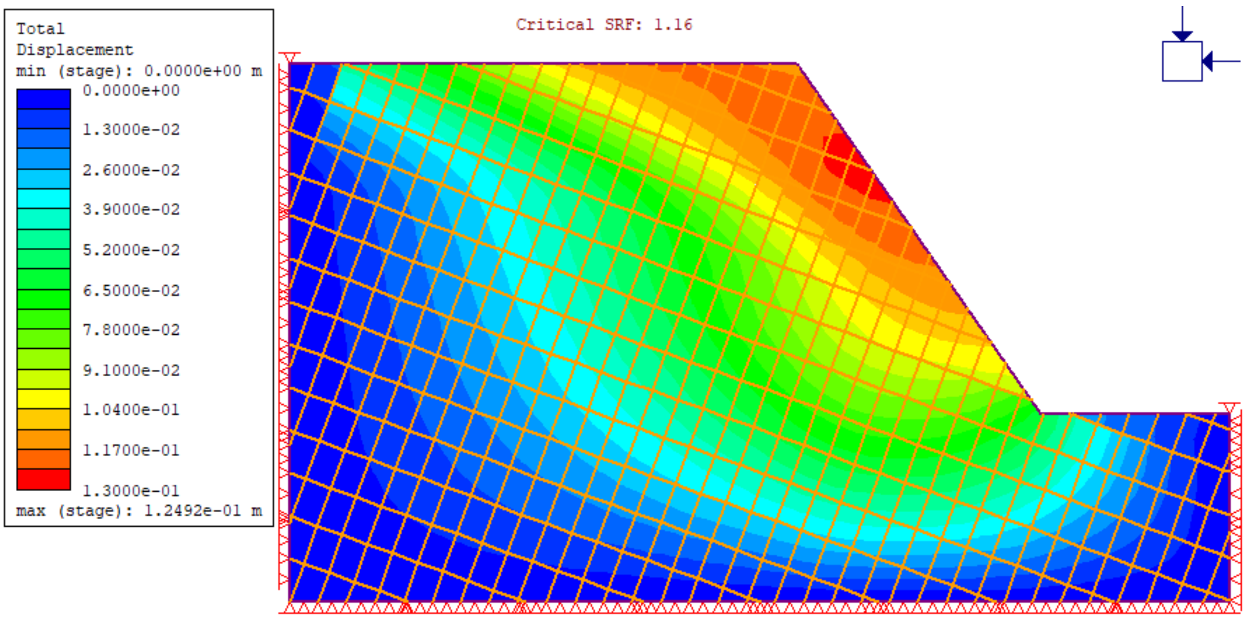


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

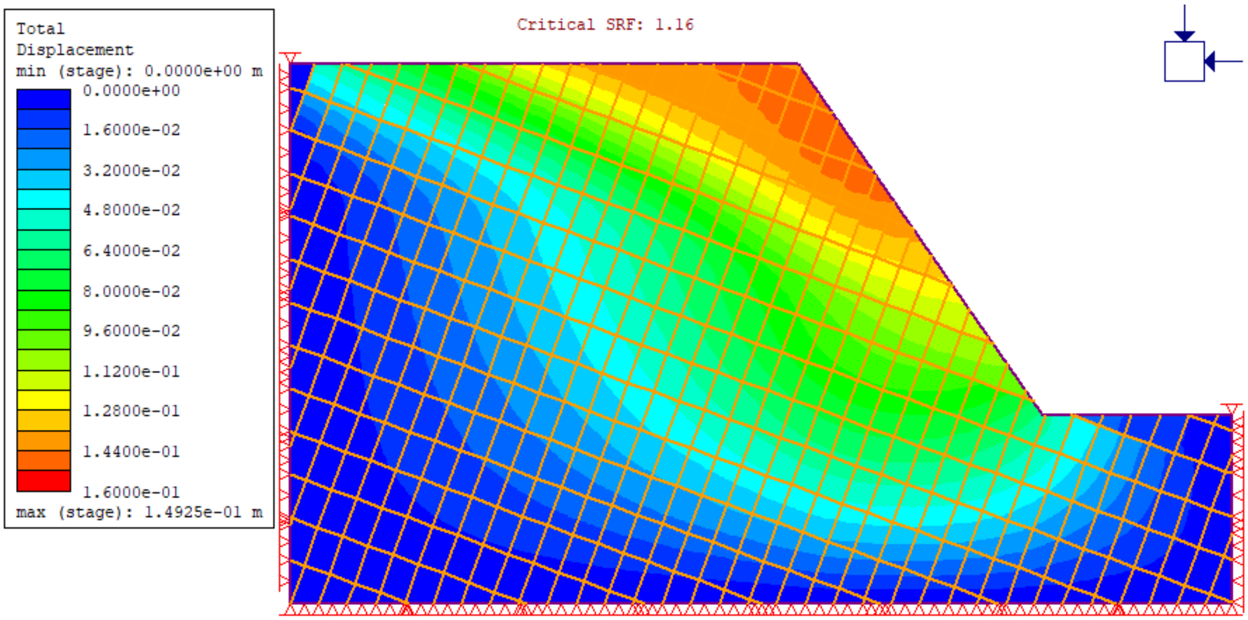


Figure 4: Solid Displacement at SRF of 1.14: FEM Joints

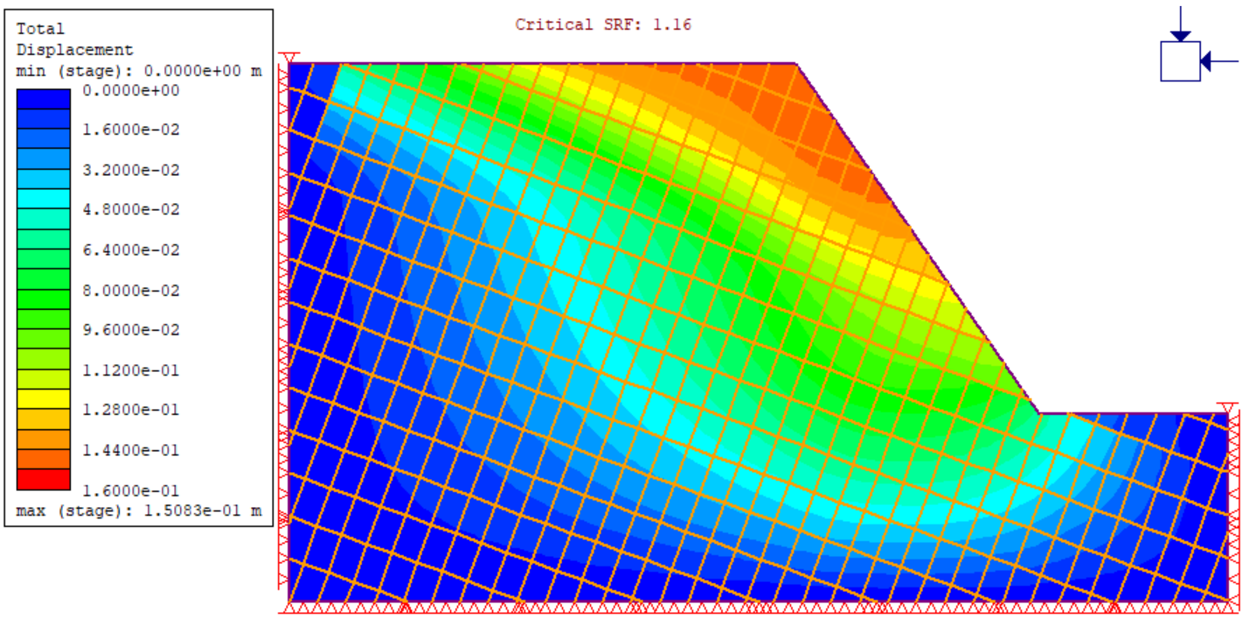


Figure 5: Solid Displacement at SRF of 1.14: XFEM Joints

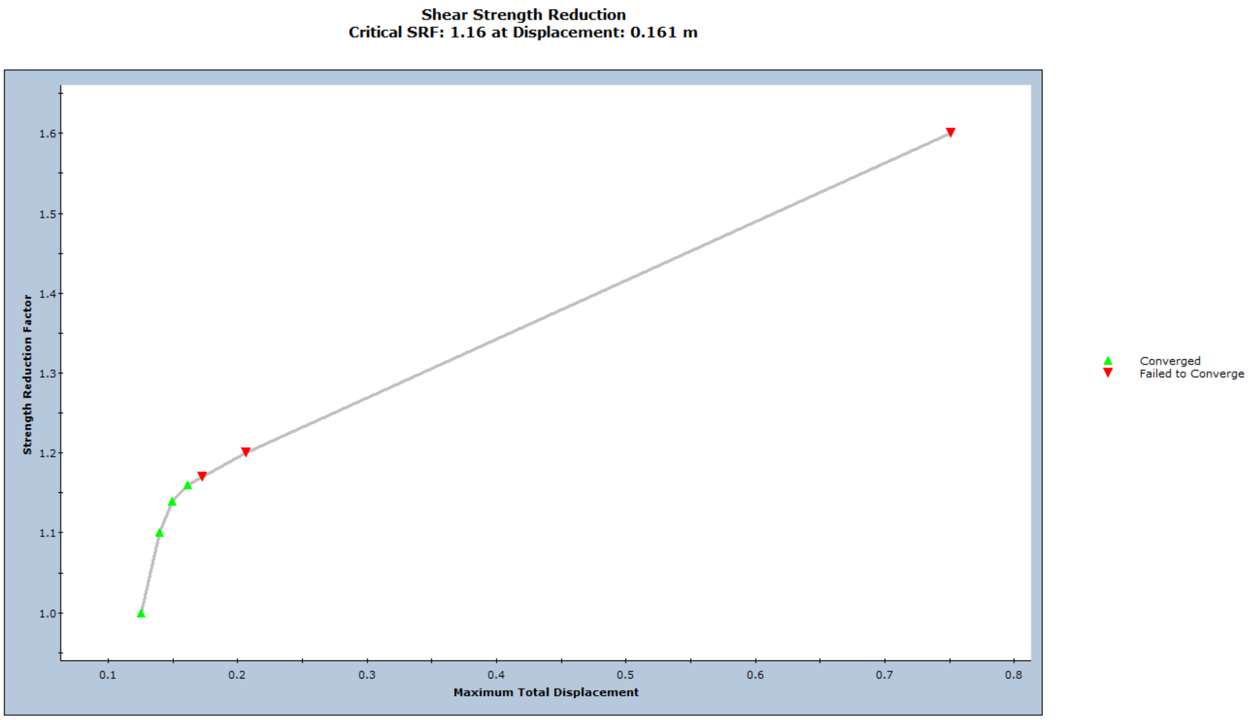


Figure 6: Shear Strength Reduction Plot: FEM Joints

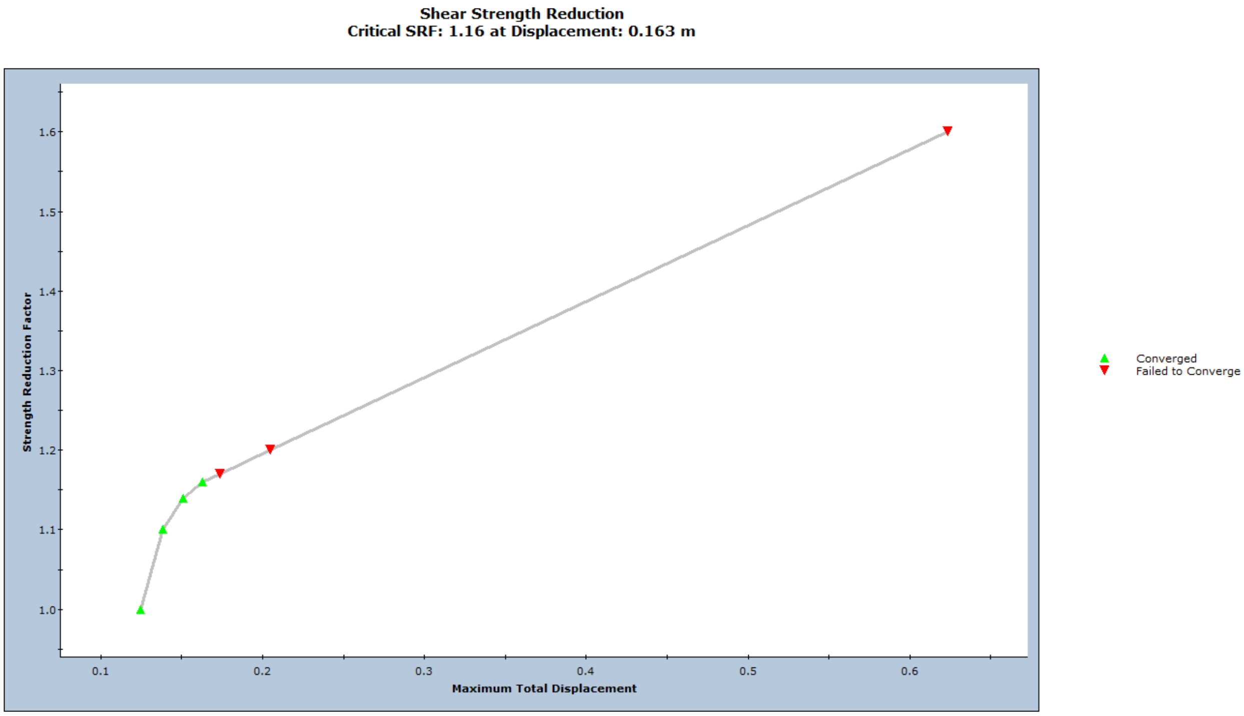


Figure 7: Shear Strength Reduction Plot: XFEM Joints

2 Joint Network 2

2.1 Introduction

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example is verified with the backward block toppling example given in:

Lorig, L., & Varona, P. (2004). Toppling Failure - Block and Flexural. In D. C. Wyllie, & C. W. Mah, Rock Slope Engineering Civil and Mining 4th Edition (pp. 234-238). New York: Spon Press Taylor & Francis Group.

2.2 Problem Description

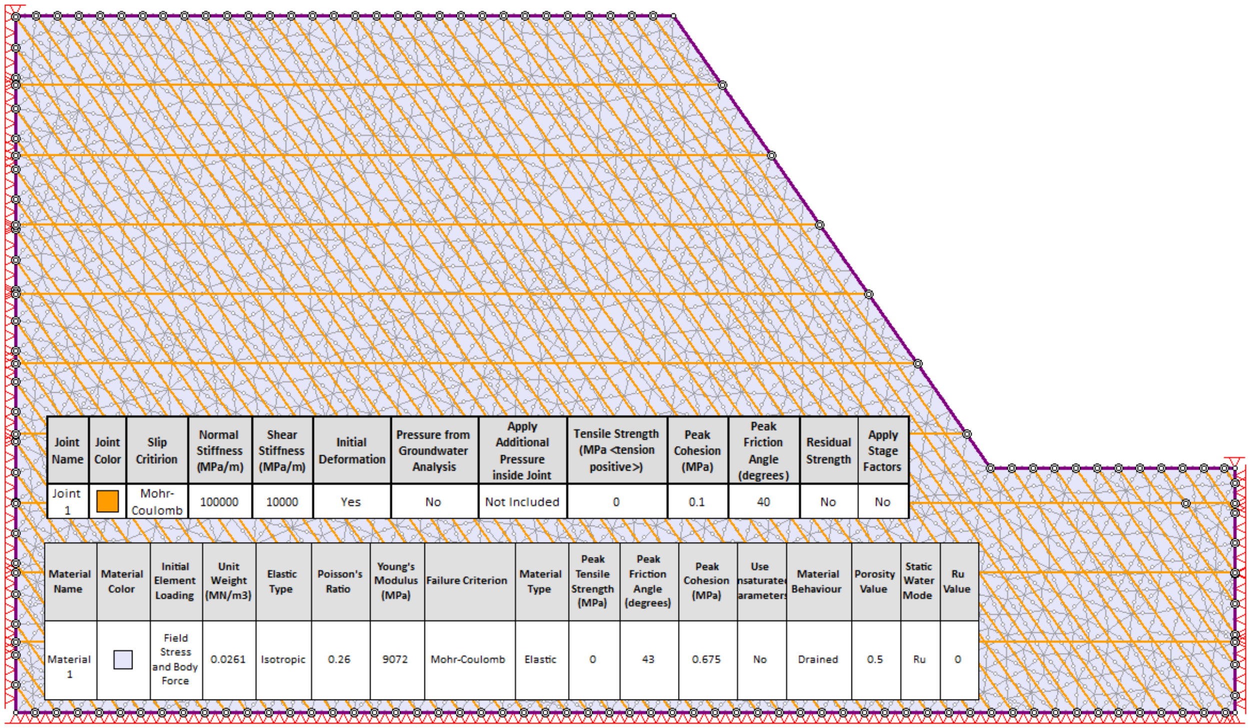
This model is from verification problem #5 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model is analyzed for backward block toppling.

The model has a slope height of 260 m, slope angle of 55 degrees, and joint angles of 55 & 0 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

2.3 Geometry and Properties

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
43	9,072	26.1	0.26	0.675	0	Mohr Coulomb Elastic



Joint Name	Joint Color	Slip Citirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0.1	40	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Use nsaturated arameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.0261	Isotropic	0.26	9072	Mohr-Coulomb	Elastic	0	43	0.675	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

2.4 RESULTS

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 1.7, lower than the critical SRF both models. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

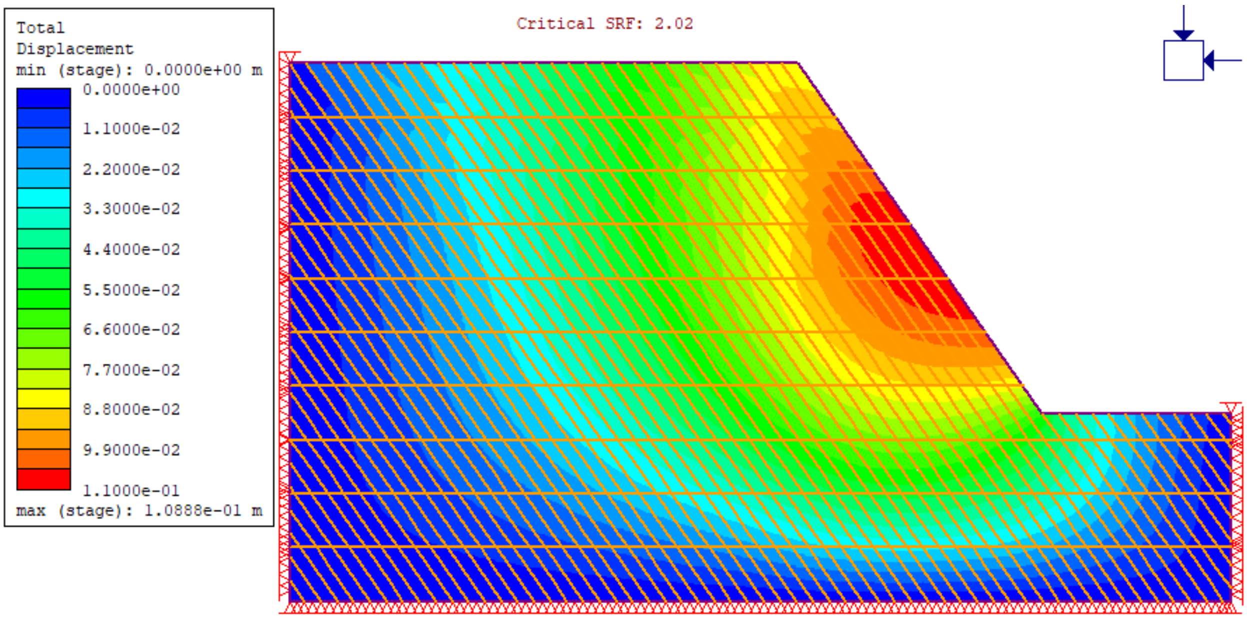


Figure 2: Solid Displacement at Initial Stage: FEM Joints

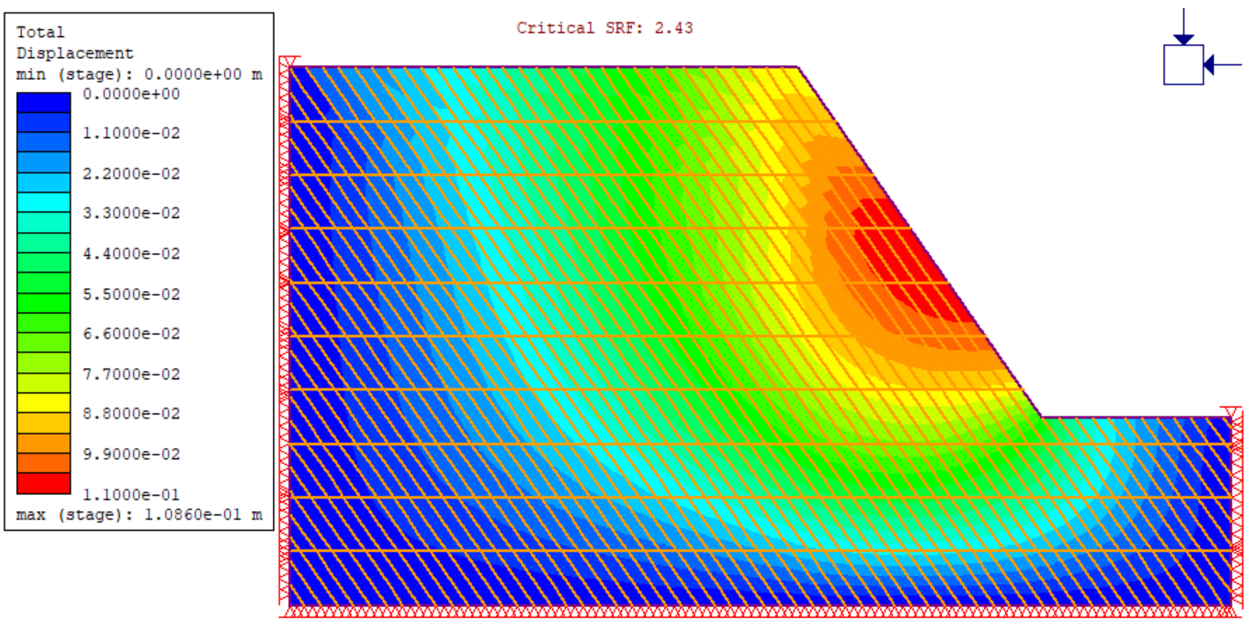


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

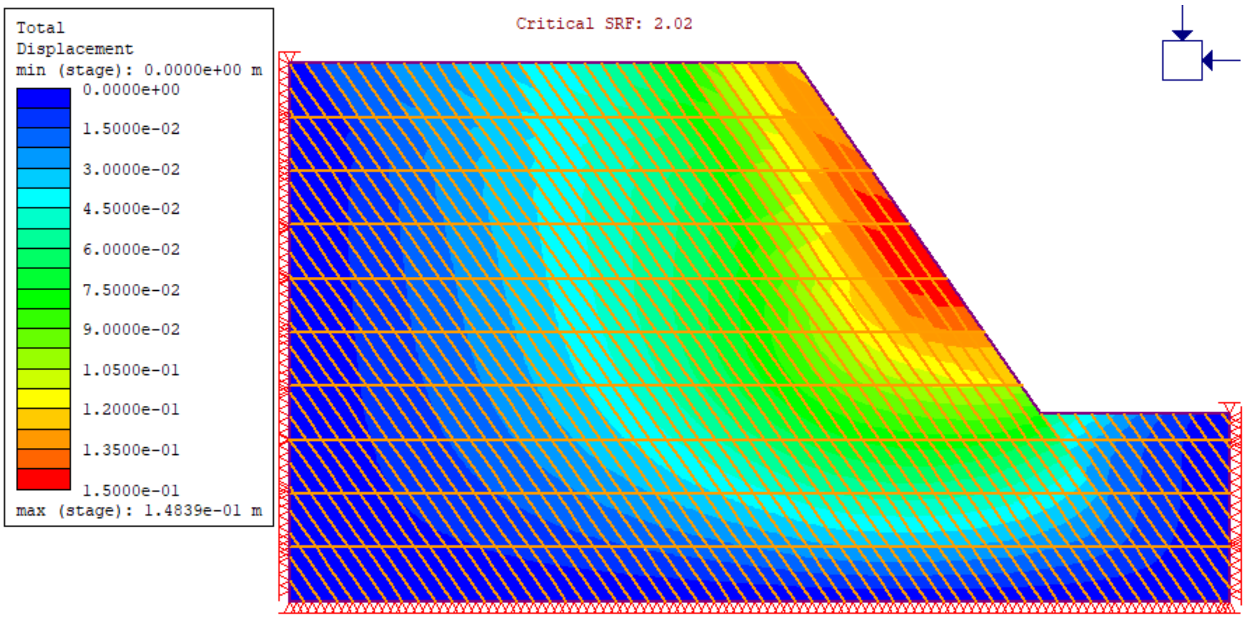


Figure 4: Solid Displacement at SRF of 1.7: FEM Joints

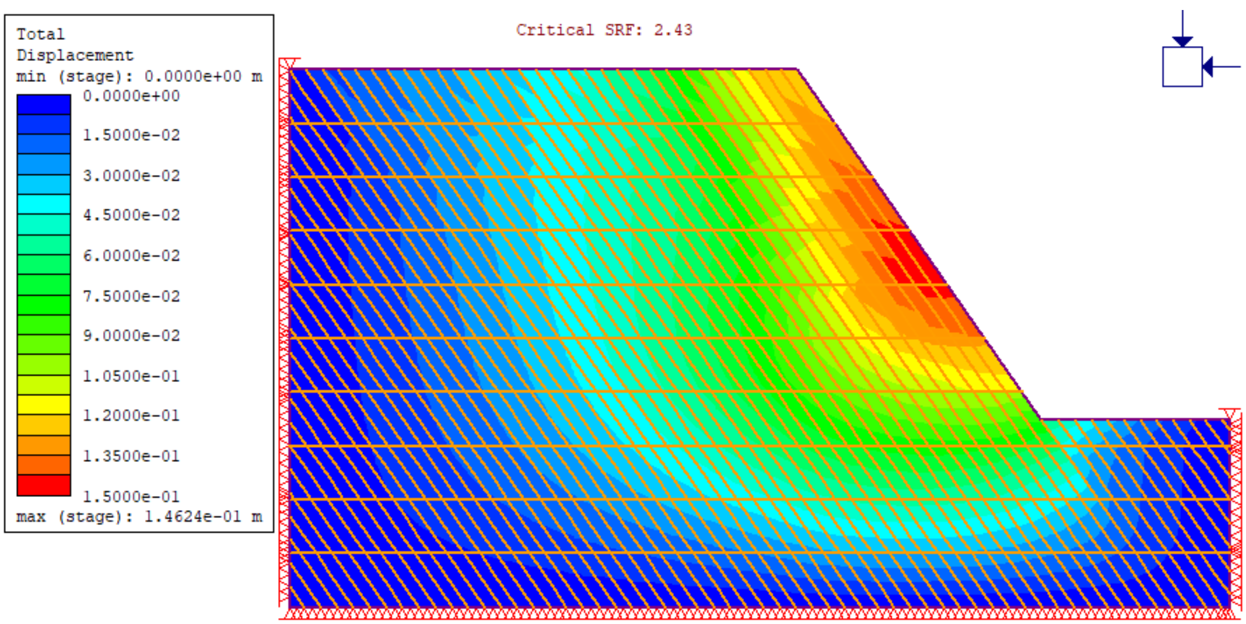


Figure 5: Solid Displacement at SRF of 1.7: XFEM Joints

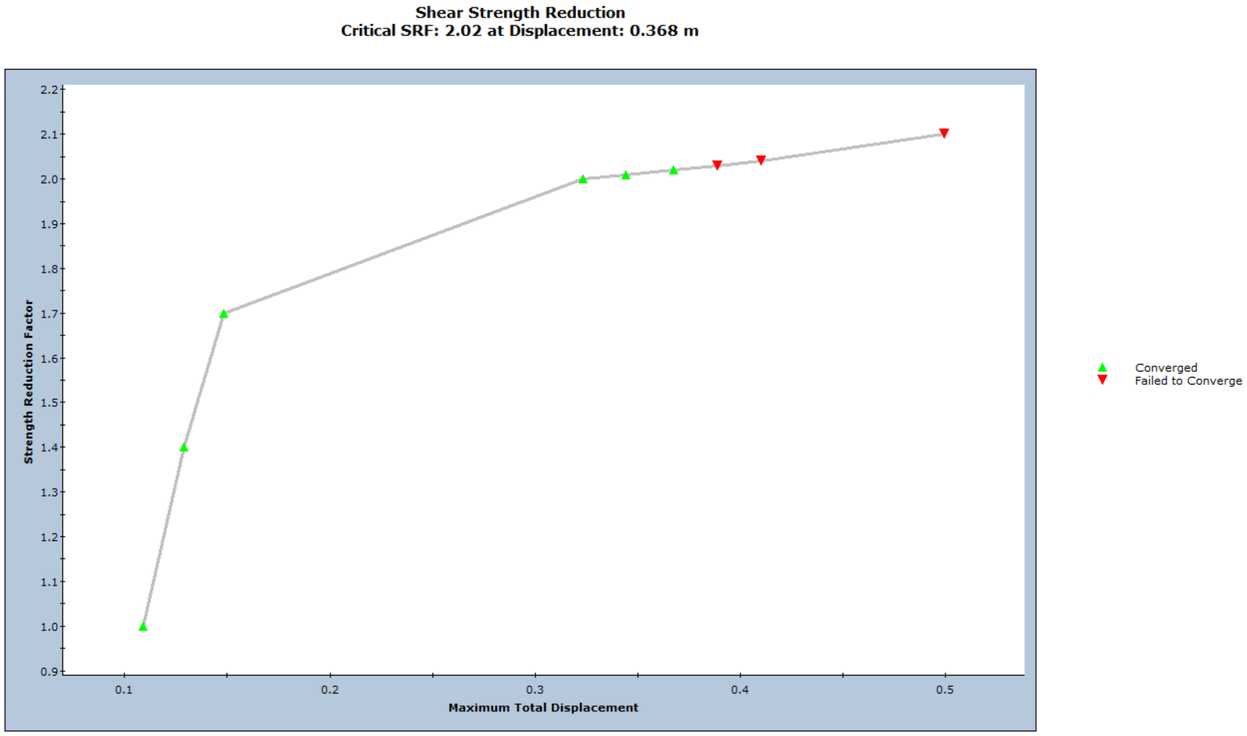


Figure 6: Shear Strength Reduction Plot: FEM Joints

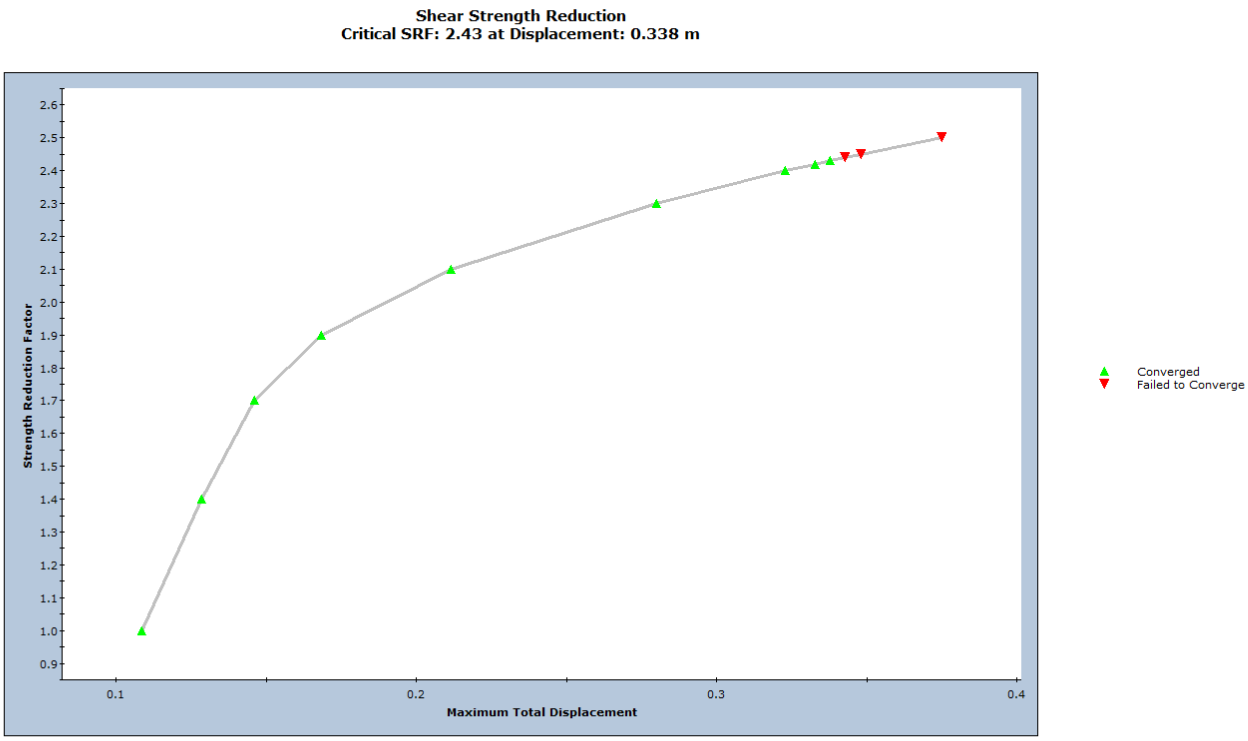


Figure 7: Shear Strength Reduction Plot: XFEM Joints

3 JOINT NETWORK 3

3.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example is verified with the plane failure example given in:

Lorig, L., & Varona, P. (2004). Plane Failure - Daylighting and Non-Daylighting. In D. C. Wyllie, & C. W. Mah, Rock Slope Engineering Civil and Mining 4th Edition (pp. 233-235). New York: Spon Press Taylor & Francis Group

3.2 PROBLEM DESCRIPTION

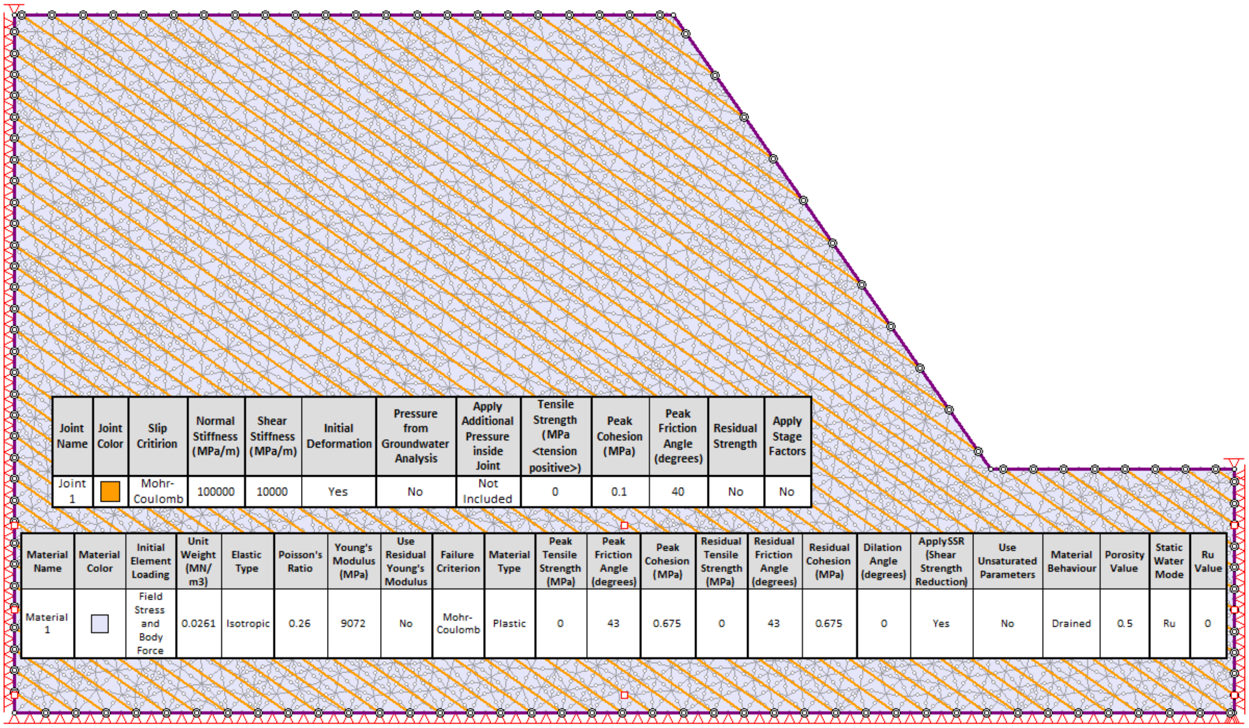
This model is from verification problem #6 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model is analyzed for plane failure.

The model has a slope height of 260 m, slope angle of 55 degrees, and joint angle of 35 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

3.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
43	9,072	26.1	0.26	0.675	0	Mohr Coulomb Plastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0.1	40	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	Apply SSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.0261	Isotropic	0.26	9072	No	Mohr-Coulomb	Plastic	0	43	0.675	0	43	0.675	0	Yes	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

3.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at the common critical SRF of 1.3. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

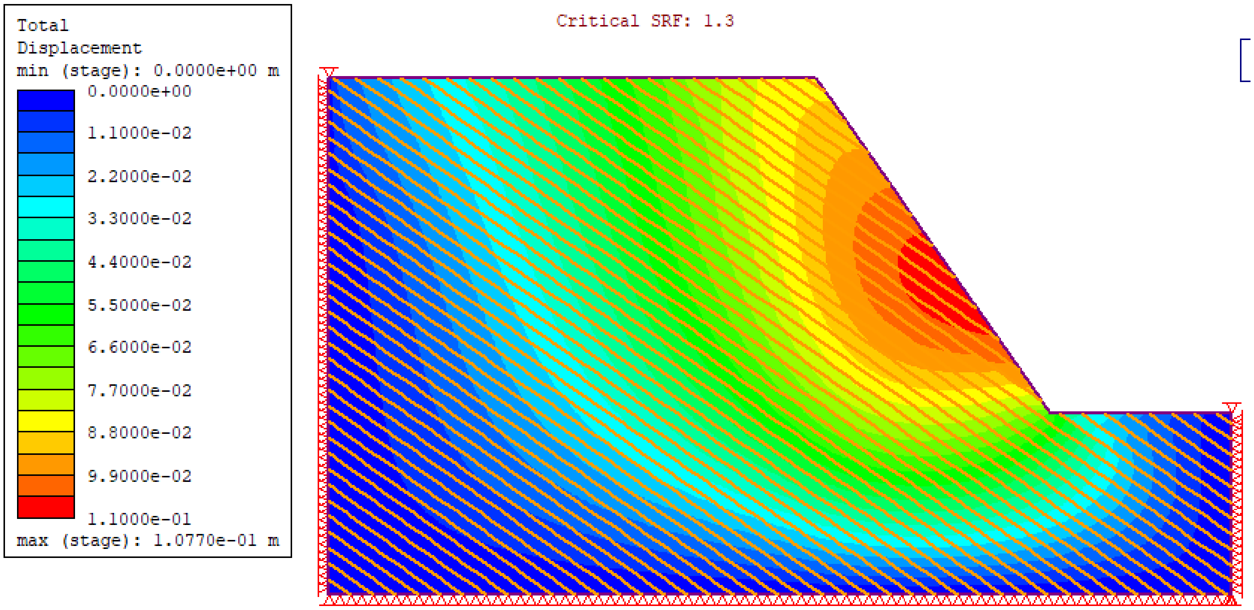


Figure 2: Solid Displacement at Initial Stage: FEM Joints

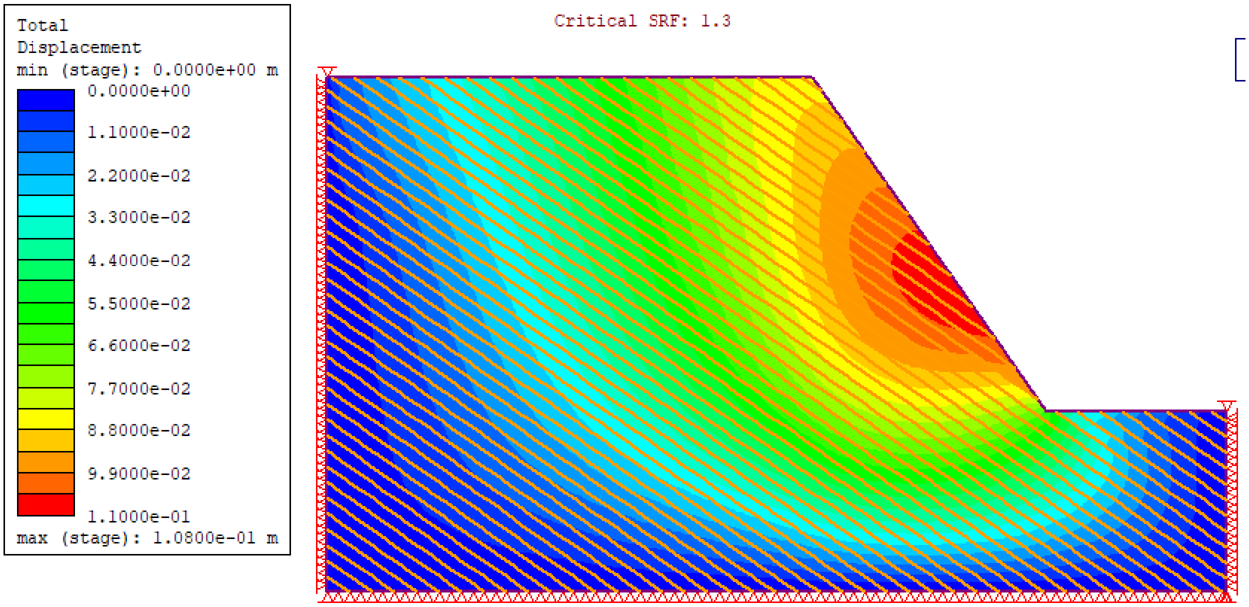


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

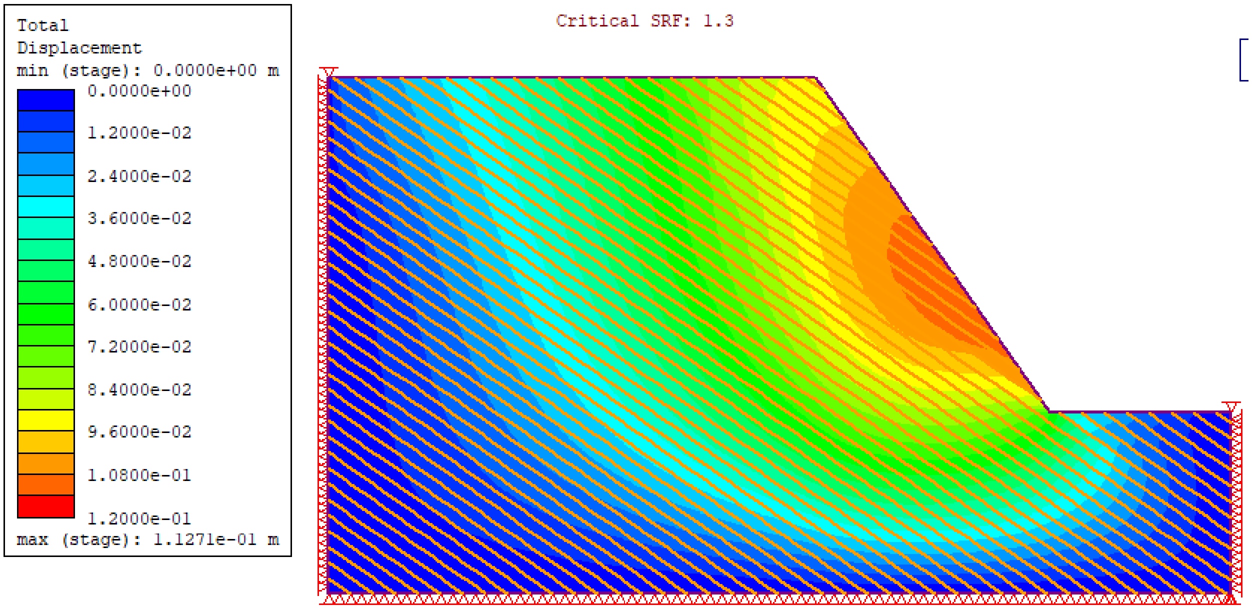


Figure 4: Solid Displacement at SRF of 1.3: FEM Joints

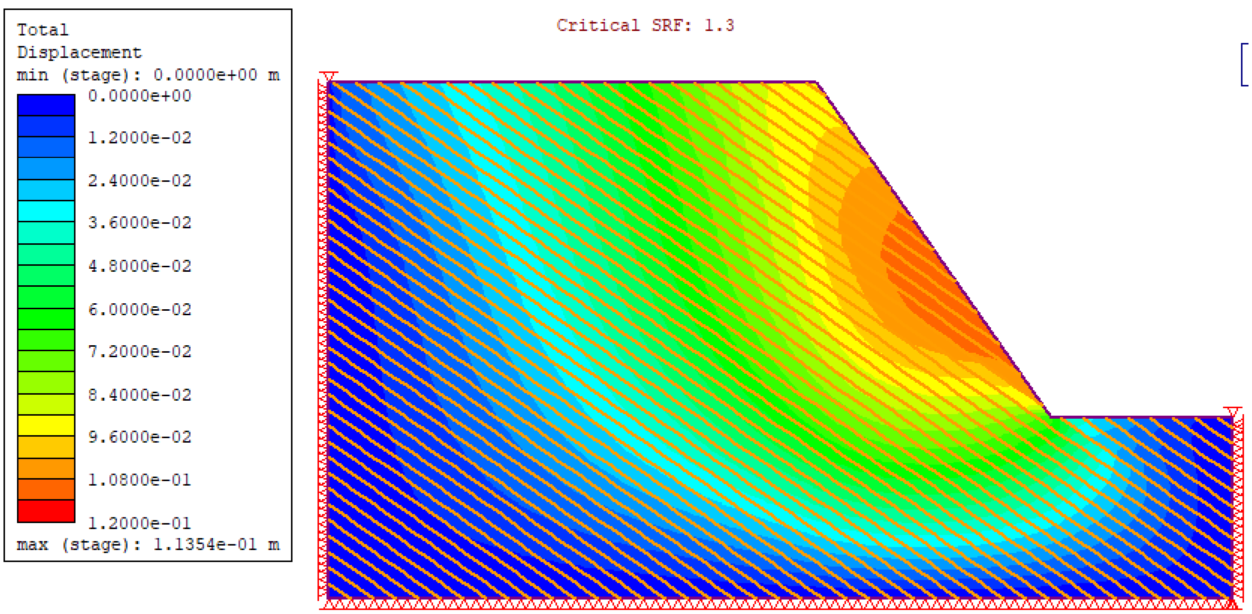


Figure 5: Solid Displacement at SRF of 1.3: XFEM Joints

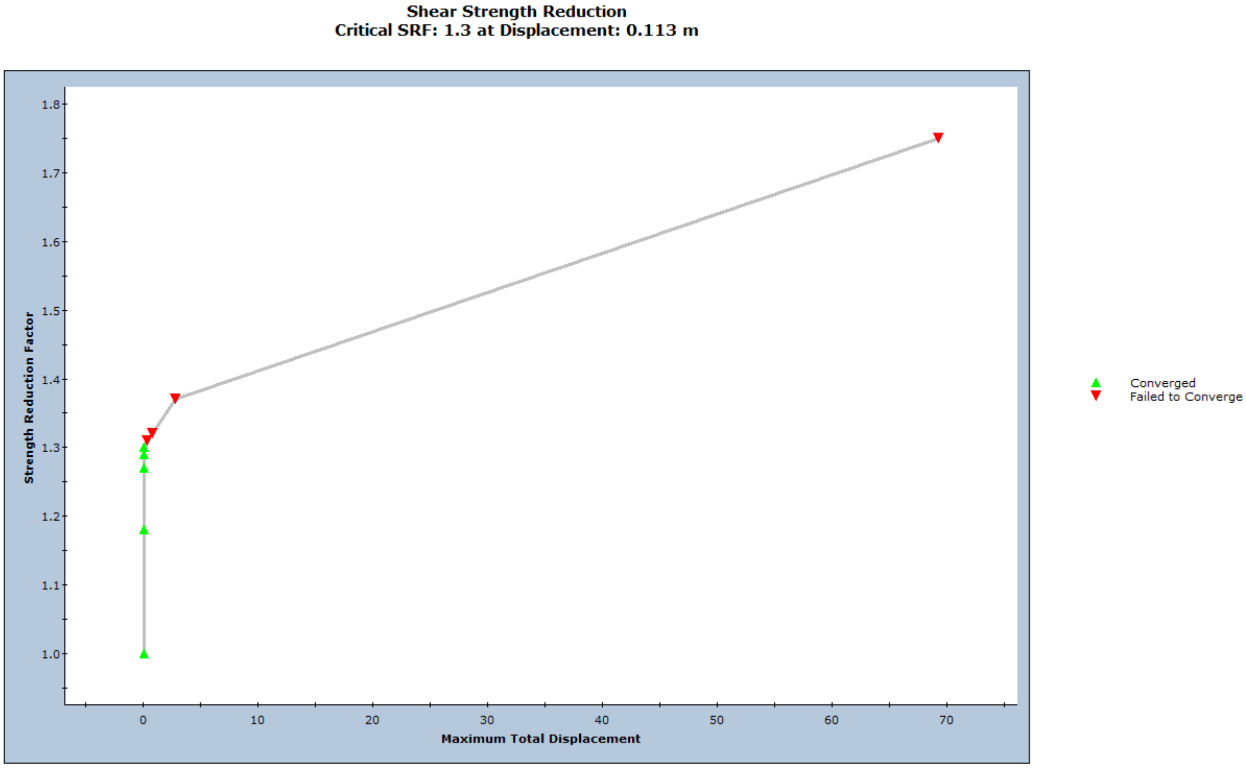


Figure 6: Shear Strength Reduction Plot: FEM Joints

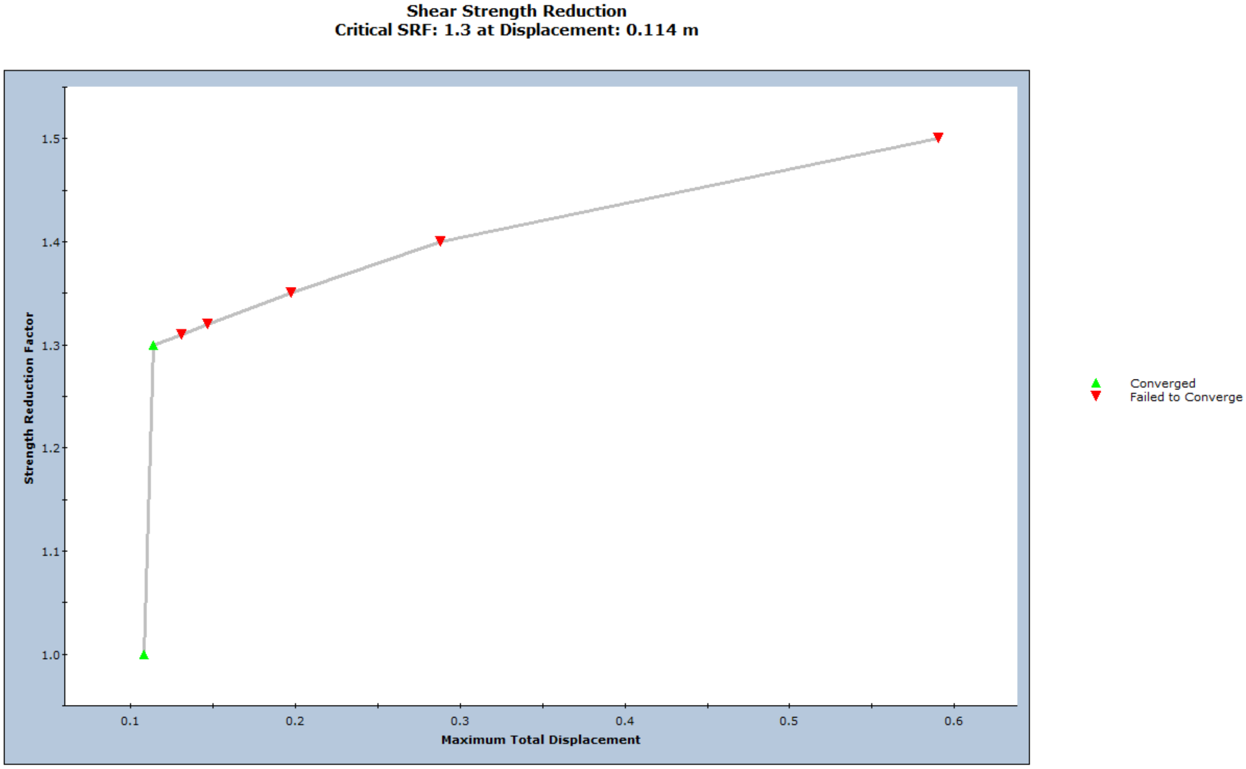


Figure 7: Shear Strength Reduction Plot: XFEM Joints

4 JOINT NETWORK 4

4.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This verification looks at the plane failure example given in:

Lorig, L., & Varona, P. (2004). Plane Failure - Daylighting and Non-Daylighting. In D. C. Wyllie, & C. W. Mah, Rock Slope Engineering Civil and Mining 4th Edition (pp. 233-235). New York: Spon Press Taylor & Francis Group

4.2 PROBLEM DESCRIPTION

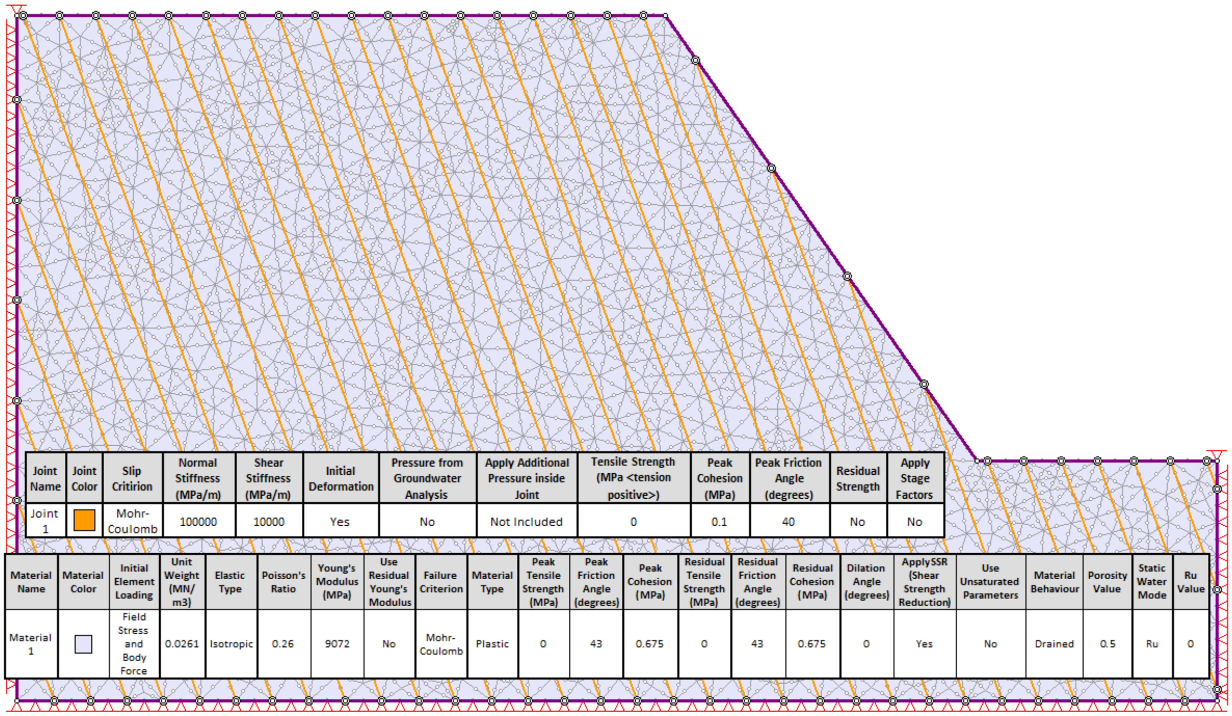
This model is from verification problem #7 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model is analyzed for plane failure with non-daylighting discontinuities.

The model has a slope height of 260 m, slope angle of 55 degrees, and joint angle of 70 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

4.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
43	9,072	26.1	0.26	0.675	0	Mohr Coulomb Plastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0.1	40	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	ApplySSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.0261	Isotropic	0.26	9072	No	Mohr-Coulomb	Plastic	0	43	0.675	0	43	0.675	0	Yes	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

4.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 1.55 and 1.56 respectively, lower than the critical SRF both models. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

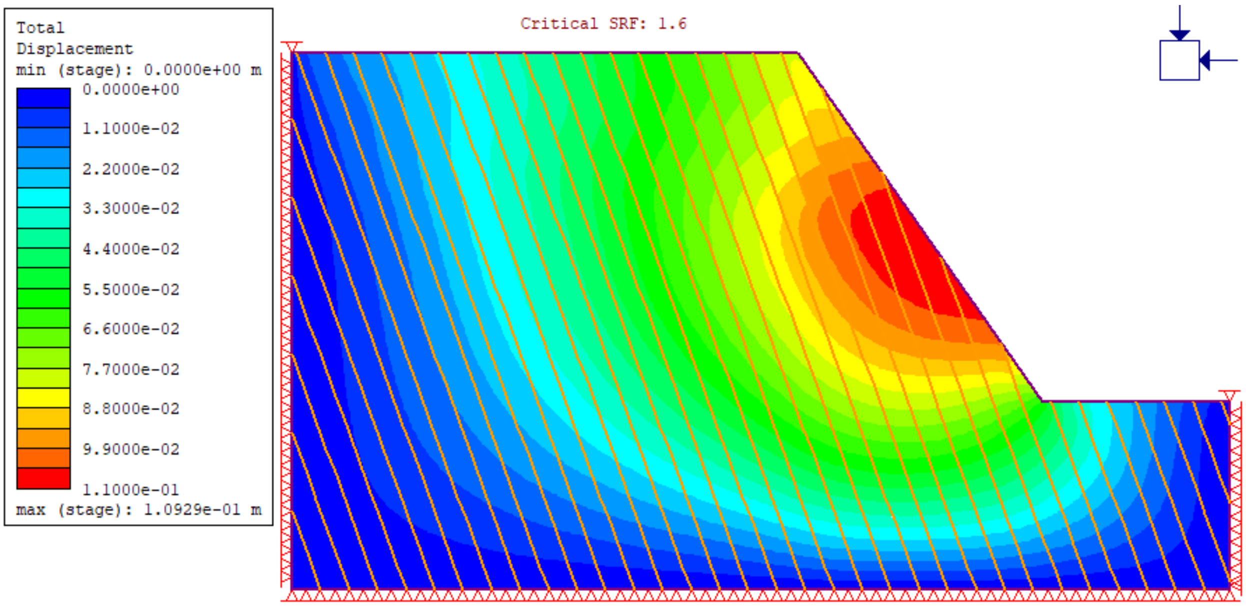


Figure 2: Solid Displacement at Initial Stage: FEM Joints

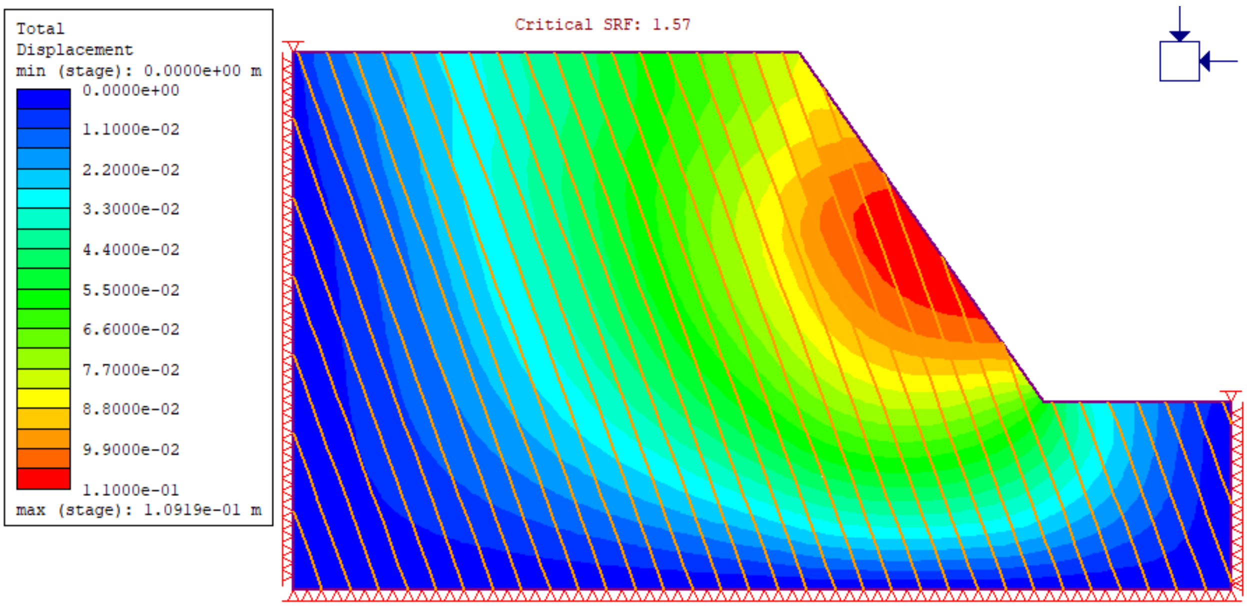


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

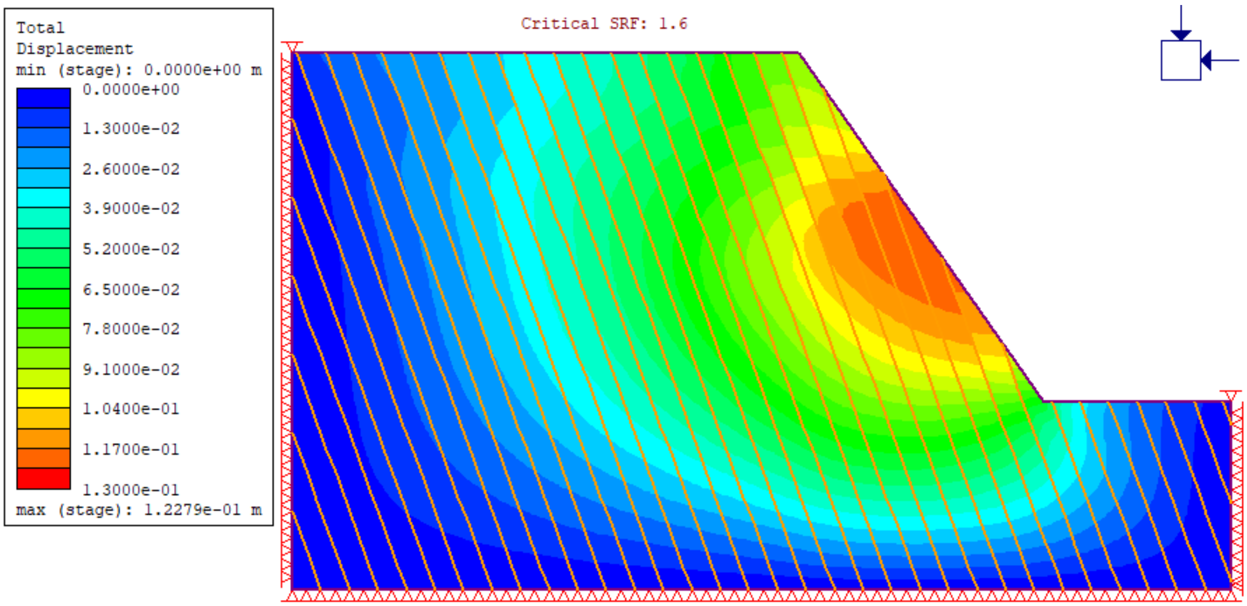


Figure 4: Solid Displacement at SRF of 1.56: FEM Joints

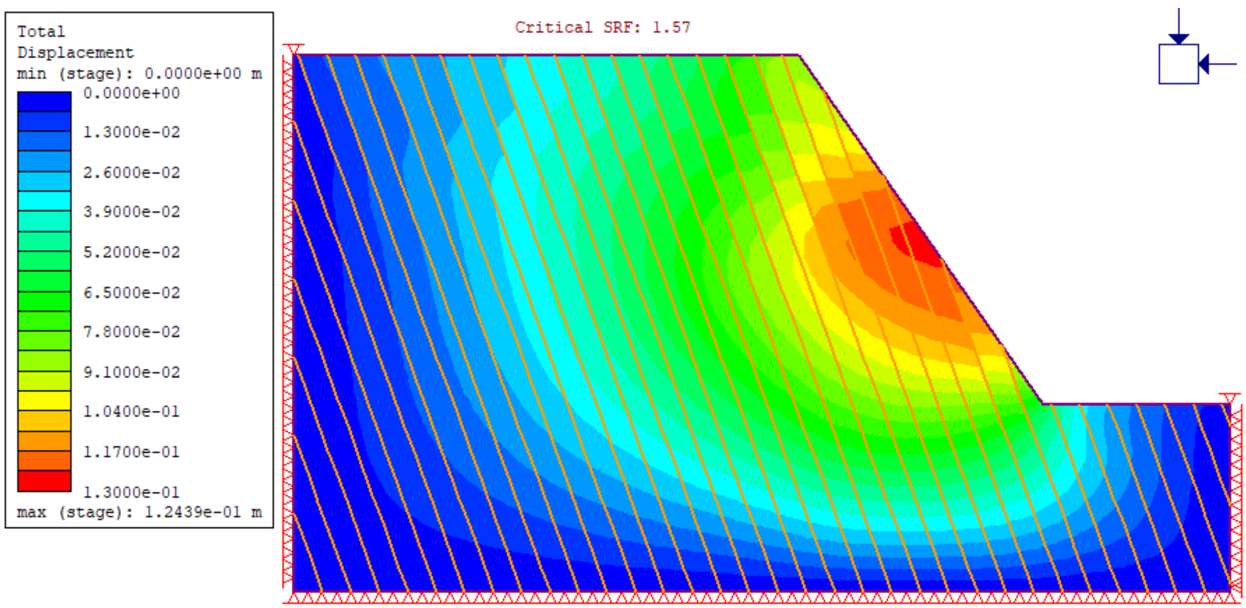


Figure 5: Solid Displacement at SRF of 1.55: XFEM Joints

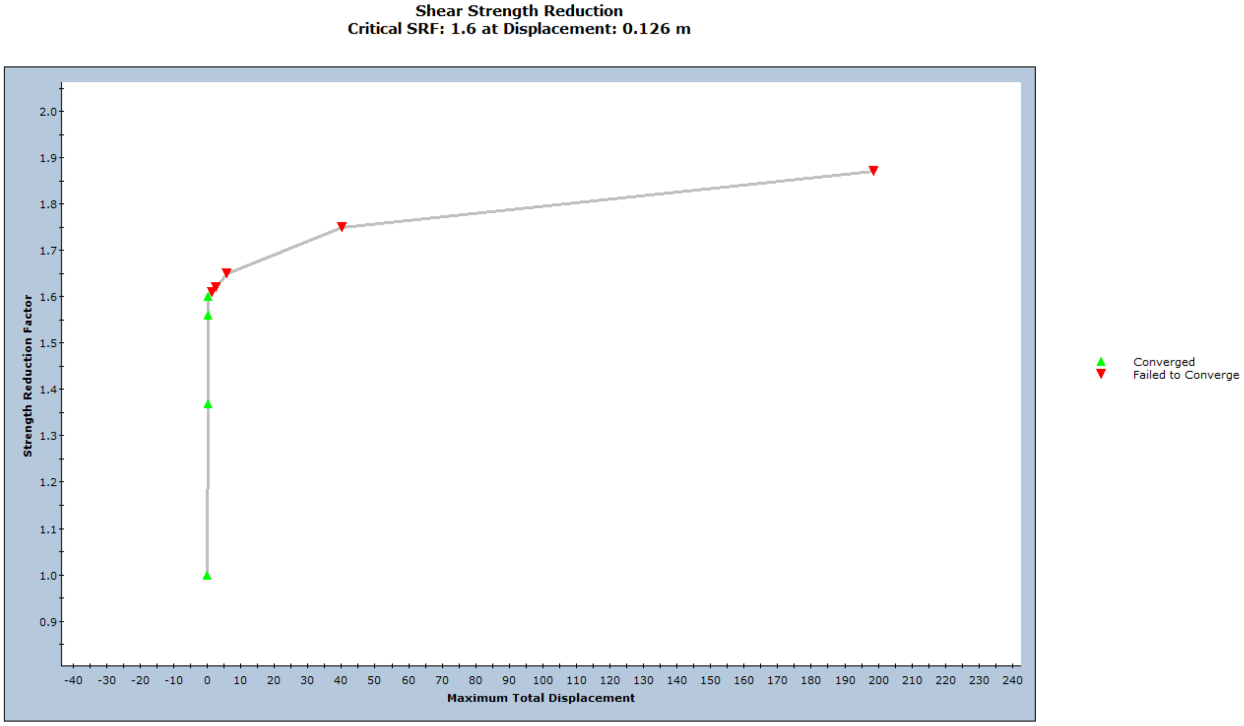


Figure 6: Shear Strength Reduction Plot: FEM Joints

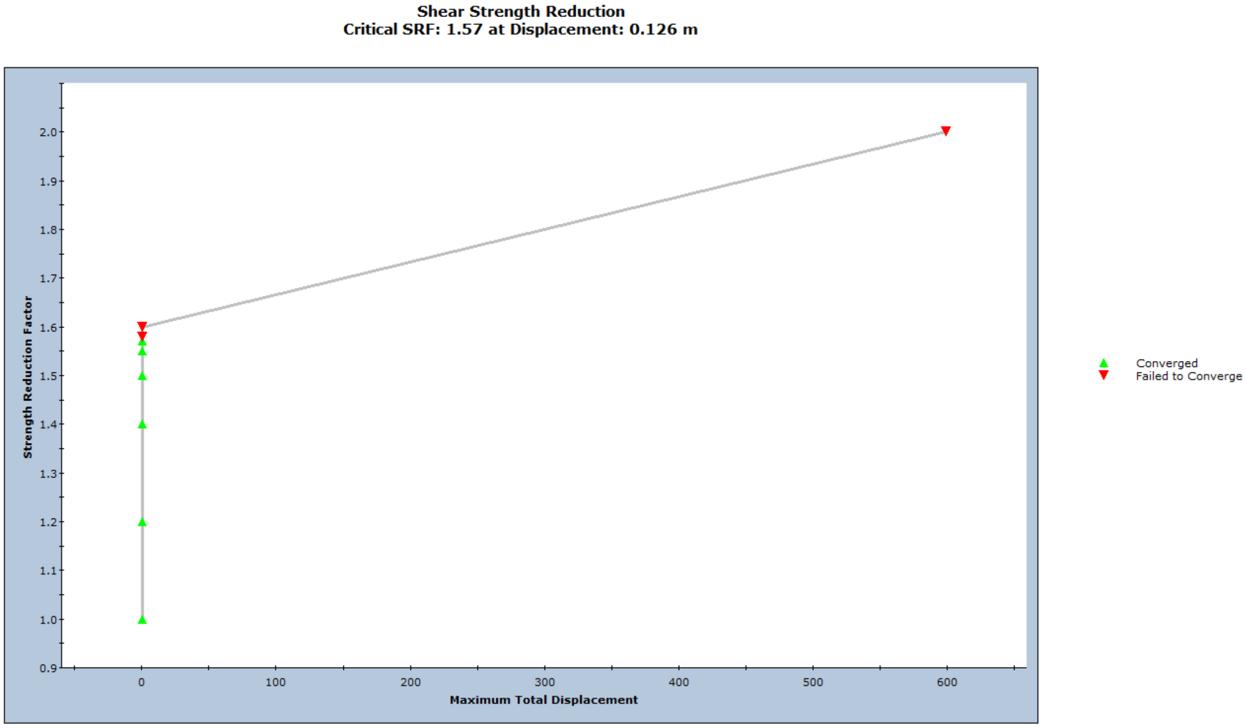


Figure 7: Shear Strength Reduction Plot: XFEM Joints

5 JOINT NETWORK 5

5.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This verification looks at the base friction example from:

Pritchard, M. A., & Savigny, K. W. (1990). Numerical Modelling of Toppling. Canadian Geotechnical Journal, 823-834.

5.2 PROBLEM DESCRIPTION

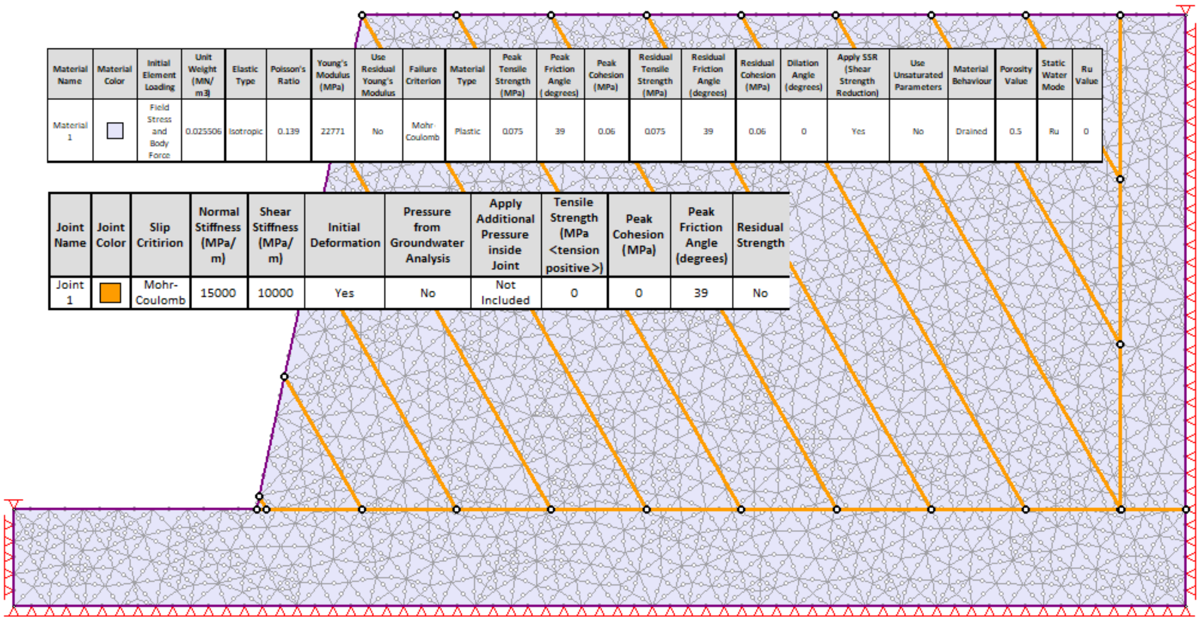
This model is from verification problem #8 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The small-scale base friction table model of flexural toppling was replicated in RS2 and scaled up 100 times.

The model has a slope height of 30.5 m, slope angle of 78 degrees, and joint angle of 60 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

5.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
39	22,771	25.506	0.139	0.06	0.075	Mohr Coulomb Plastic



Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	Apply SSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.025506	Isotropic	0.139	22771	No	Mohr-Coulomb	Plastic	0.075	39	0.06	0.075	39	0.06	0	Yes	No	Drained	0.5	Ru	0

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength
Joint 1		Mohr-Coulomb	15000	10000	Yes	No	Not Included	0	0	39	No

Figure 1: RS2 Model Geometry with XFEM Joints

5.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Note that the initial stage is equivalent to a SRF of 1, which is greater than the common critical SRF of 0.75 for both models. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 0.72. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

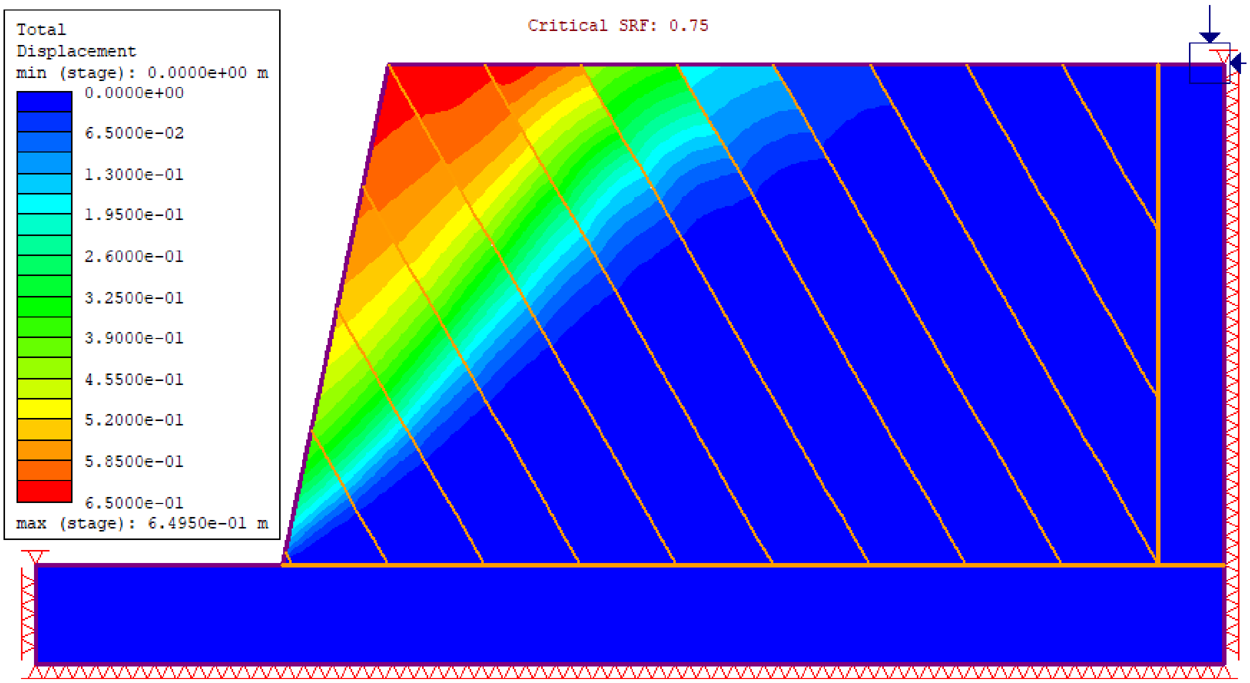


Figure 2: Solid Displacement at Initial Stage: FEM Joints

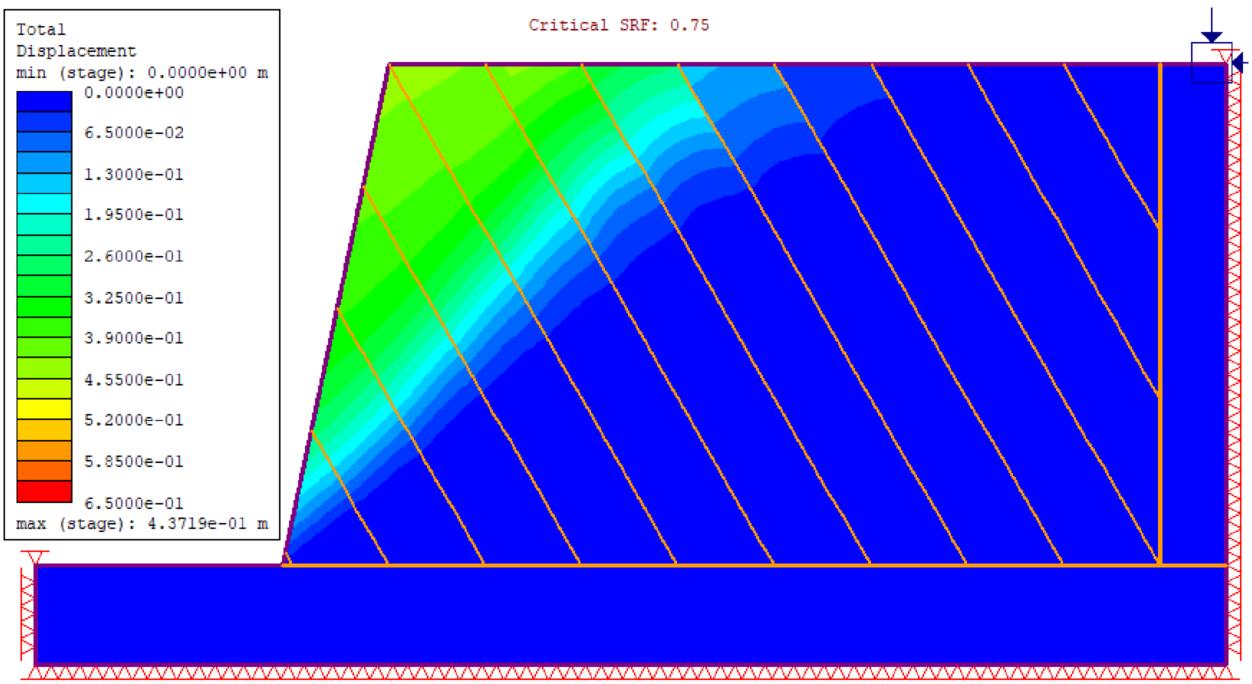


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

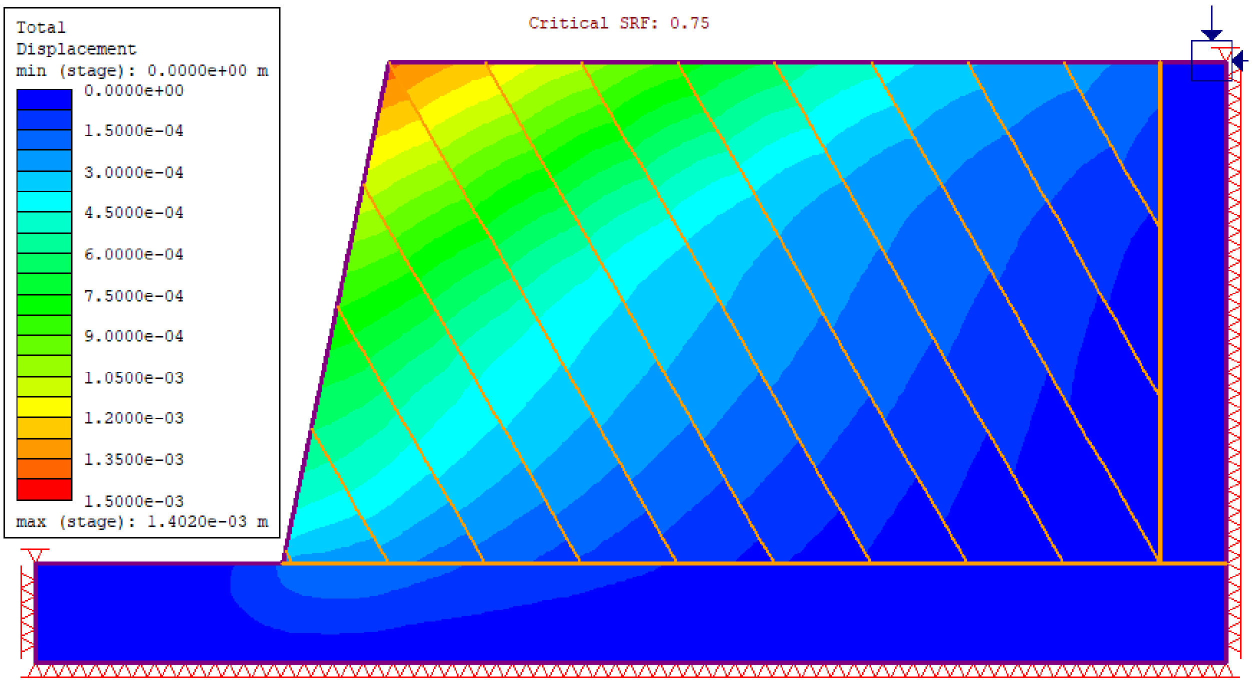


Figure 4: Solid Displacement at SRF of 0.72: FEM Joints

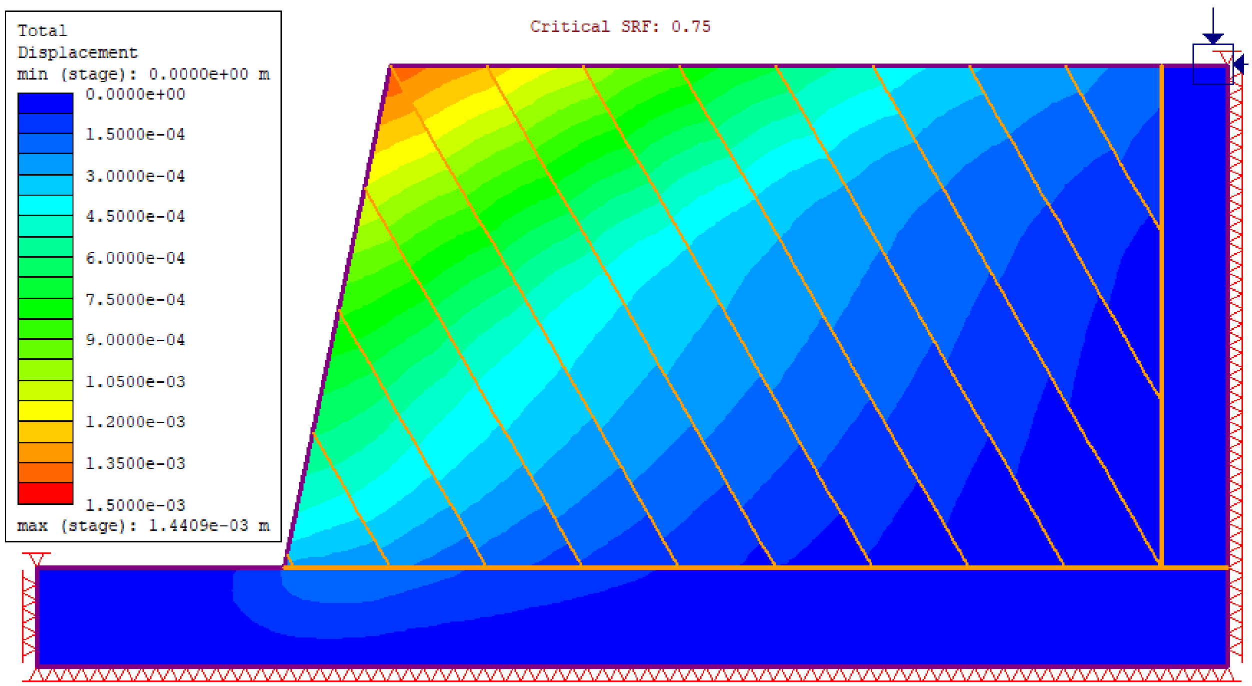


Figure 5: Solid Displacement at SRF of 0.72: XFEM Joints

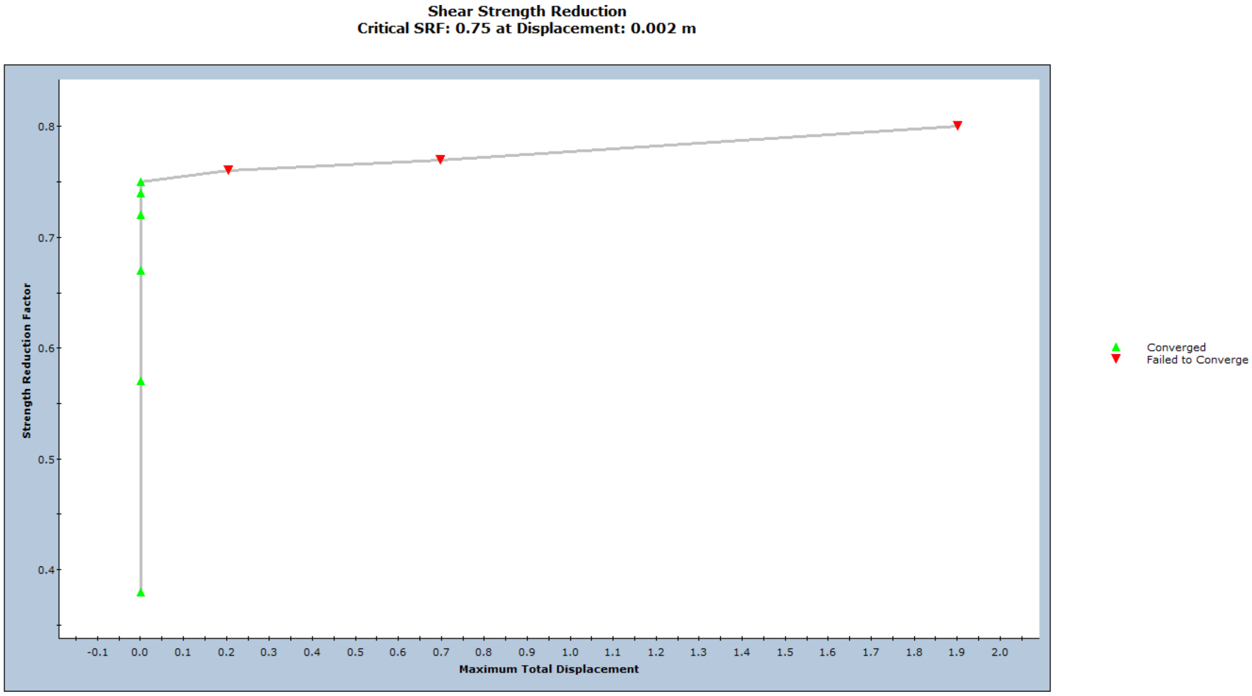


Figure 6: Shear Strength Reduction Plot: FEM Joints

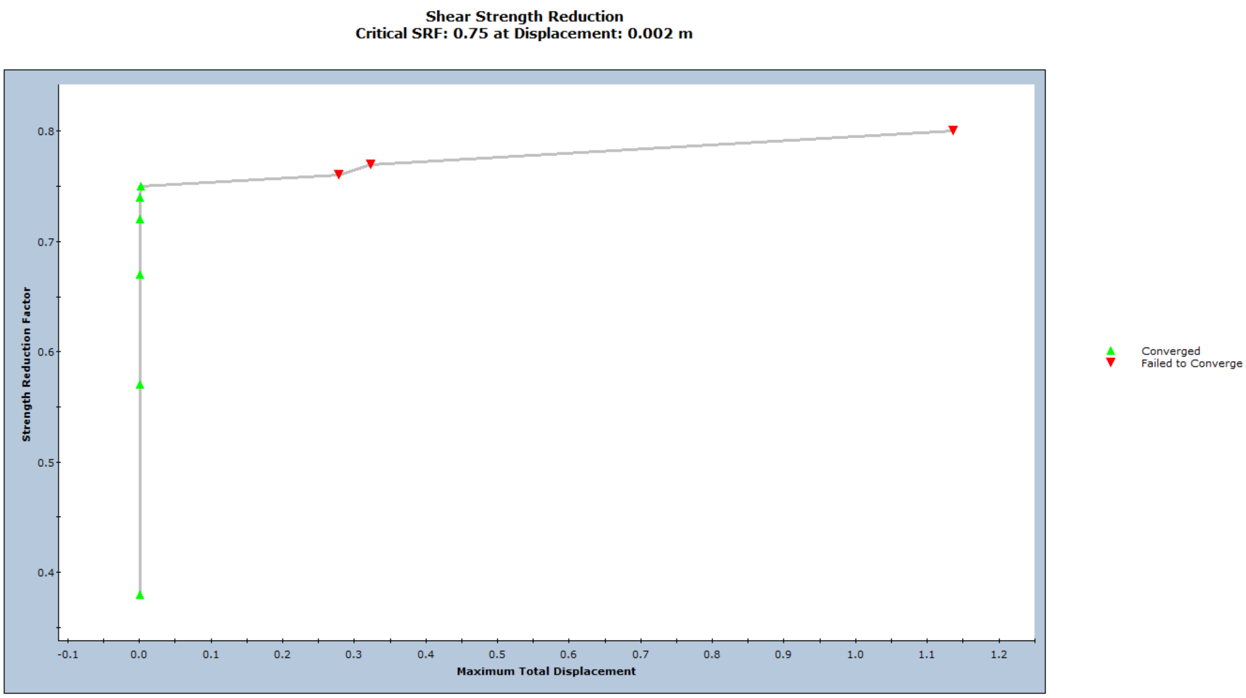


Figure 7: Shear Strength Reduction Plot: XFEM Joints

6 JOINT NETWORK 6

6.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This verification looks at the partially joint-controlled slope failure example from:

Alejano, L. R., Ferrero, A. M., Ramirez-Oyanguren, P., & Alvarez Fernandez, M. I. (2011). Comparison of Limit-Equilibrium, Numerical and Physical Models of Wall Slope Stability. International Journal of Rock Mechanics and Mining Sciences, 16-26.

6.2 PROBLEM DESCRIPTION

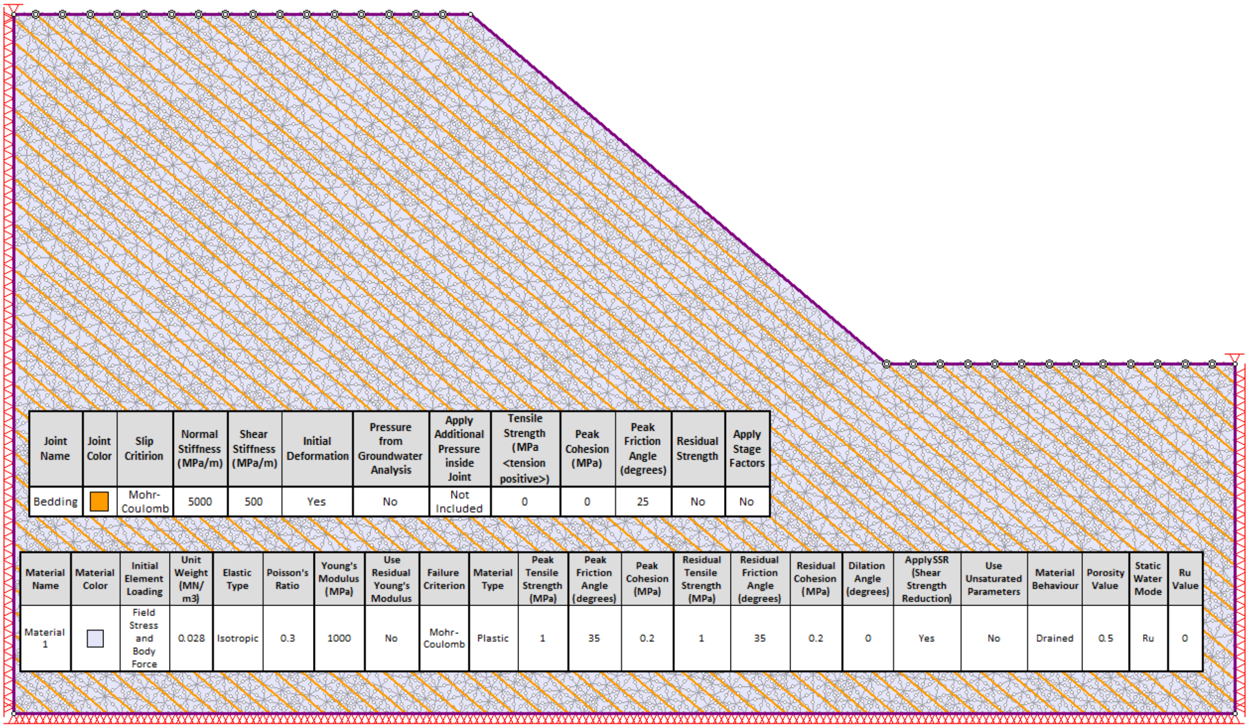
This model is from verification problem #15 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model is analyzed for partially joint-controlled slope failure. The joint network dips in the same direction and angle as the slope, leading to the failure mechanism of joint slip coupled with break-through failure of the rock mass at the toe of the slope.

The model has a slope height of 25 m as well as slope & joint angle of 40 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

6.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
35	1,000	28	0.3	0.2	1	Mohr Coulomb Plastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Bedding		Mohr-Coulomb	5000	500	Yes	No	Not Included	0	0	25	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	ApplySSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.028	Isotropic	0.3	1000	No	Mohr-Coulomb	Plastic	1	35	0.2	1	35	0.2	0	Yes	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

6.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 1.25, which is the critical SRF for the XFEM model but less than the critical SRF of the FEM model. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

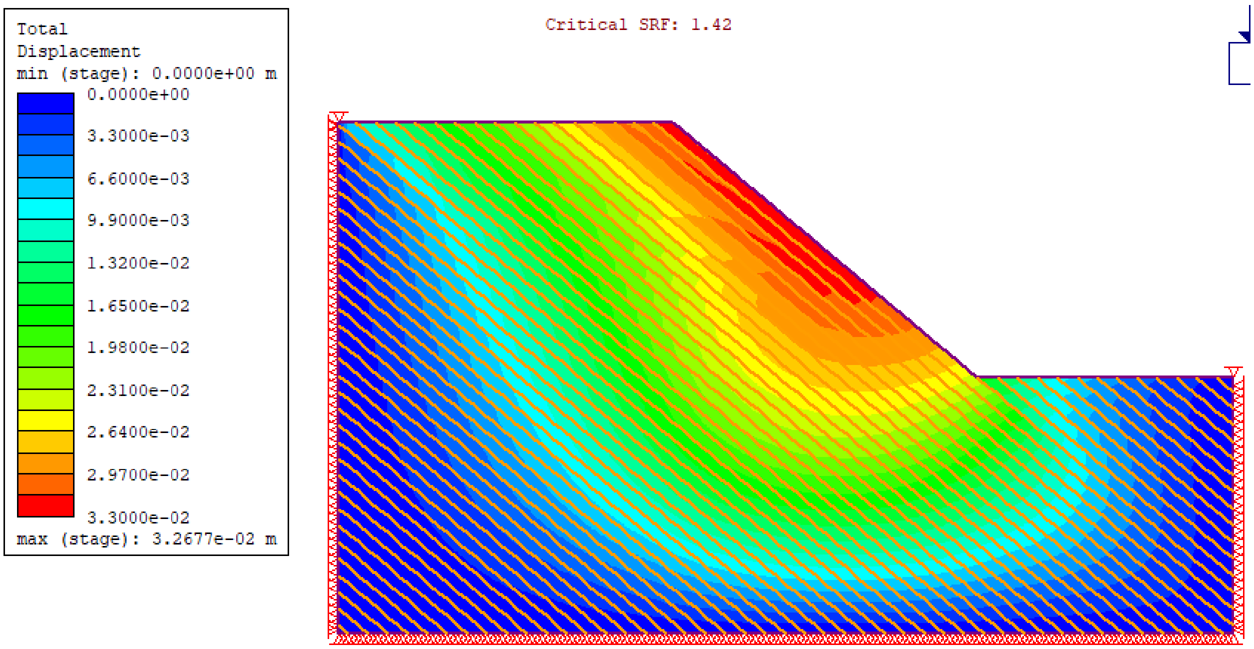


Figure 2: Solid Displacement at Initial Stage: FEM Joints

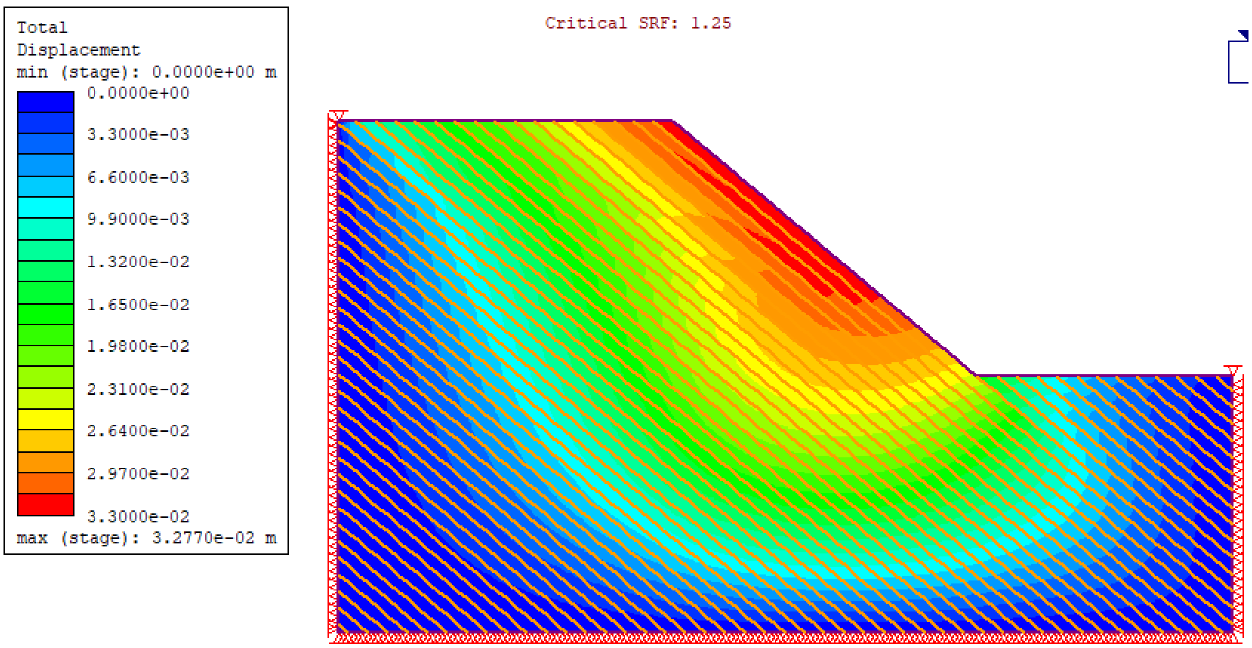


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

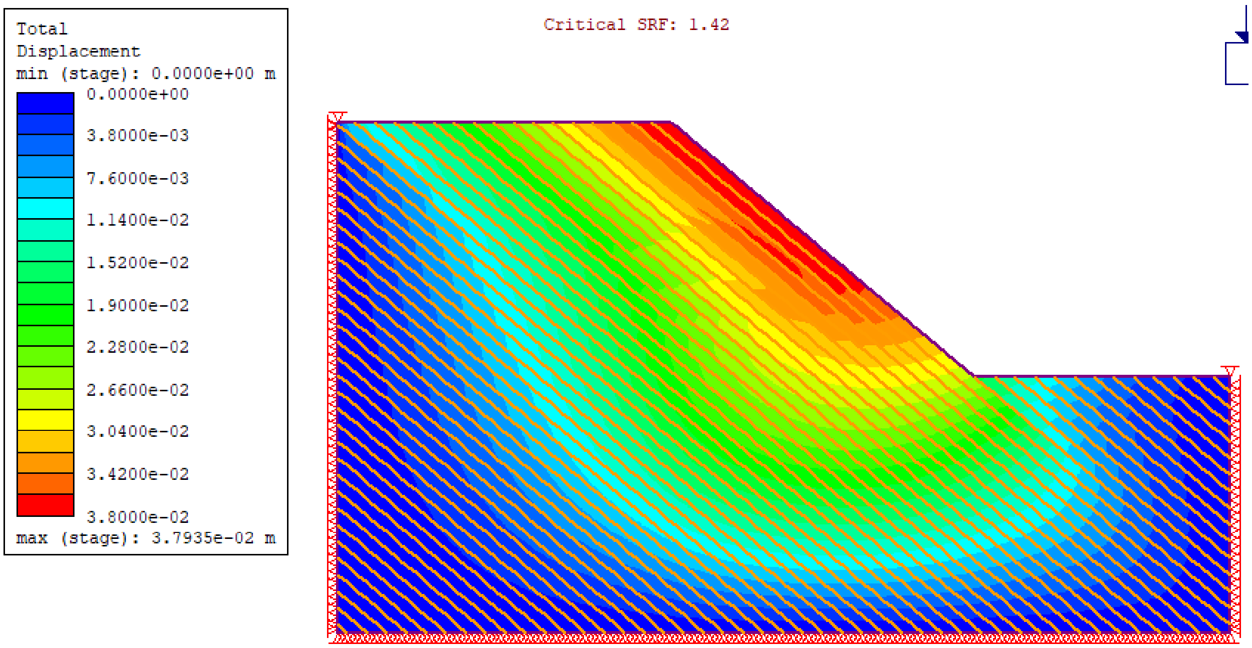


Figure 4: Solid Displacement at SRF of 1.25: FEM Joints

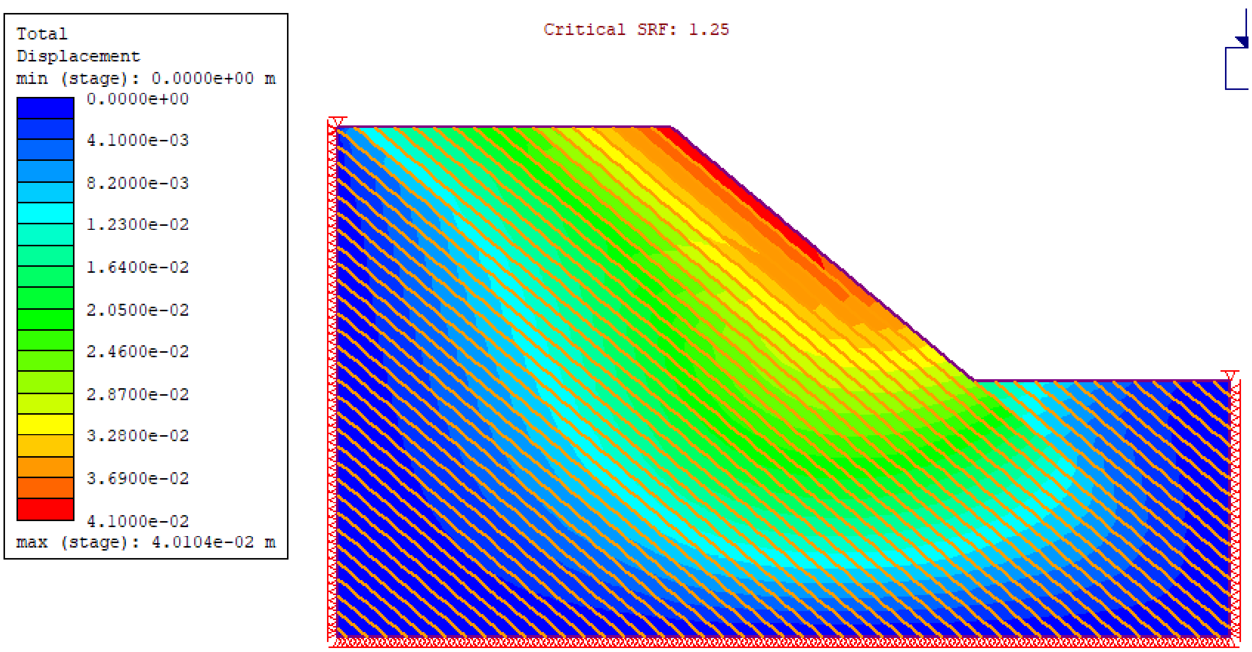


Figure 5: Solid Displacement at SRF of 1.25: XFEM Joints

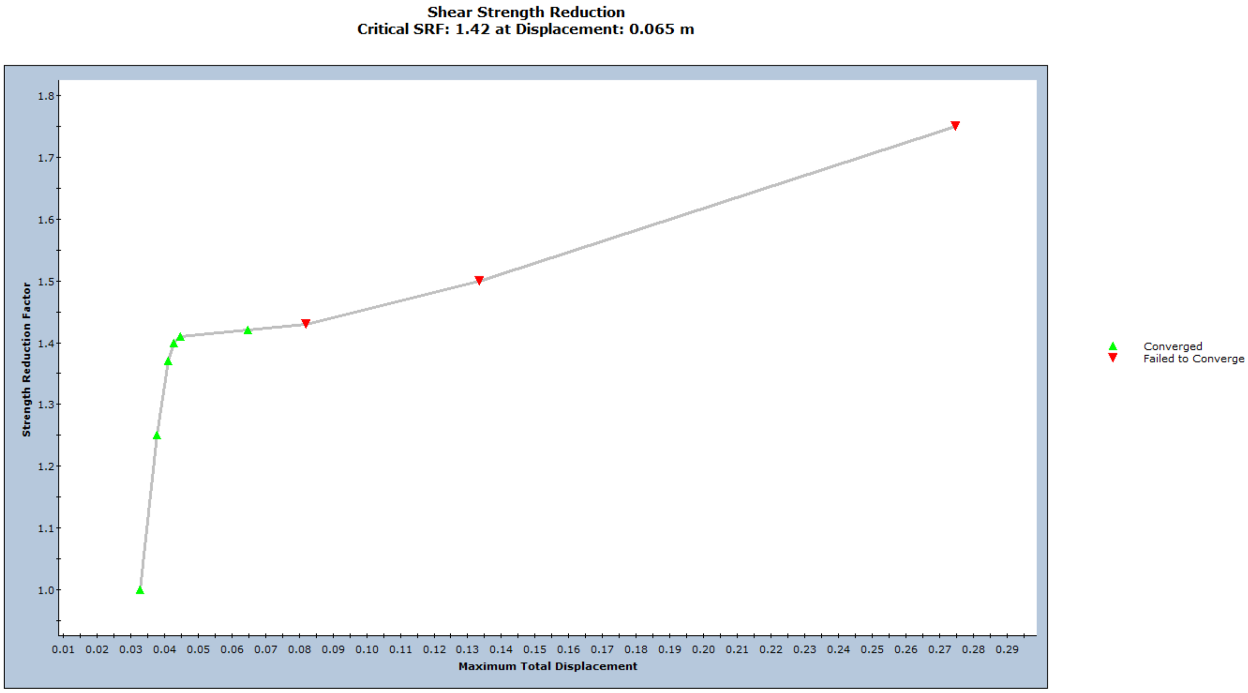


Figure 6: Shear Strength Reduction Plot: FEM Joints

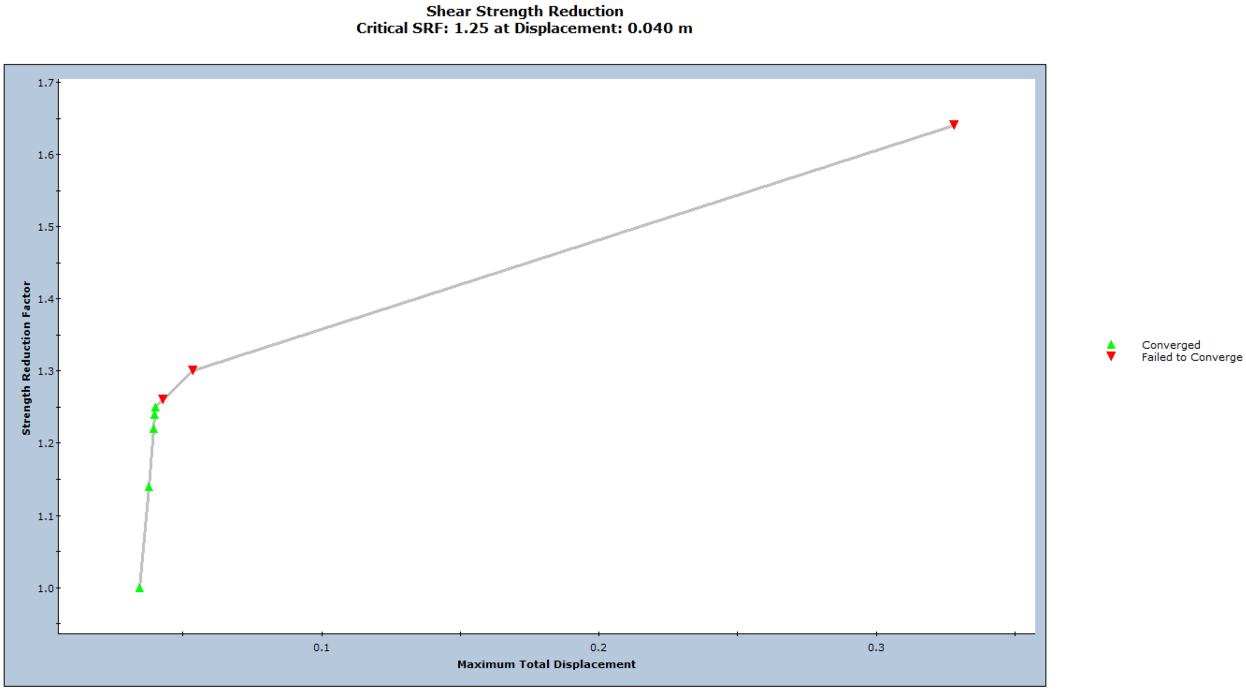


Figure 7: Shear Strength Reduction Plot: XFEM Joints

7 JOINT NETWORK 7

7.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example is verified with:

Itasca Consulting Group Inc. (2011). Step-Path Failure of Rock Slopes. In I. C. Inc., UDEC Version 5.0 Example Applications (pp. 13-1 to 13-9). Minneapolis.

7.2 PROBLEM DESCRIPTION

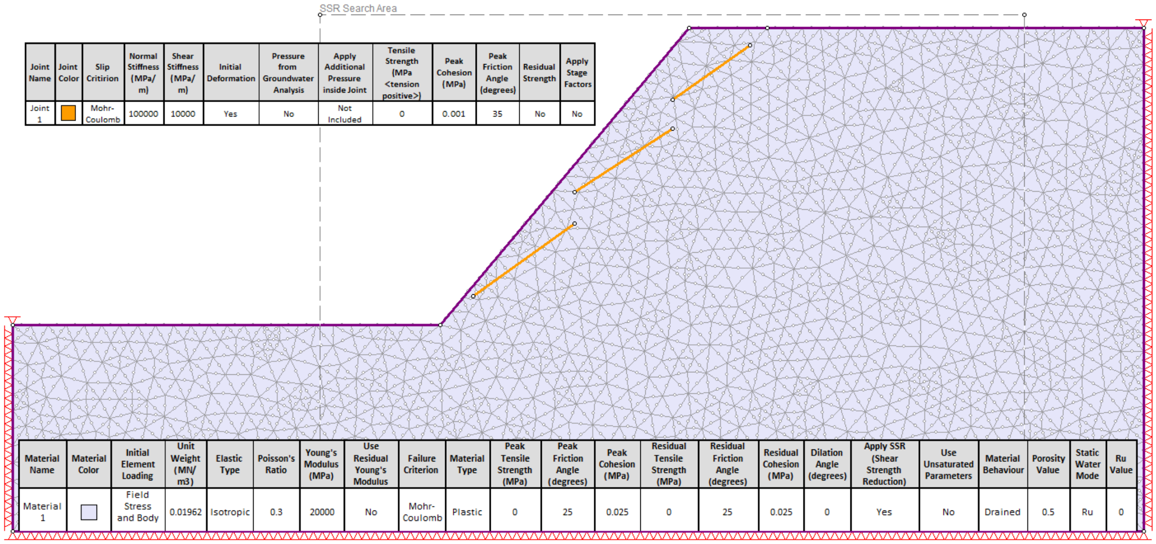
This model is from verification problem #17 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model contains 3 non-continuous en-echelon joints and is analyzed for step-path failure.

The model has a slope height of 11.8 m, slope angle of 50 degrees, and joint angle of 36.1 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

7.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
25	20,000	19.62	0.3	0.025	0	Mohr Coulomb Plastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0.001	35	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	Apply SSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body	0.01962	Isotropic	0.3	20000	No	Mohr-Coulomb	Plastic	0	25	0.025	0	25	0.025	0	Yes	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

7.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 1.15, lower than the common critical SRF of 1.2. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

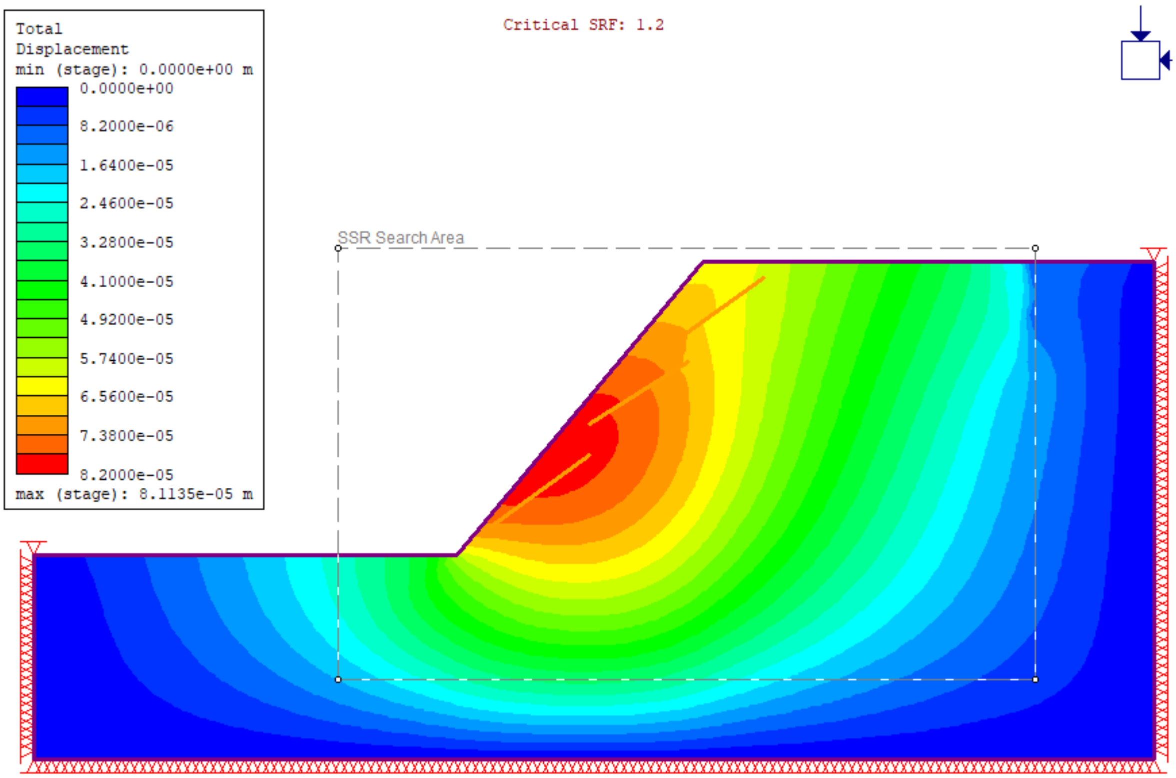


Figure 2: Solid Displacement at Initial Stage: FEM Joints

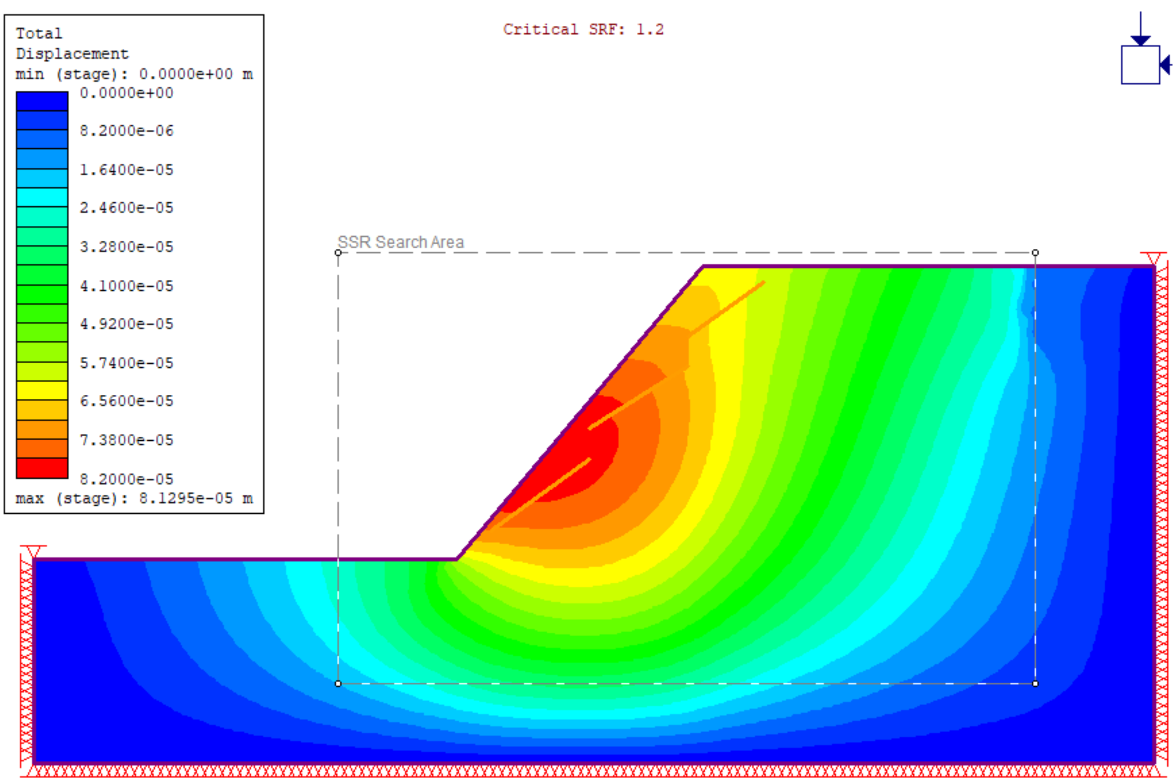


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

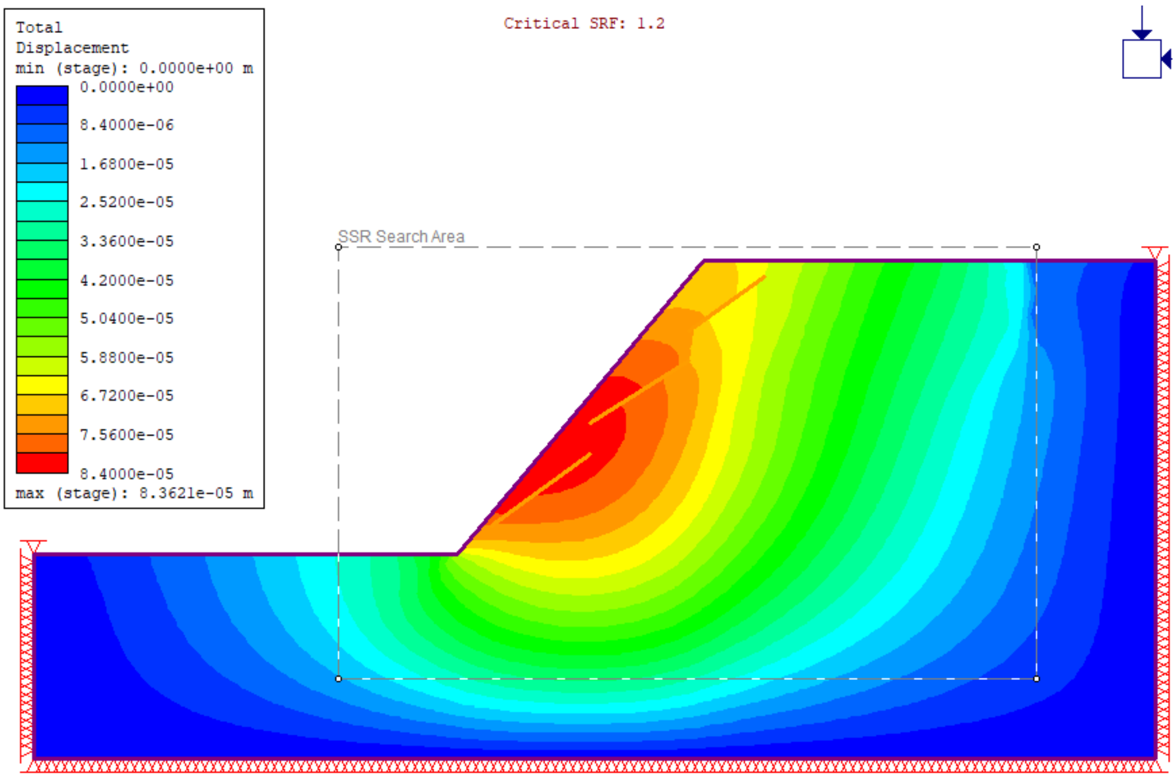


Figure 4: Solid Displacement at SRF of 1.15: FEM Joints

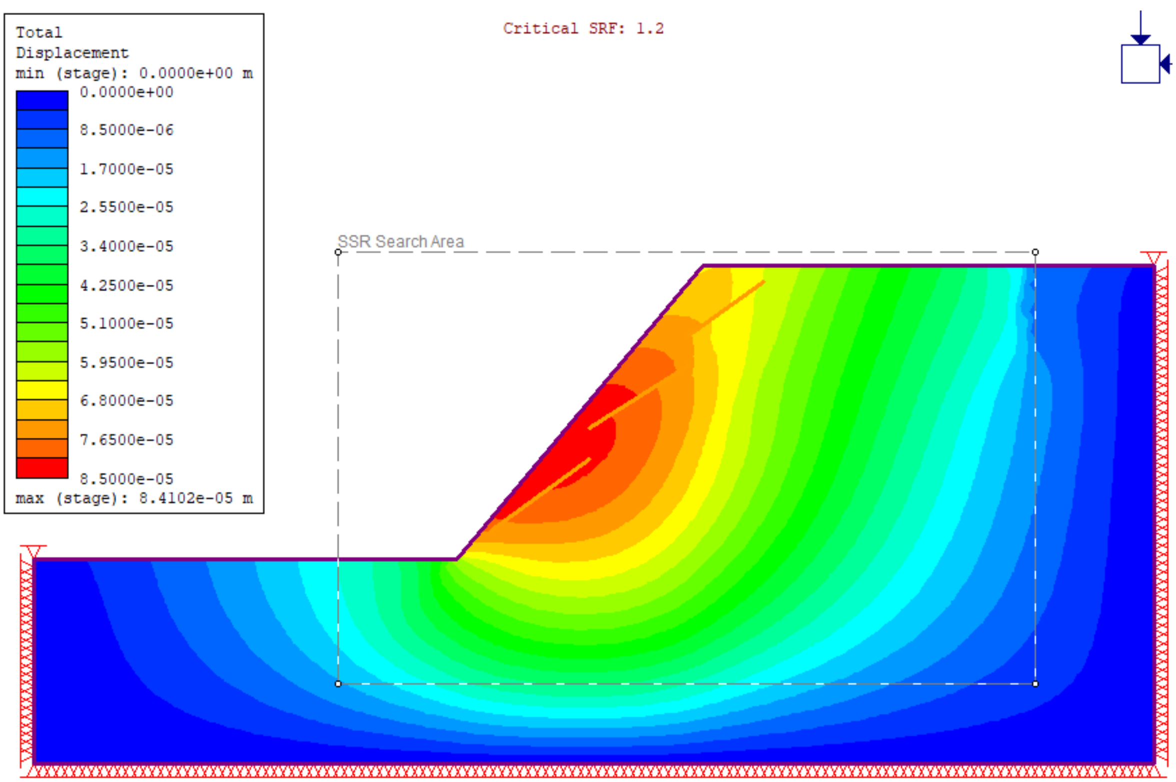


Figure 5: Solid Displacement at SRF of 1.15: XFEM Joints

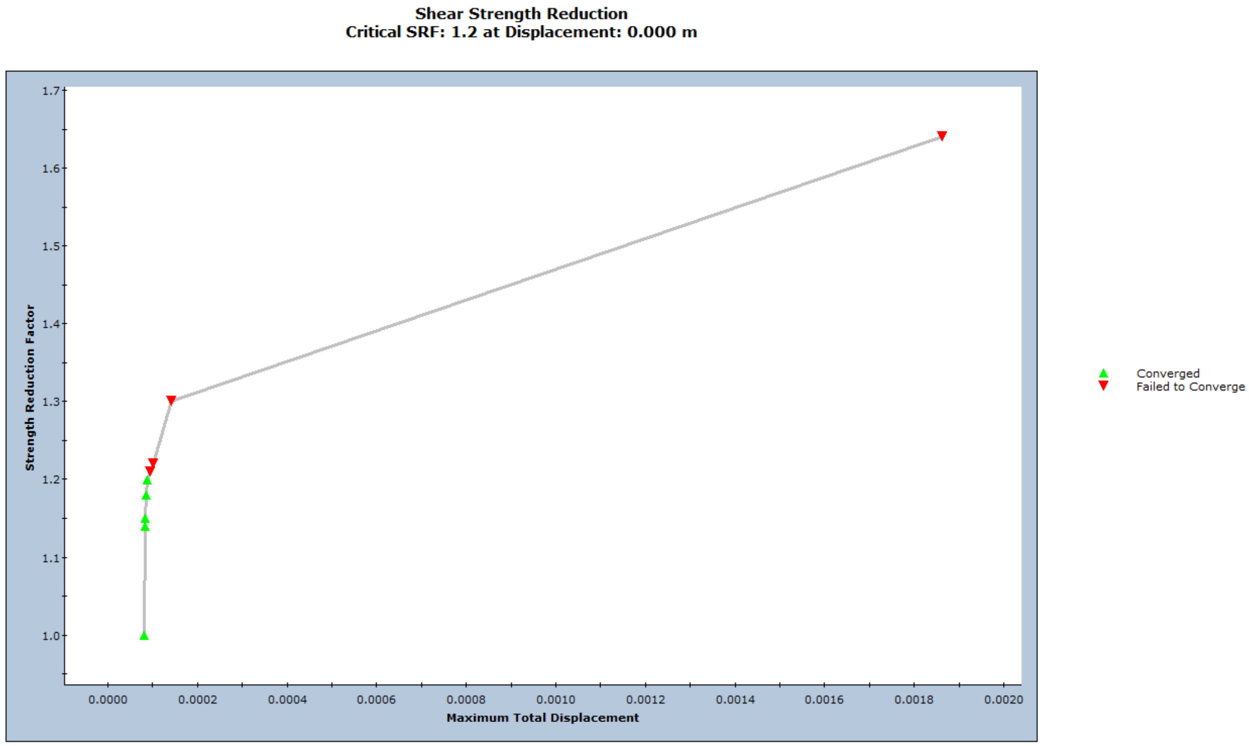


Figure 6: Shear Strength Reduction Plot: FEM Joints

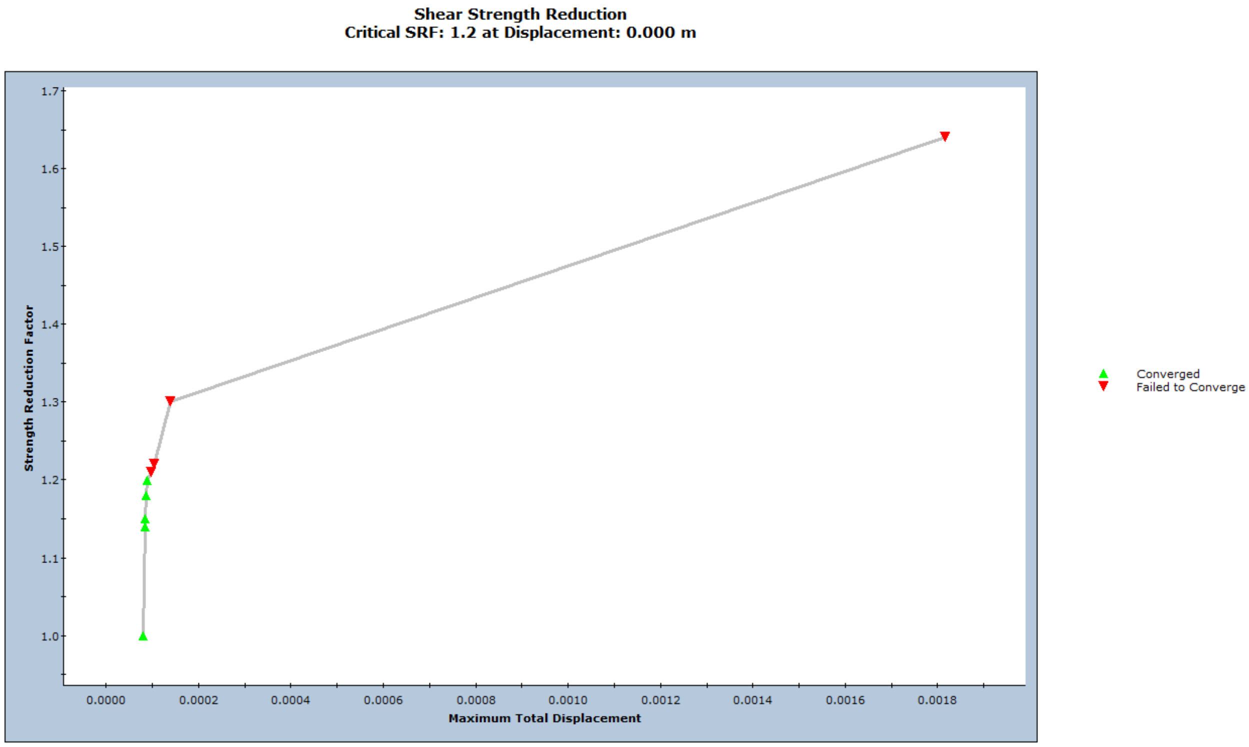


Figure 7: Shear Strength Reduction Plot: XFEM Joints

8 JOINT NETWORK 8

8.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example is verified with:

Itasca Consulting Group Inc. (2011). Step-Path Failure of Rock Slopes. In I. C. Inc., UDEC Version 5.0 Example Applications (pp. 13-1 to 13-9). Minneapolis.

8.2 PROBLEM DESCRIPTION

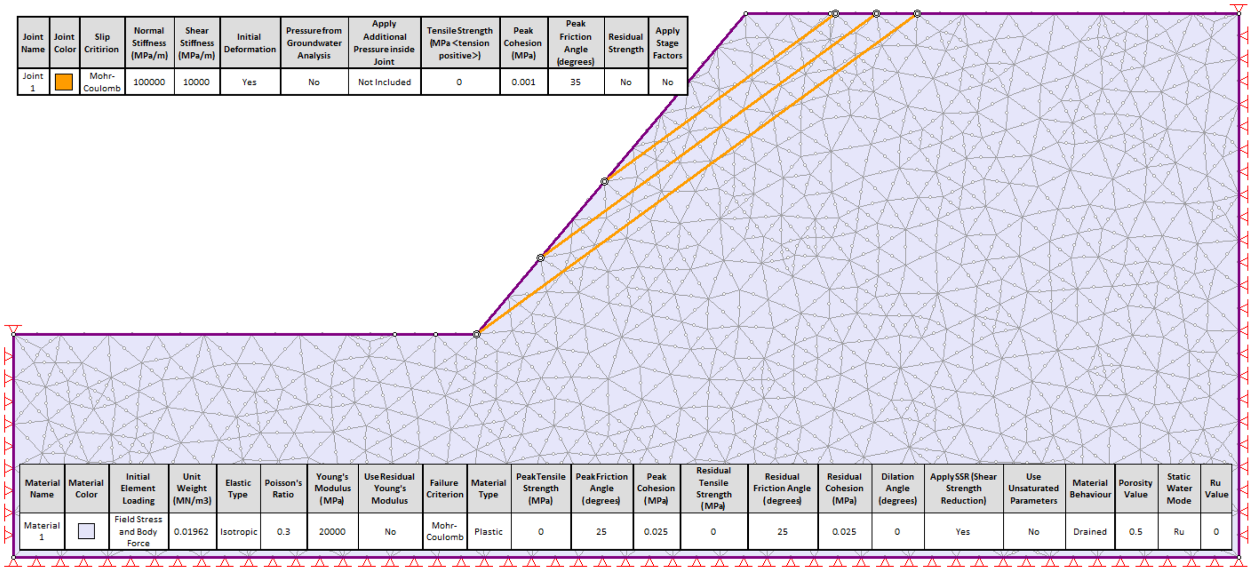
This model is from verification problem #18 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model contains 3 continuous joints along the rock slope and is analyzed for step-path failure.

The model has a slope height of 11.8 m, slope angle of 50 degrees, and joint angle of 36.1 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

8.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
25	20,000	19.62	0.3	0.025	0	Mohr Coulomb Plastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0.001	35	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)
Material 1		Field Stress and Body Force	0.01962	Isotropic	0.3	20000	No	Mohr-Coulomb	Plastic	0	25

Material Name	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	Apply SSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1	0.025	0	25	0.025	0	Yes	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

8.4 RESULTS

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities, which in this case also doubles as the results near the Critical SRF of 1 for FEM and 1.01 for XFEM. Figures 4 & 5 compares the shear strength reduction plots of the models.

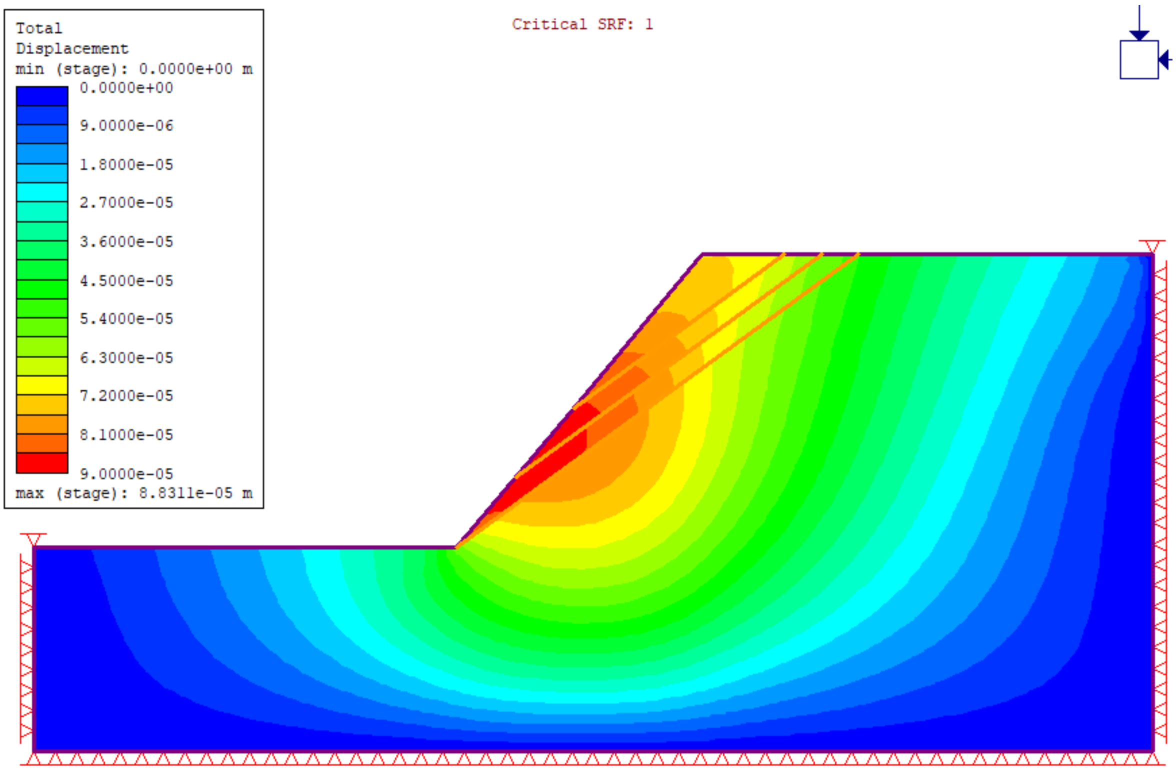


Figure 2: Solid Displacement at Initial Stage: FEM Joints

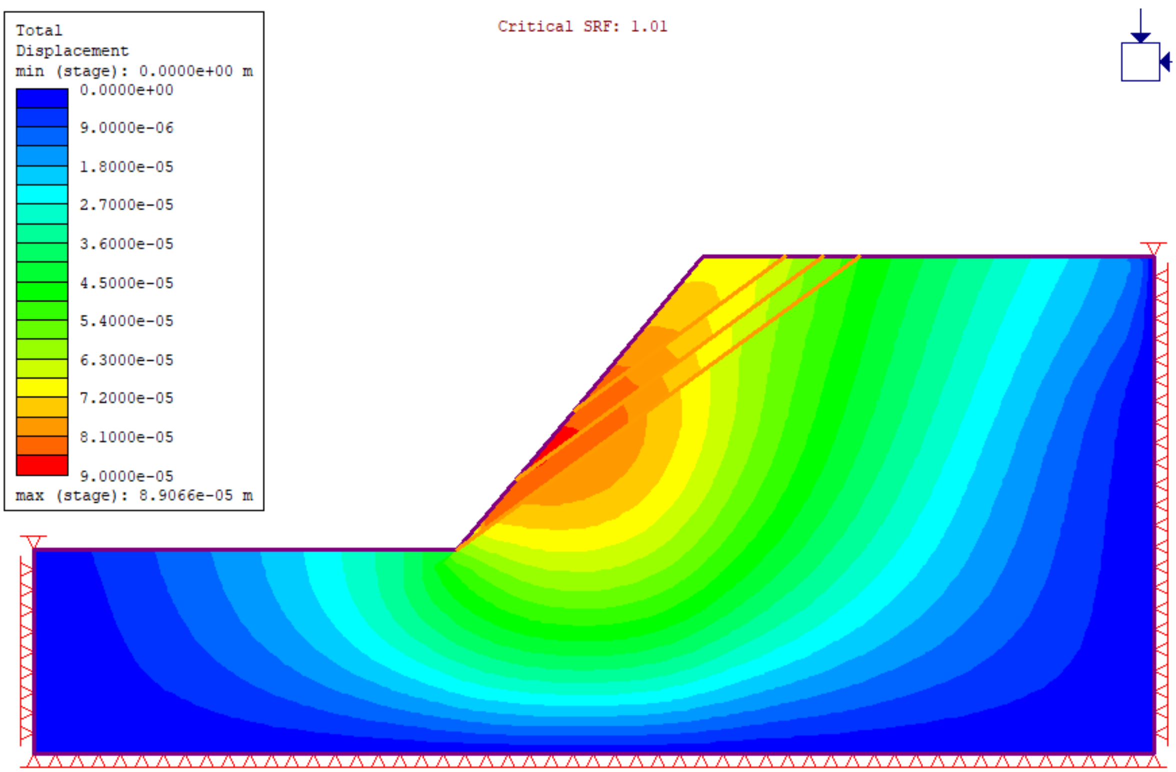


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

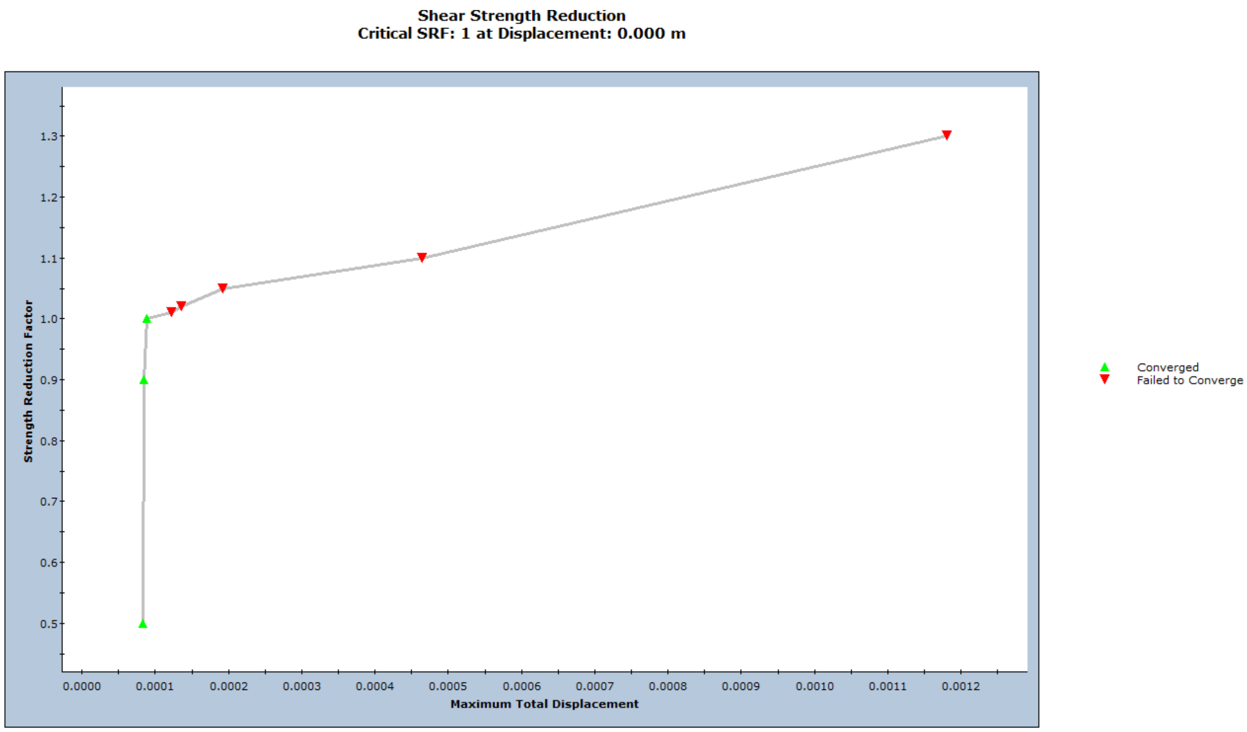


Figure 4: Shear Strength Reduction Plot: FEM Joints

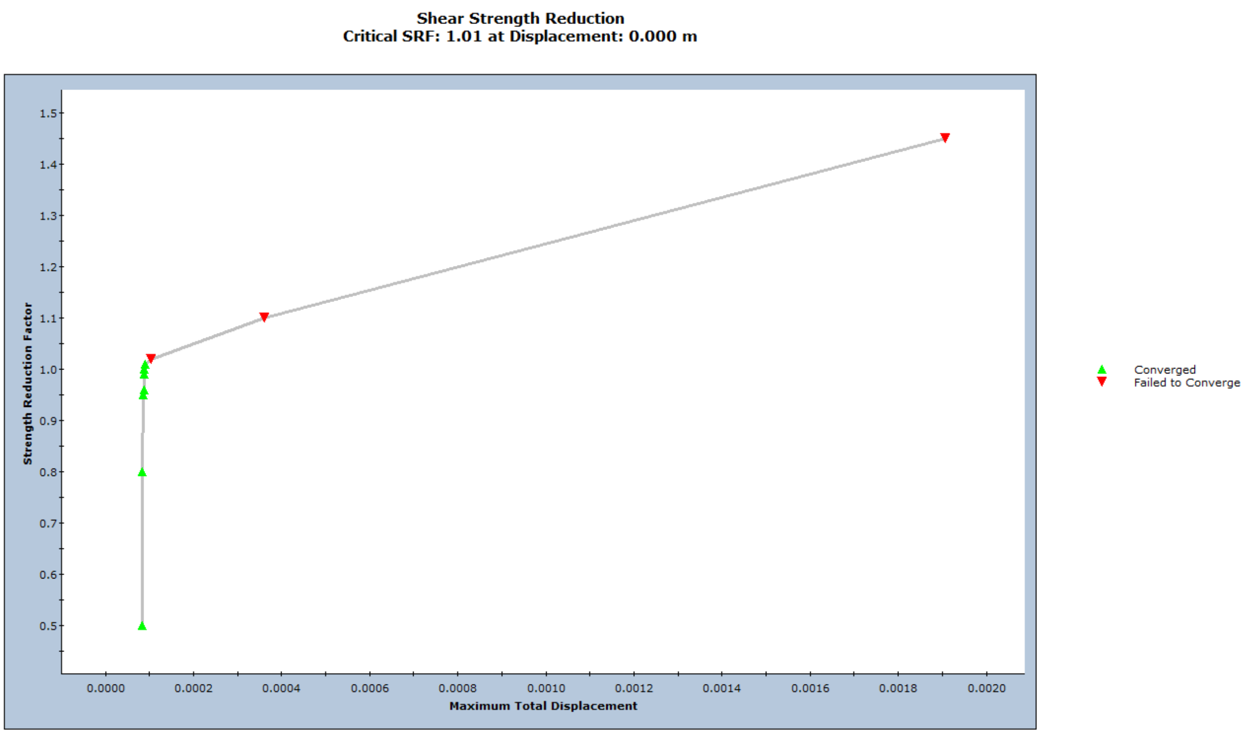


Figure 5: Shear Strength Reduction Plot: XFEM Joints

9 JOINT NETWORK 9

9.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example is verified with:

Yan, M., Elmo, D., & Stead, D. (2007). Characterization of Step-Path Failure Mechanisms: A Combined Field-Based Numerial Modelling Study. In E. Eberhardt, D. Stead, & T. Morrison, Rock Mechanics Meeting Society's Challenges and Demands Volume 1: Fundamentals, New Technologies and New Ideas (p. 499). London, U.K.: Taylor and Francis Group.

9.2 PROBLEM DESCRIPTION

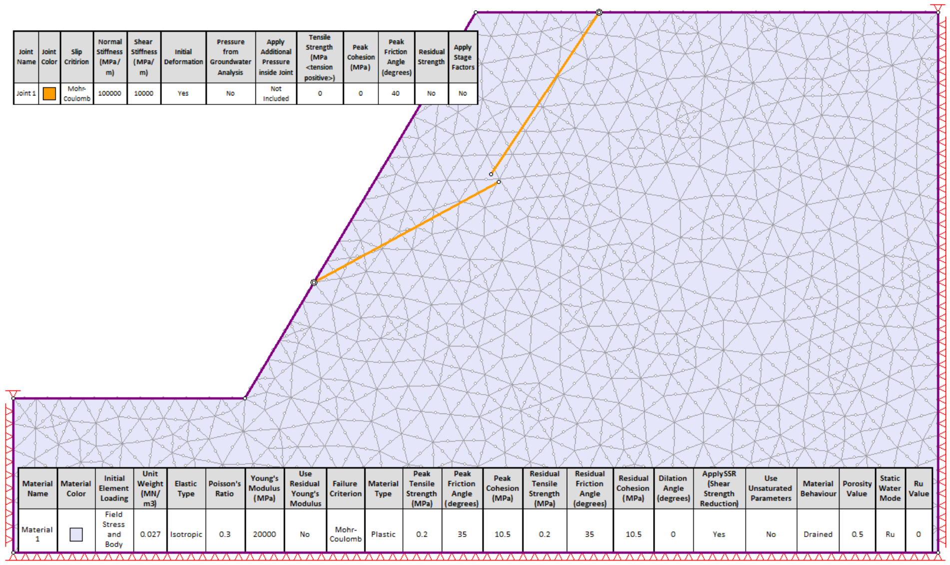
This model is from verification problem #19 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model contains 2 discontinuous joints and is analyzed for step-path failure.

The model has a slope height of 50 m, slope angle of 50 degrees, and joint angle of 59 degrees. There are fully fixed boundary conditions at the left, right, and bottom boundaries.

9.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
35	20,000	27	0.3	10.5	0.2	Mohr Coulomb Plastic



Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	100000	10000	Yes	No	Not Included	0	0	40	No	No

Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	Apply SSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body	0.027	Isotropic	0.3	20000	No	Mohr-Coulomb	Plastic	0.2	35	10.5	0.2	35	10.5	0	Yes	No	Drained	0.5	Ru	0

Figure 1: RS2 Model Geometry with XFEM Joints

9.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at the common critical SRF of 1.42. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

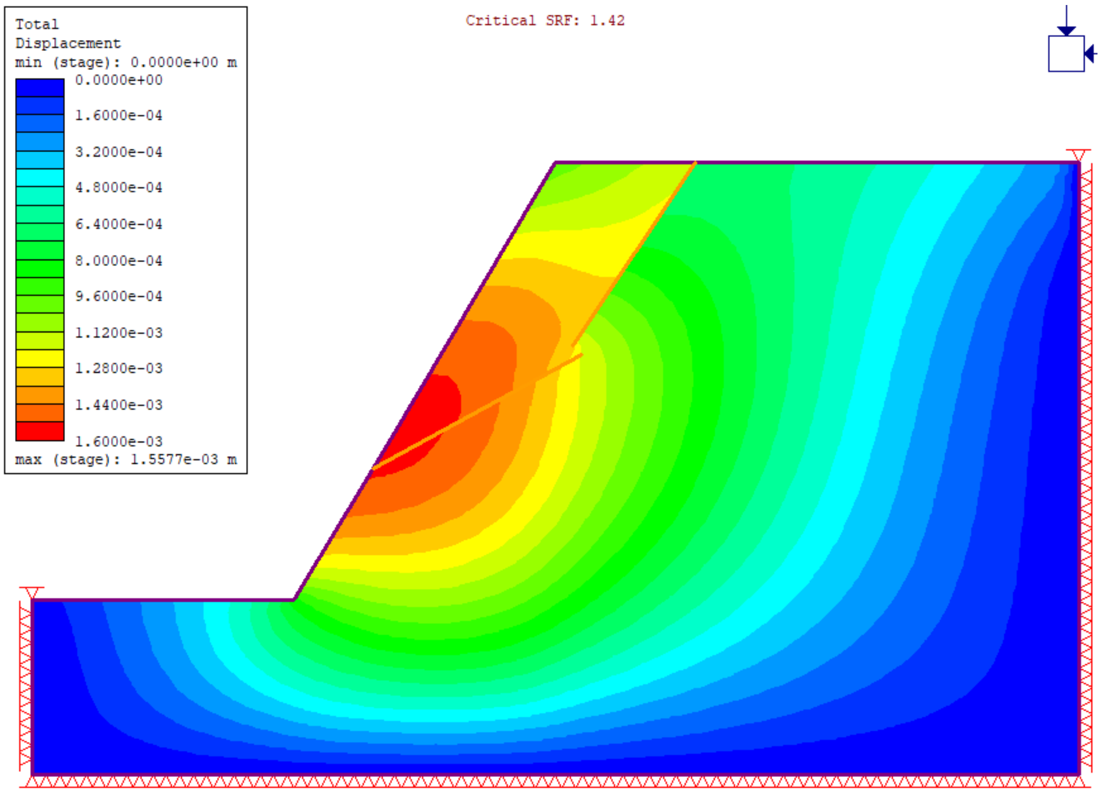


Figure 2: Solid Displacement at Initial Stage: FEM Joints

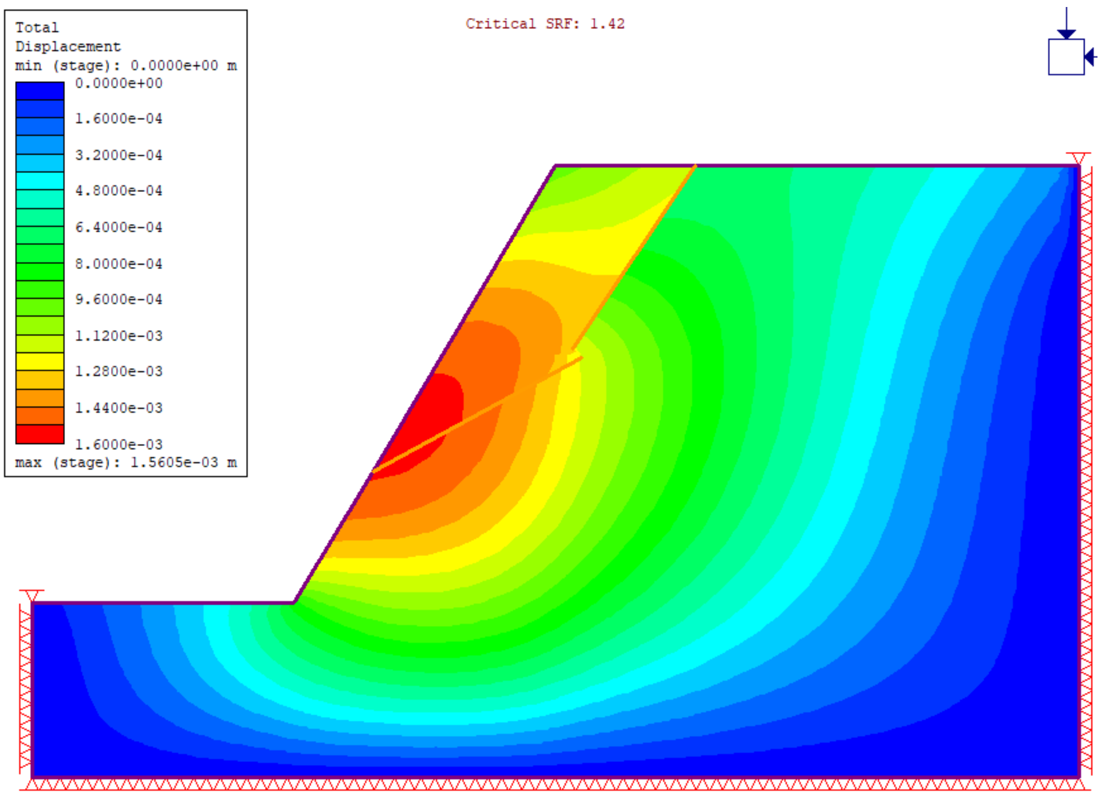


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

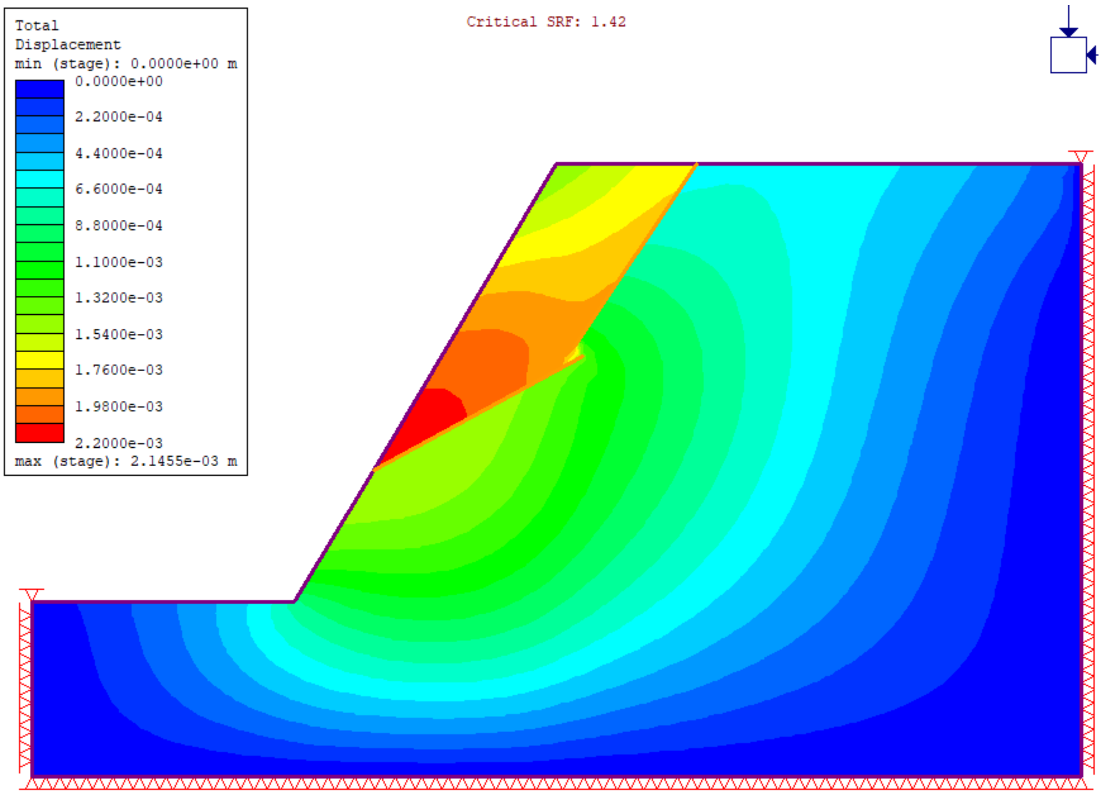


Figure 4: Solid Displacement at SRF of 1.42: FEM Joints

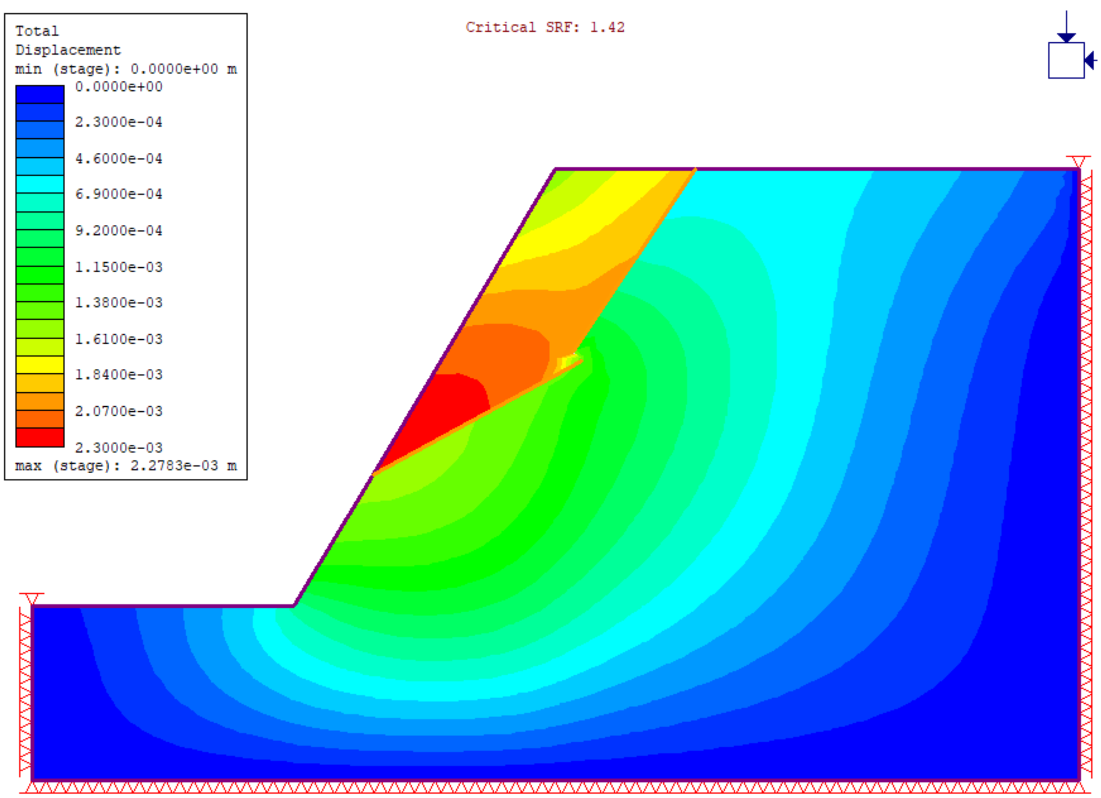


Figure 5: Solid Displacement at SRF of 1.42: XFEM Joints

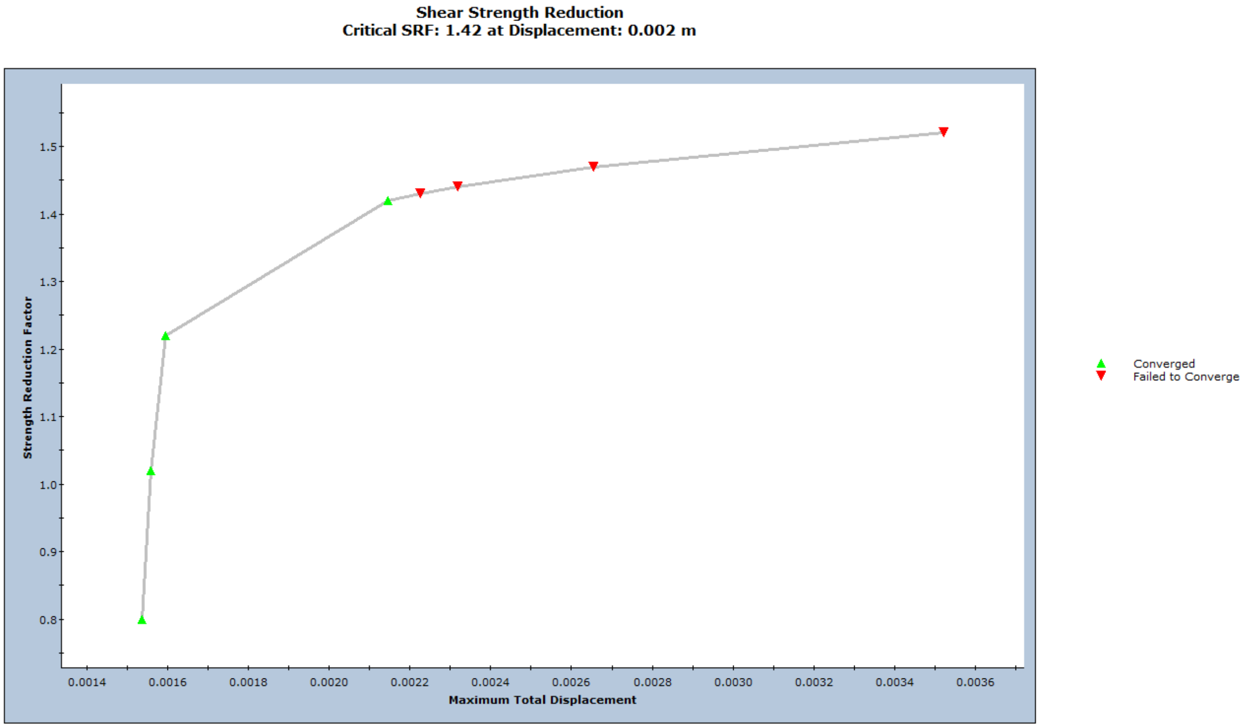


Figure 6: Shear Strength Reduction Plot: FEM Joints

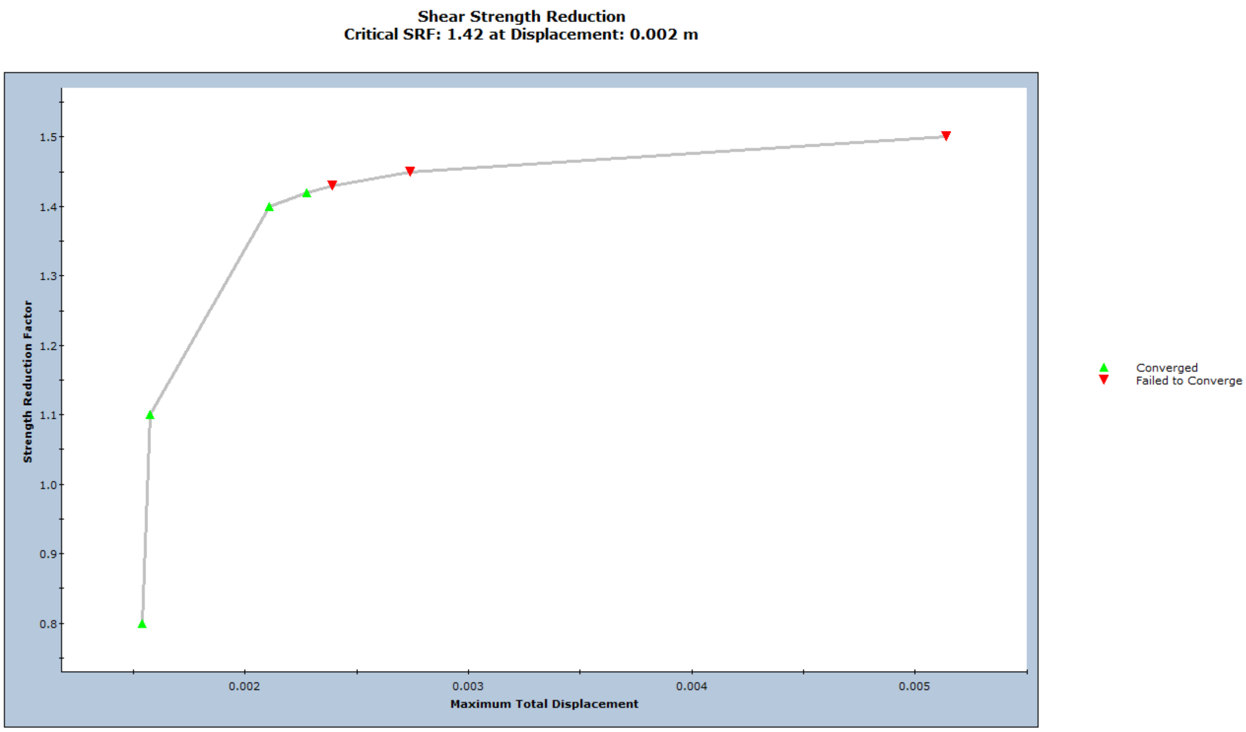


Figure 7: Shear Strength Reduction Plot: XFEM Joints

10 JOINT NETWORK 10

10.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example compared with the tutorial example given in:

Itasca Consulting Group Inc. (2011). A Simple Tutorial - Use of GIIC. In I. C. Inc., UDEC Version 5.0 User's Guide (pp. 2-17 to 2-29). Minneapolis.

10.2 PROBLEM DESCRIPTION

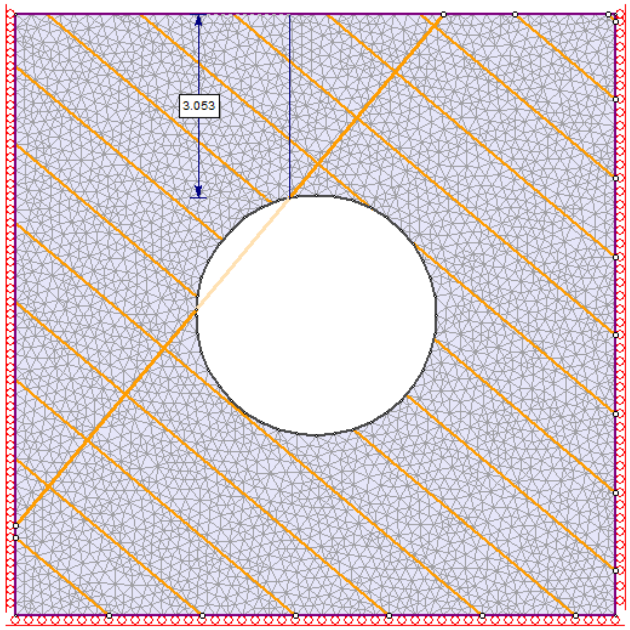
This model is from verification problem #21 from the RS2 Joint Verification Manual, the model was re-meshed for the XFEM portion of the analysis. The model is used to analyze the failure mode in a tunnel at shallow depth.

The model has a tunnel radius of 2m, depth to crown of 3m, bedding angle of 40 degrees, and fault angle of 50 degrees. The left and right boundaries are restrained in the x direction and the bottom boundary is restrained in the y direction.

10.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (MPa)	γ (kN/m3)	υ	c (MPa)	Tensile Strength (MPa)	Material Model
35	17,900	19.62	0.2	10.5	0	Mohr Coulomb Plastic



Material Name	Material Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Poisson's Ratio	Young's Modulus (MPa)	Use Residual Young's Modulus	Failure Criterion	Material Type	Peak Tensile Strength (MPa)	Peak Friction Angle (degrees)	Peak Cohesion (MPa)	Residual Tensile Strength (MPa)	Residual Friction Angle (degrees)	Residual Cohesion (MPa)	Dilation Angle (degrees)	Apply SSR (Shear Strength Reduction)	Use Unsaturated Parameters	Material Behaviour	Porosity Value	Static Water Mode	Ru Value
Material 1		Field Stress and Body Force	0.01962	Isotropic	0.2	17900	No	Mohr-Coulomb	Plastic	0	35	10.5	0	35	10.5	0	Yes	No	Drained	0.5	Ru	0

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Joint 1		Mohr-Coulomb	10000	10000	Yes	No	Not Included	0.1	0.1	40	No	No

Figure 1: RS2 Model Geometry with XFEM Joints

10.4 Results

Figures 2 & 3 compares the displacement results at excavation using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 7, lower than both critical SRF. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

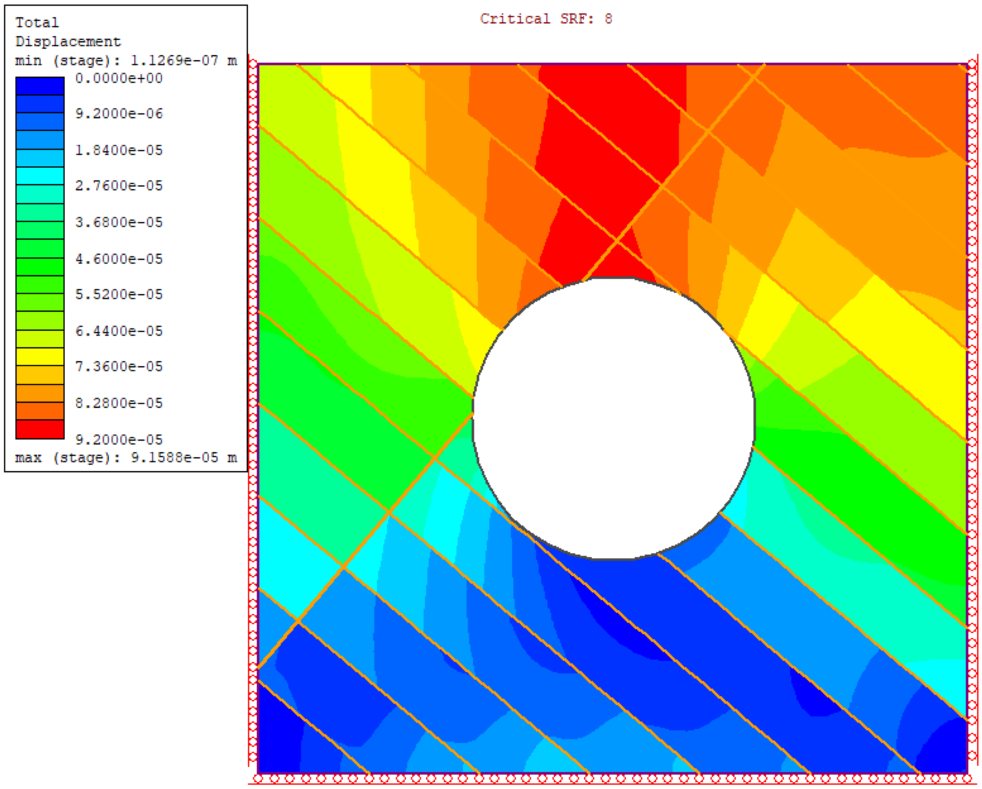


Figure 2: Solid Displacement at Excavation Stage: FEM Joints

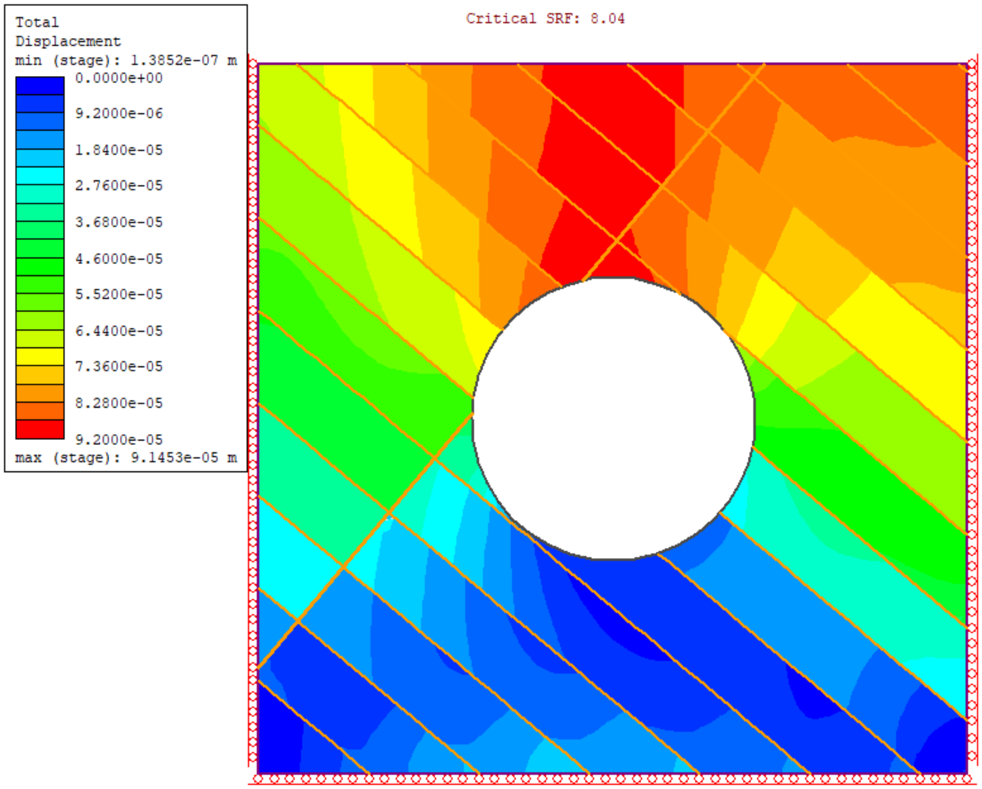


Figure 3: Solid Displacement at Excavation Stage: XFEM Joints

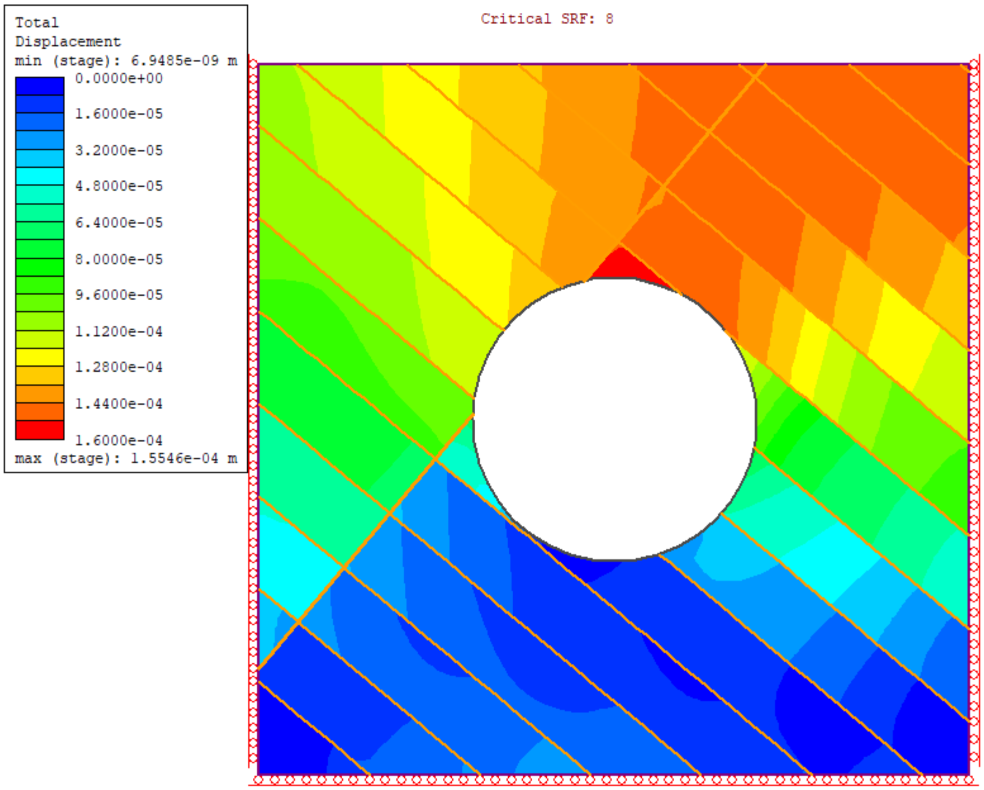


Figure 4: Solid Displacement at SRF of 7: FEM Joints

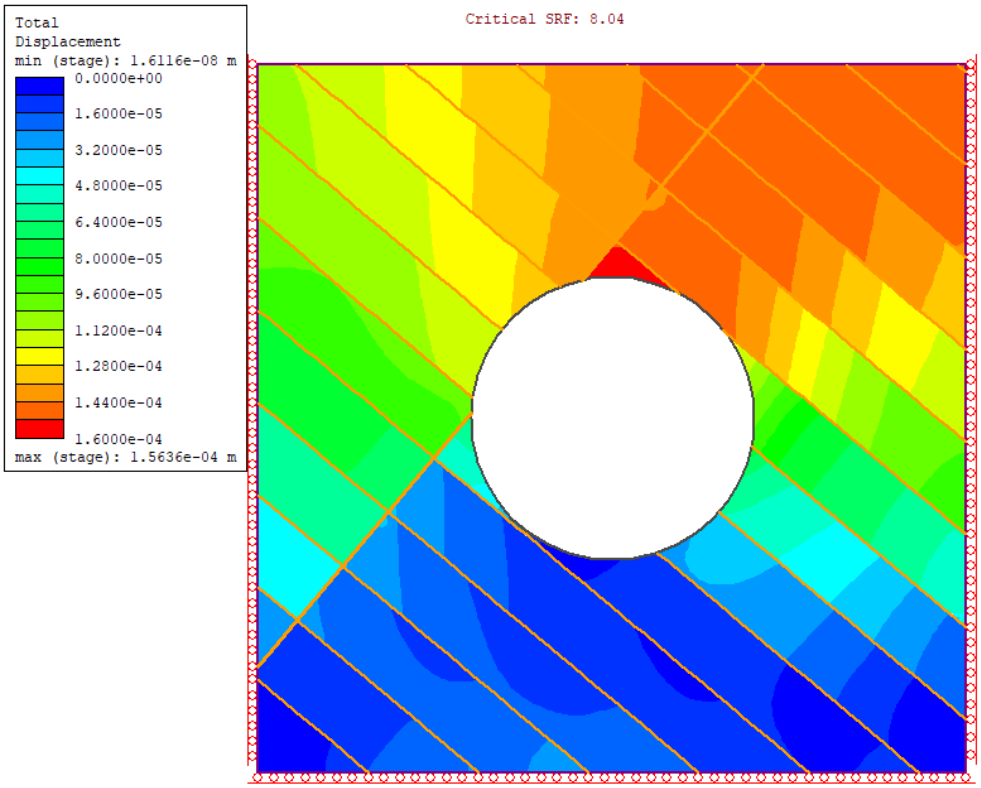


Figure 5: Solid Displacement at SRF of 7: XFEM Joints

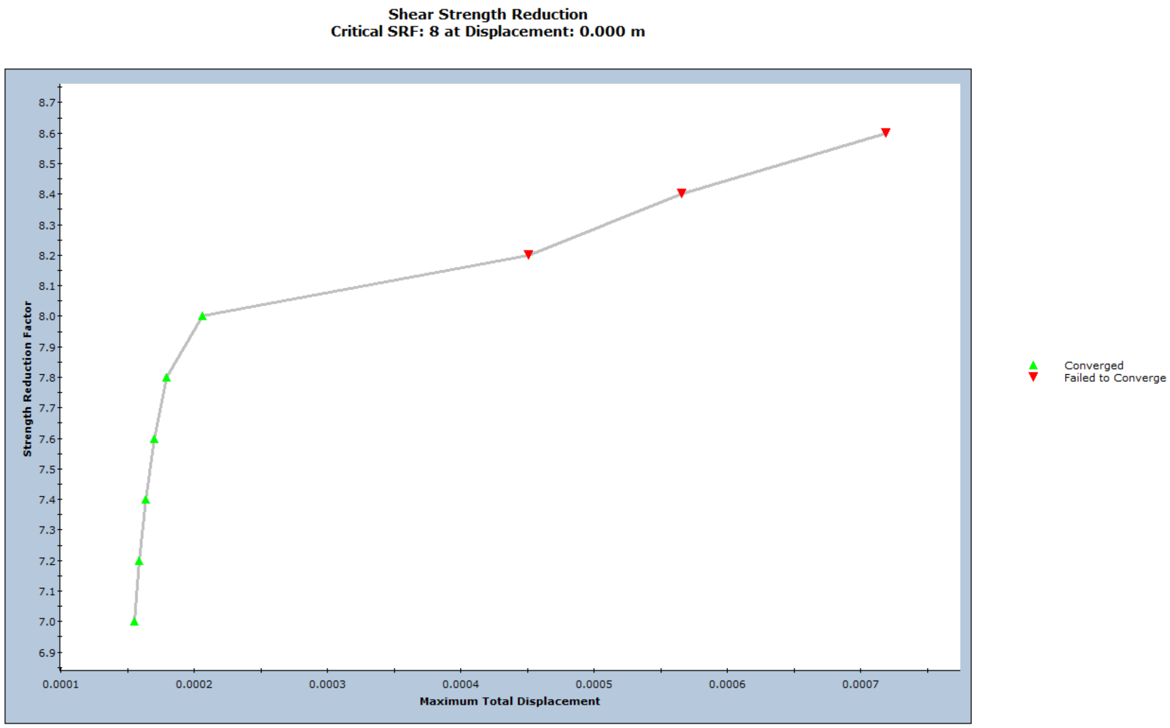


Figure 6: Shear Strength Reduction Plot: FEM Joints

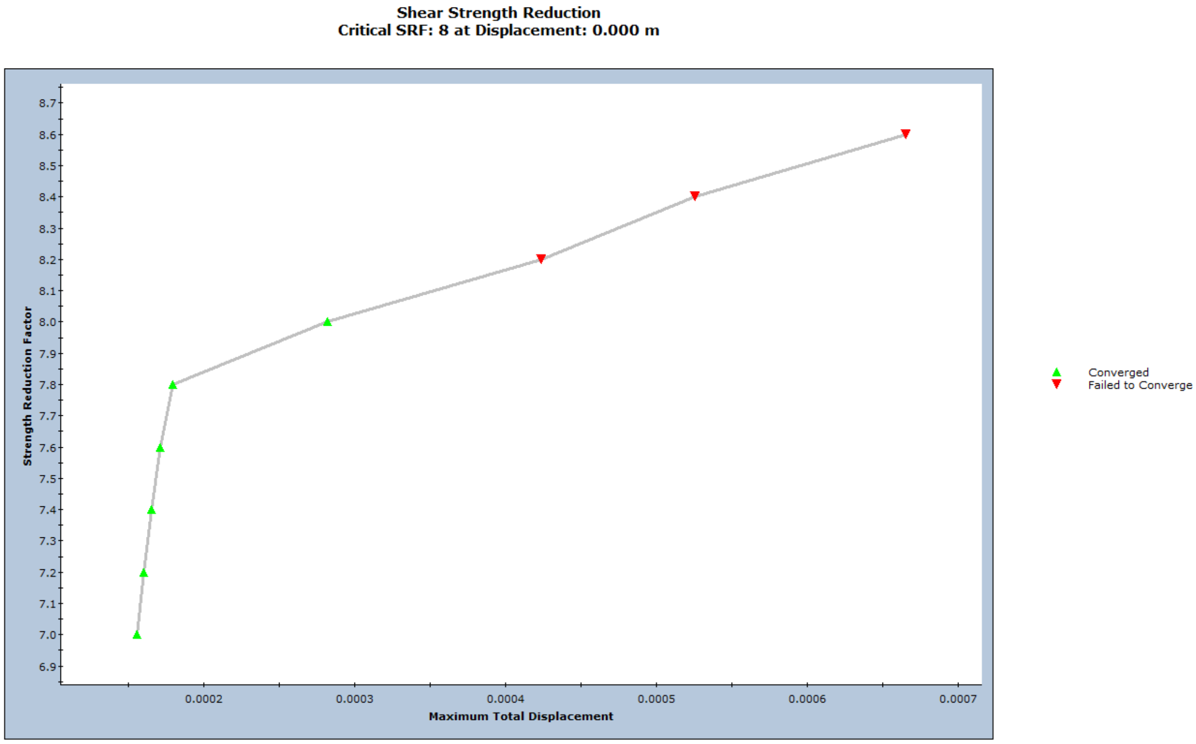


Figure 7: Shear Strength Reduction Plot: XFEM Joints

11 GROUNDWATER SEEPAGE

11.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when interacting with stead state groundwater seepage. This example compared with the explicit joint method in RS2 software by Rocscience Inc.

11.2 PROBLEM DESCRIPTION

This model is built upon the model from the Finite Element Groundwater Seepage RS2 tutorial. As shown in the tutorial, the model is used to simulate stead state groundwater seepage and includes a ponded water load as well as discharge section at the top of the slope.

The model has a slope of 1/2 and only has one stage, the boundary condition is fixed at the left, right, and bottom boundaries. The total head is set at 31.8m at the right boundary and 26m at the ponded water near the left boundary, this induces a simulated groundwater flow.

11.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (kPa)	γ (kN/m3)	υ	c (kPa)	Tensile Strength (kPa)	Material Model
35	20,000	27	0.3	10.5	0	Mohr Coulomb Elastic

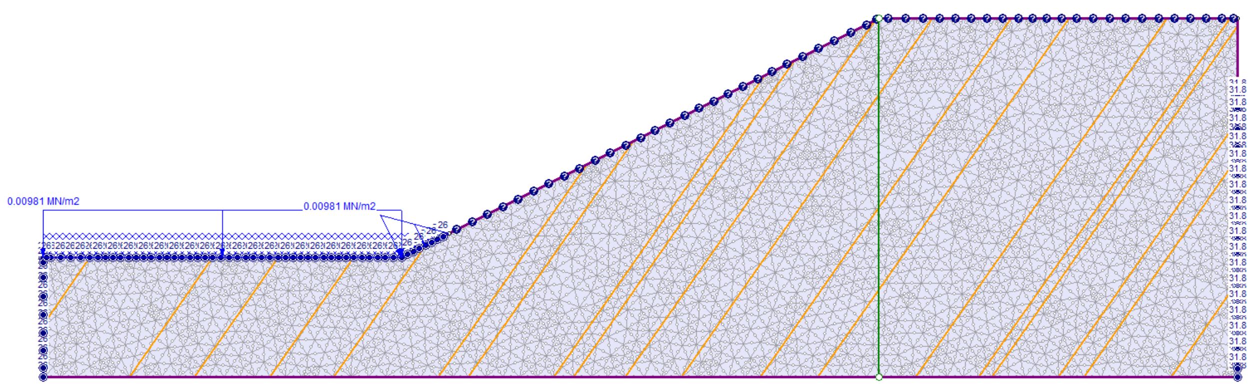


Figure 1: RS2 Model Geometry with XFEM Joints

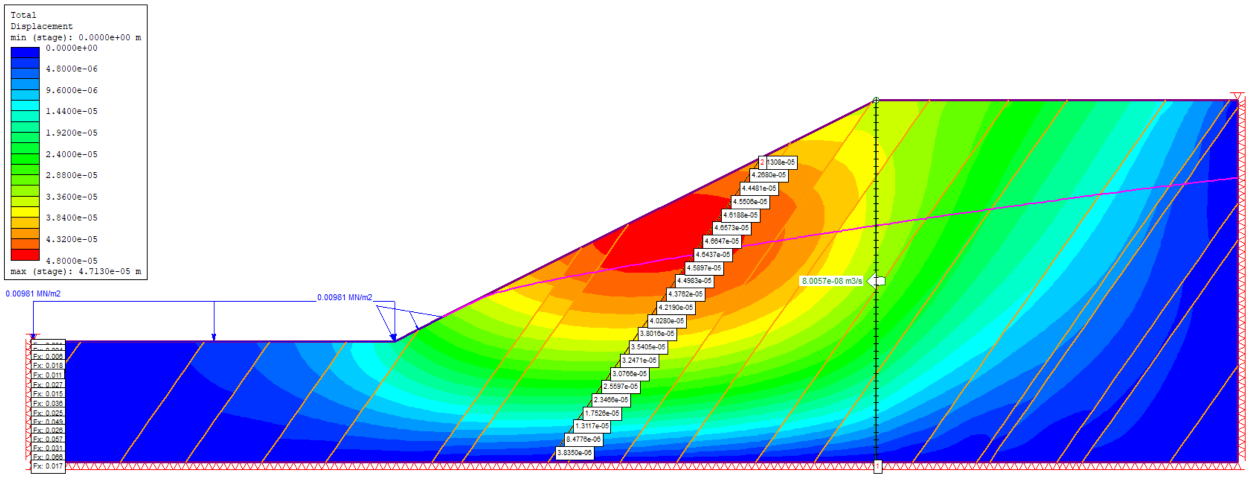


Figure 2: Query Locations

11.4 Results

Figures 2 & 3 compares the displacement results using both XFEM and FEM joints with similar mesh densities, both the displacement and discharge rate at the discharge section matches well between the two joint methods. Figure 4 compares total displacements at a material query line at the discharge section, Figure 5 compares total displacements at a boundary query line on one of the joints, and Figure 6 compares x displacements at a node query at the left boundary. Refer to Figure 2 for the query locations.

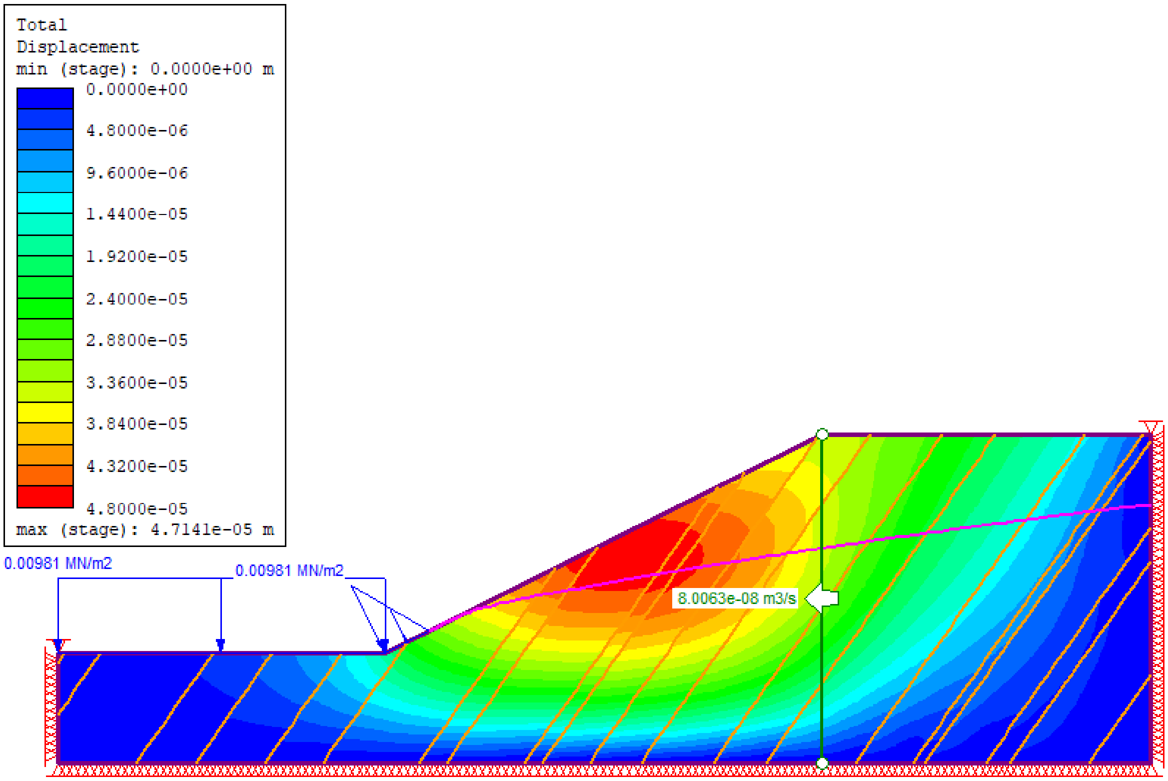


Figure 2: Solid Displacement: FEM Joints

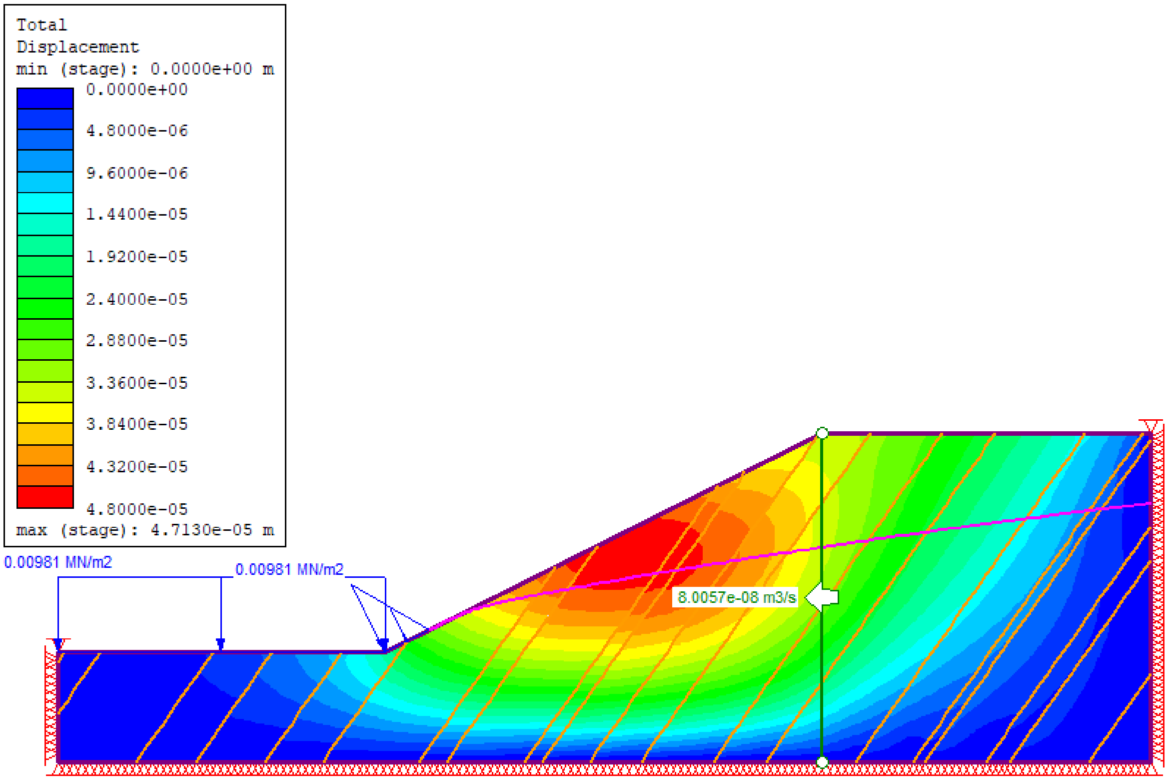


Figure 3: Solid Displacement: XFEM Joints

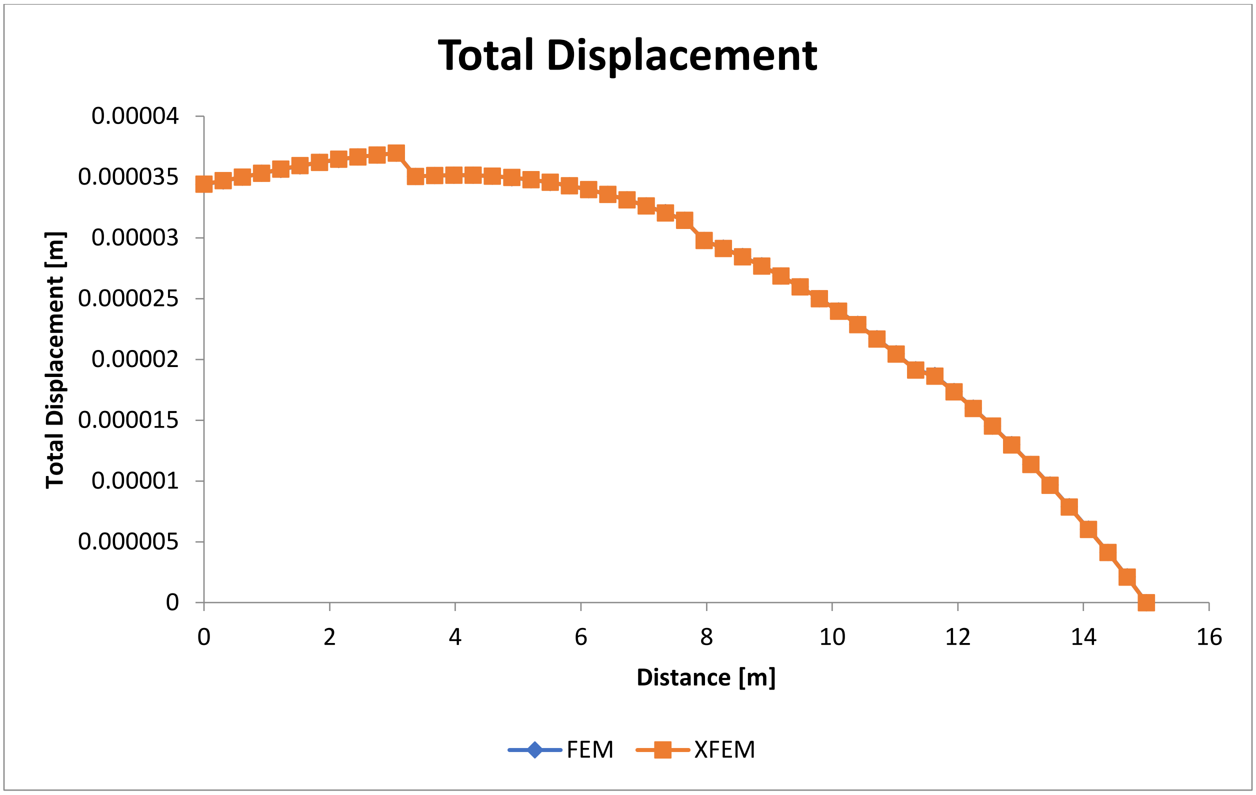


Figure 4: Solid Displacement on Material Query Line at Discharge Section

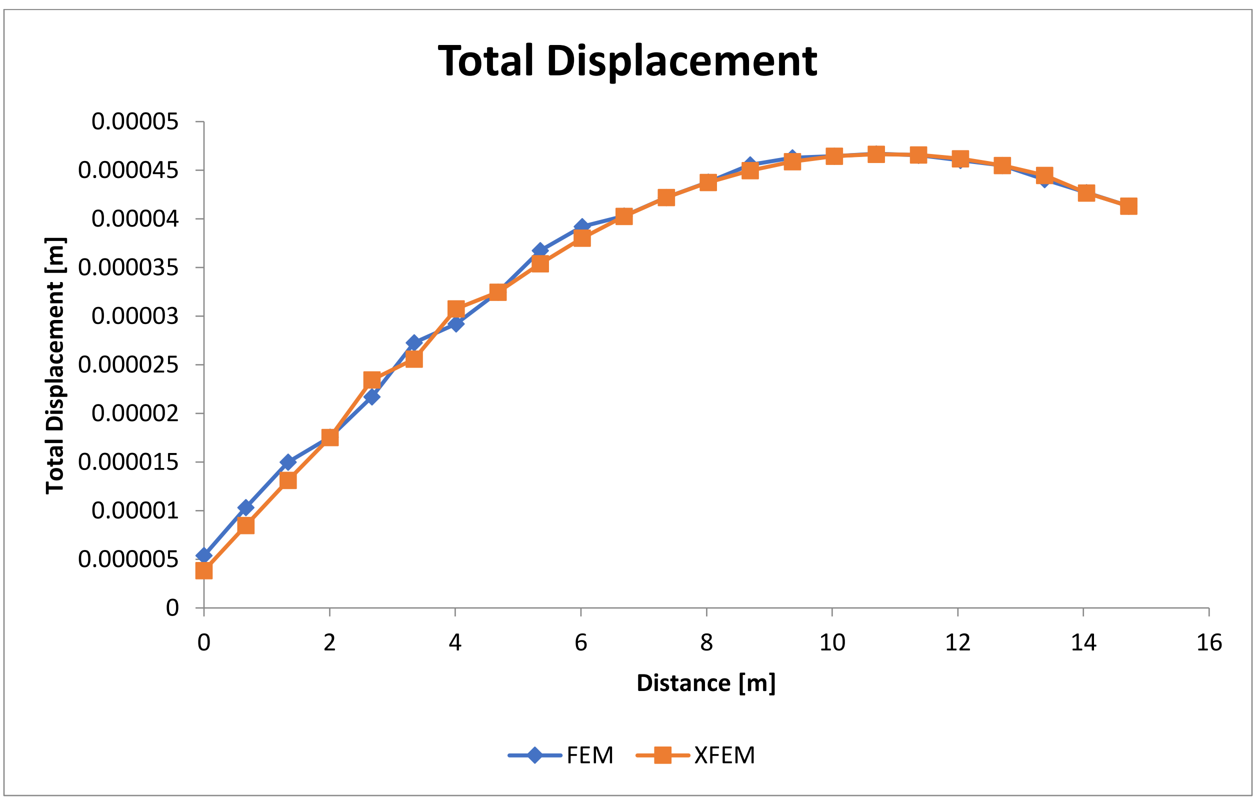


Figure 5: Solid Displacement on Boundary Query Line on a Joint

12 Slope Stability (SSR)

12.1 Introduction

This verification model is used to confirm the proper behaviour of XFEM joints when using shear strength reduction analysis. This example compared with the explicit joint method in RS2 software by Rocscience Inc.

12.2 Problem Description

This model is built from example 7 in the RS2 Slope Stability Verification Manual, a joint network was added in order to verify XFEM joints.

The model has a slope of 1/2 and has fully fixed boundary conditions at the left, right, and bottom boundaries. There is a ponded water load and ground water is modelled using a water pressure grid.

12.3 Geometry and Properties

Table 1: Material Properties

ϕ′ (deg.)	E (kPa)	γ (kN/m3)	υ	c (kPa)	Tensile Strength (kPa)	Residual Tensile Strength (kPa)	Material Model
28	50,000	20	0.4	11	11	0	Mohr Coulomb Plastic

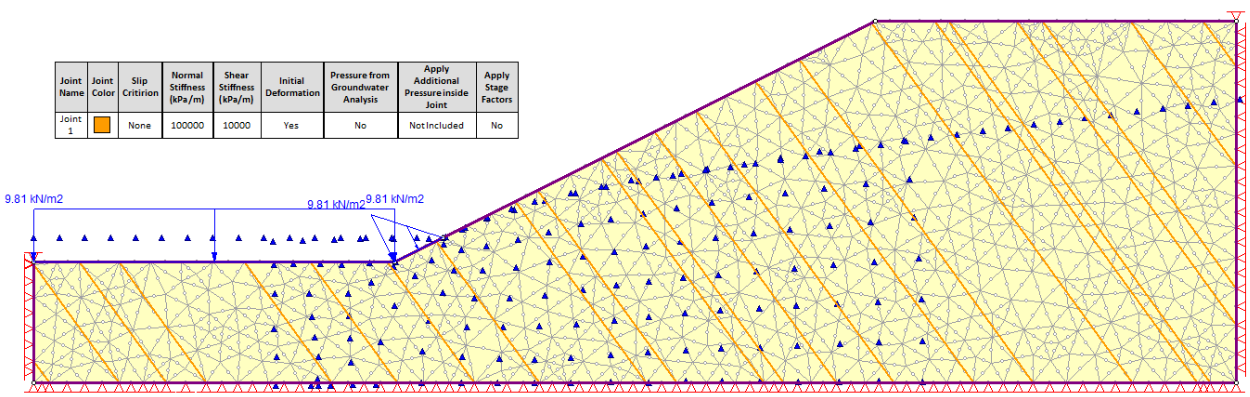


Figure 1: RS2 Model Geometry with XFEM Joints

12.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 shows the similar displacement results between XFEM and FEM jointed models at an SRF of 1.45, lower than the common critical SRF of 1.52. Figures 6 & 7 compares the shear strength reduction plots of the XFEM and FEM models.

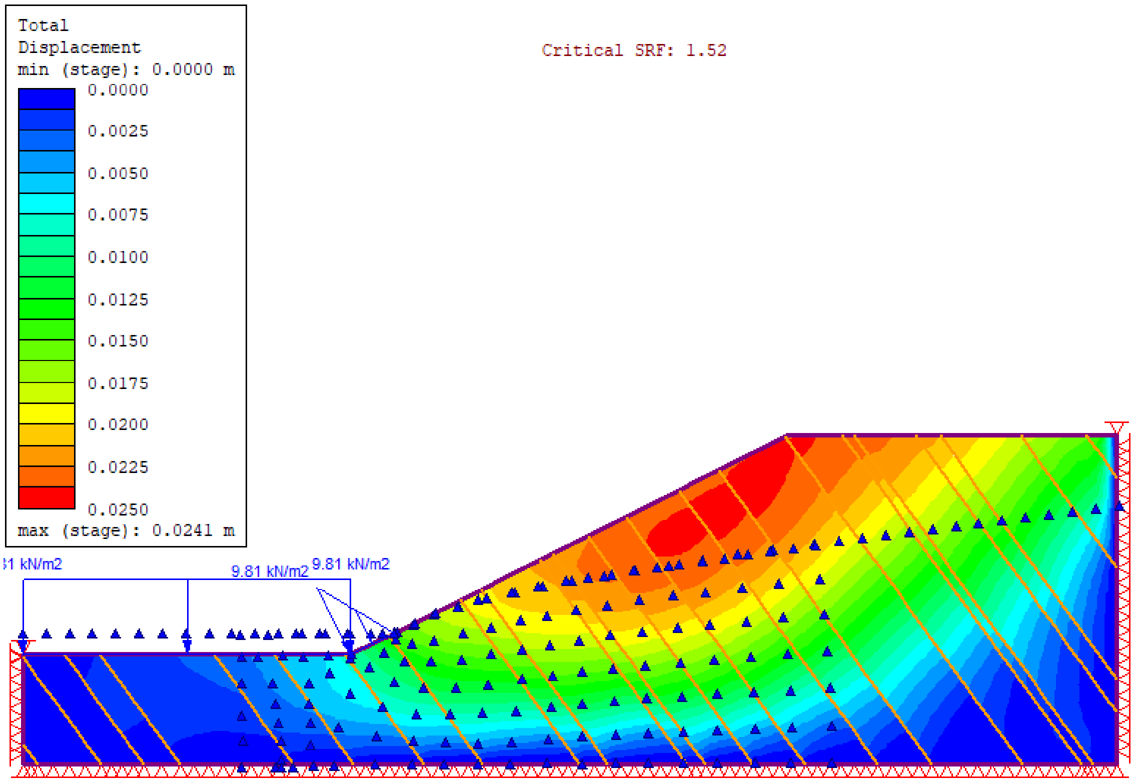


Figure 2: Solid Displacement at Initial Stage: FEM Joints

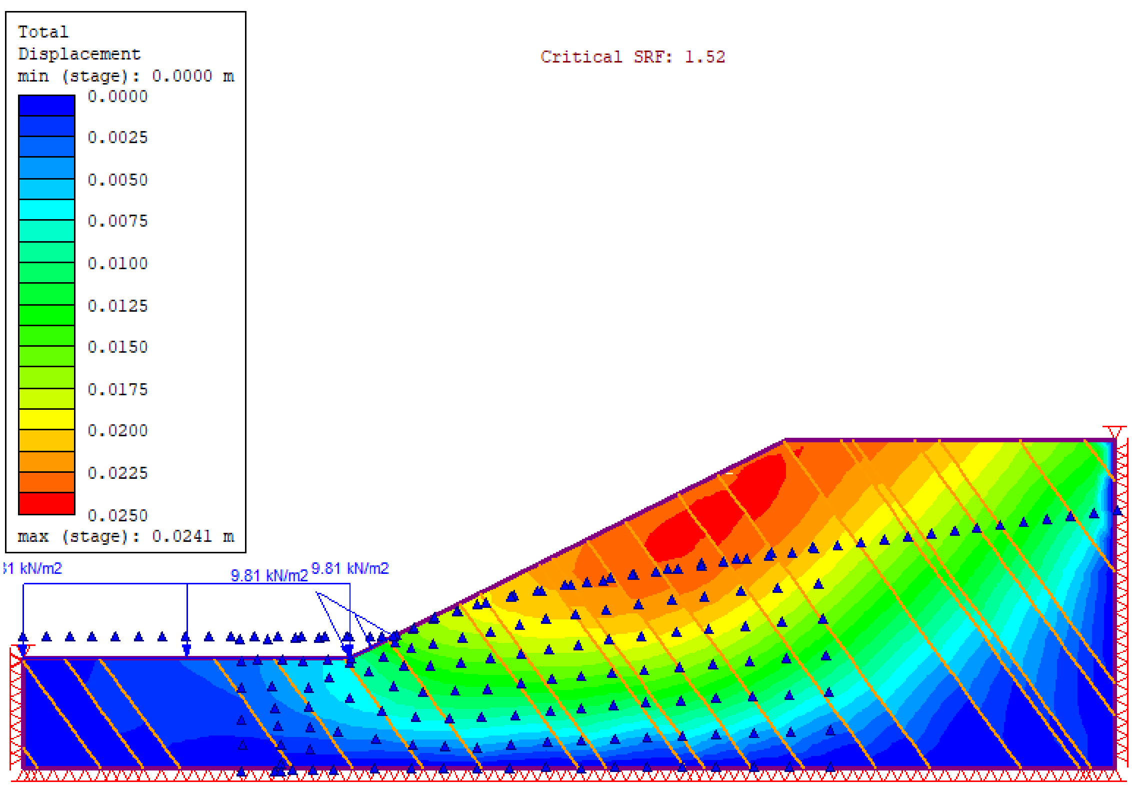


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

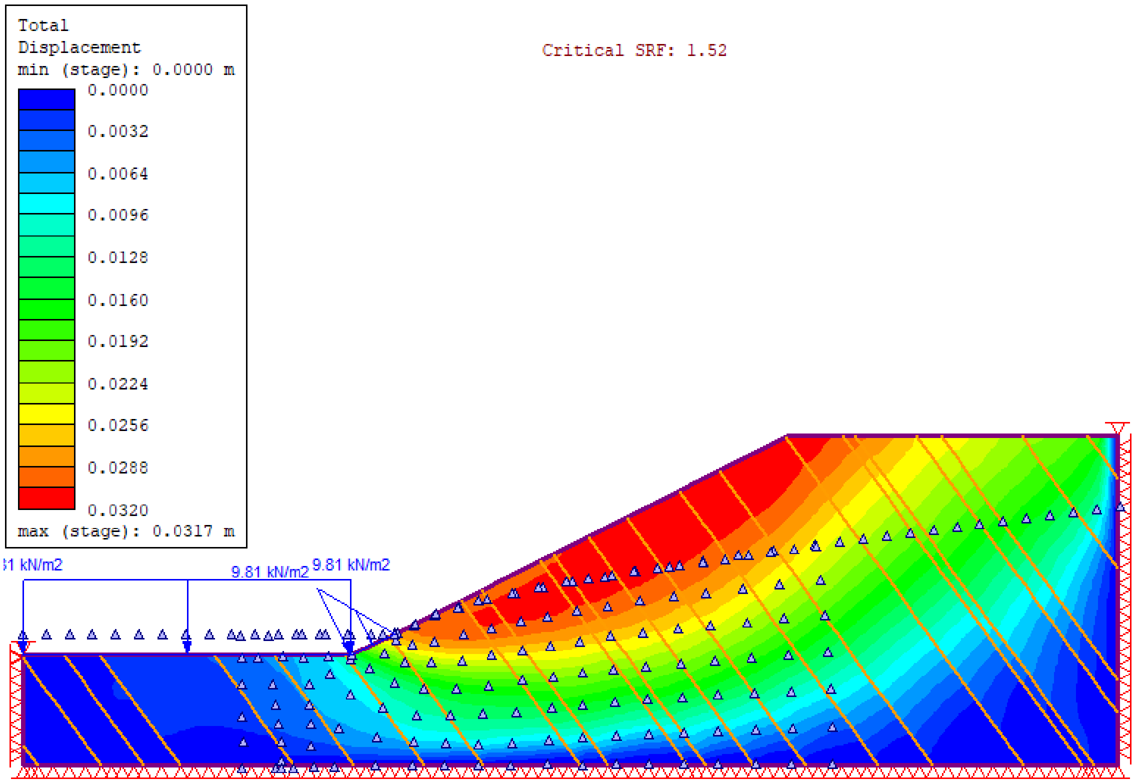


Figure 4: Solid Displacement at SRF of 1.45: FEM Joints

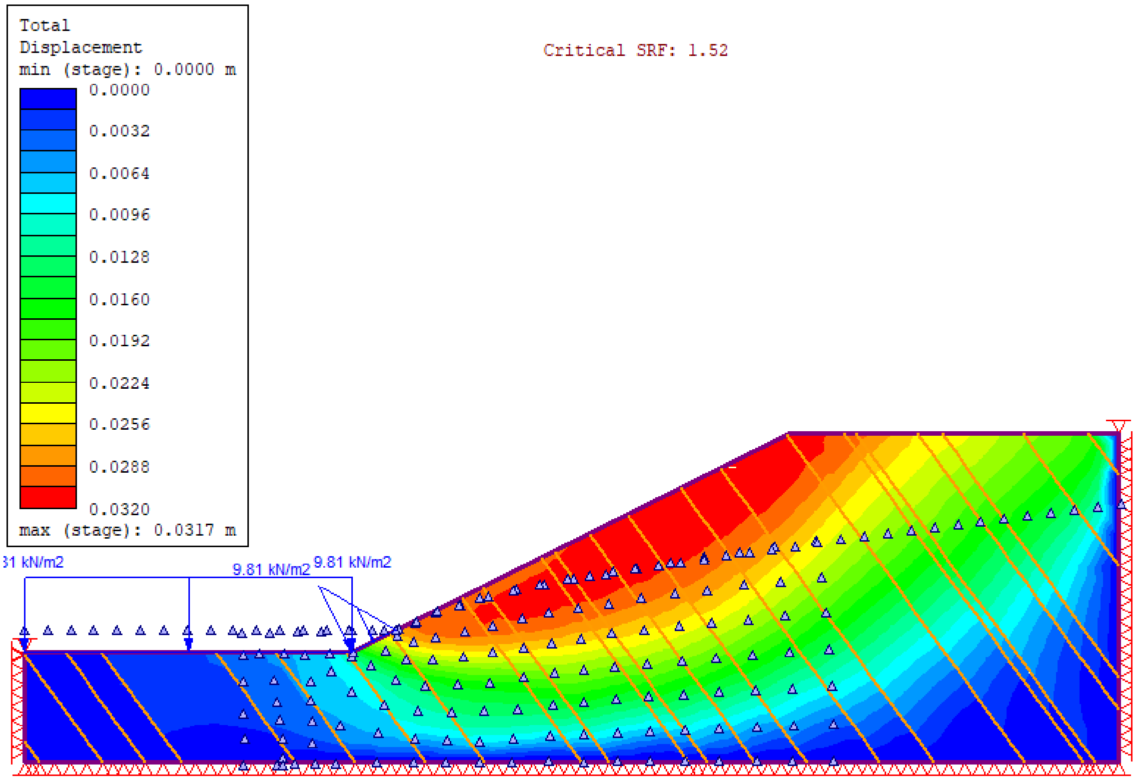


Figure 5: Solid Displacement at SRF of 1.45: XFEM Joints

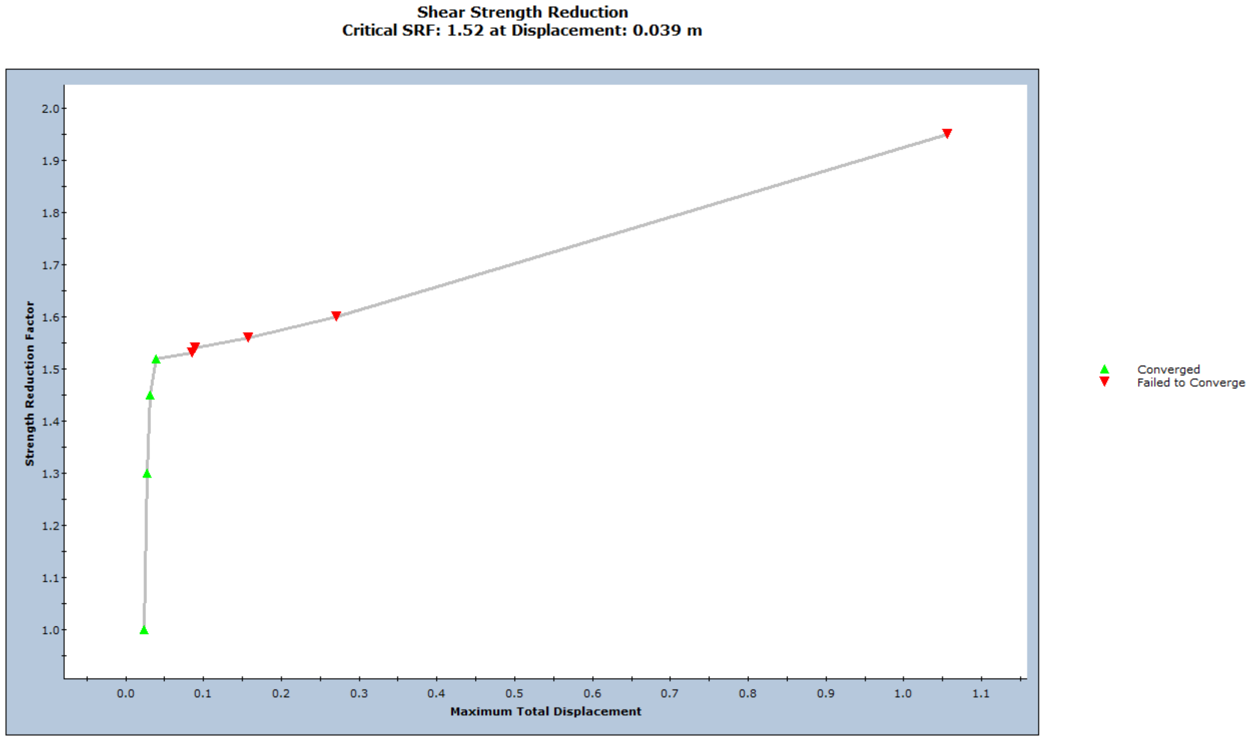


Figure 6: Shear Strength Reduction Plot: FEM Joints

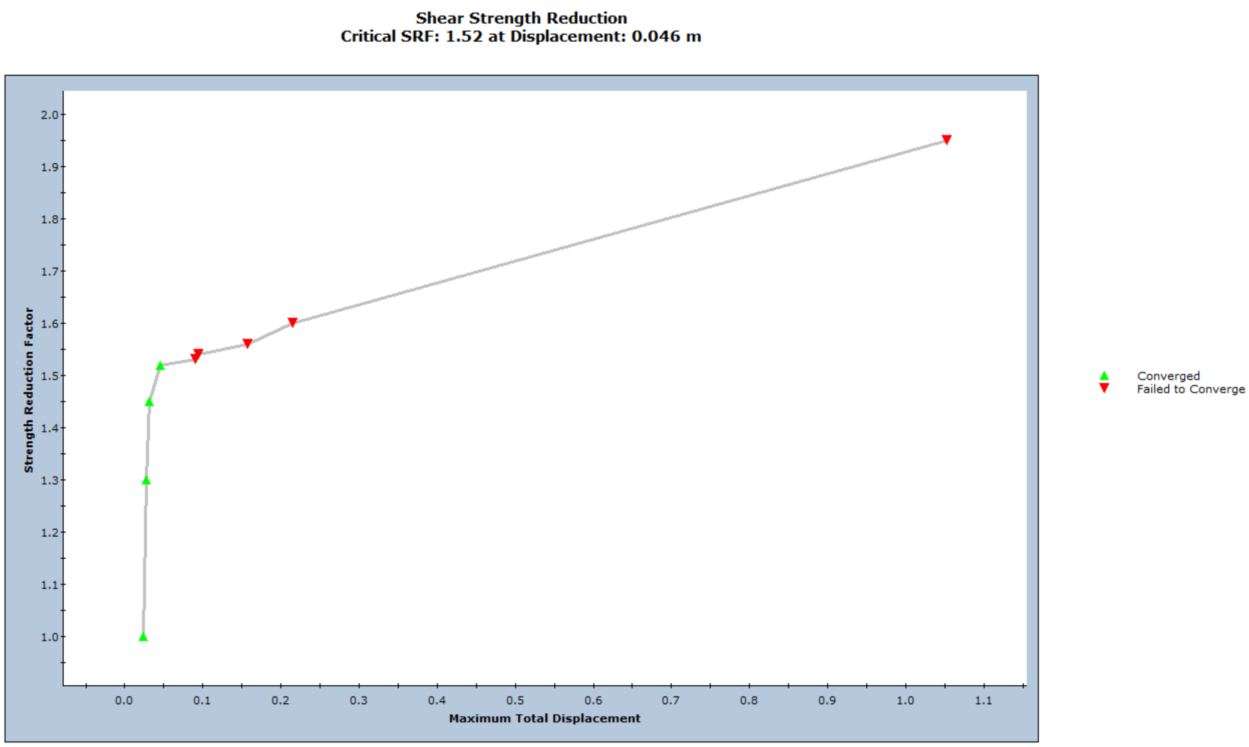


Figure 7: Shear Strength Reduction Plot: XFEM Joints

13 **Wick Drains**

13.1 Introduction

This verification model is used to confirm the proper behaviour of XFEM joints interacting with wick drains. This example compared with the explicit joint method in RS2 software by Rocscience Inc.

13.2 Problem Description

This model is built from the Wick Drains RS2 Tutorial model, a joint network was added in order to verify XFEM joints.

The model uses transient FEA groundwater analysis, x displacements are restricted at the left and right boundaries with a fully fixed bottom boundary. An embankment is built up over 14 stages, with wick drains installed right after the initial stage.

13.3 Geometry and Properties

Table 1: Material Properties

Soil Layer	ϕ' (deg.)	E (kPa)	γ (kN/m3)	υ	c (kPa)	Tensile Strength (kPa)	Dilation Angle (deg.)	Material Model
Embankment Fill	35	20,000	18	0.2	3	3	-	Mohr Coulomb Elastic
Silty Sand I	32	25,000	18	0.3	0.25	0.25	0	Mohr Coulomb Plastic
Silty Sand II	33	20,000	18	0.2	0.1	0	0	Mohr Coulomb Plastic
Dense Silty Sand	33	25,000	18	0.2	0.1	0	0	Mohr Coulomb Plastic

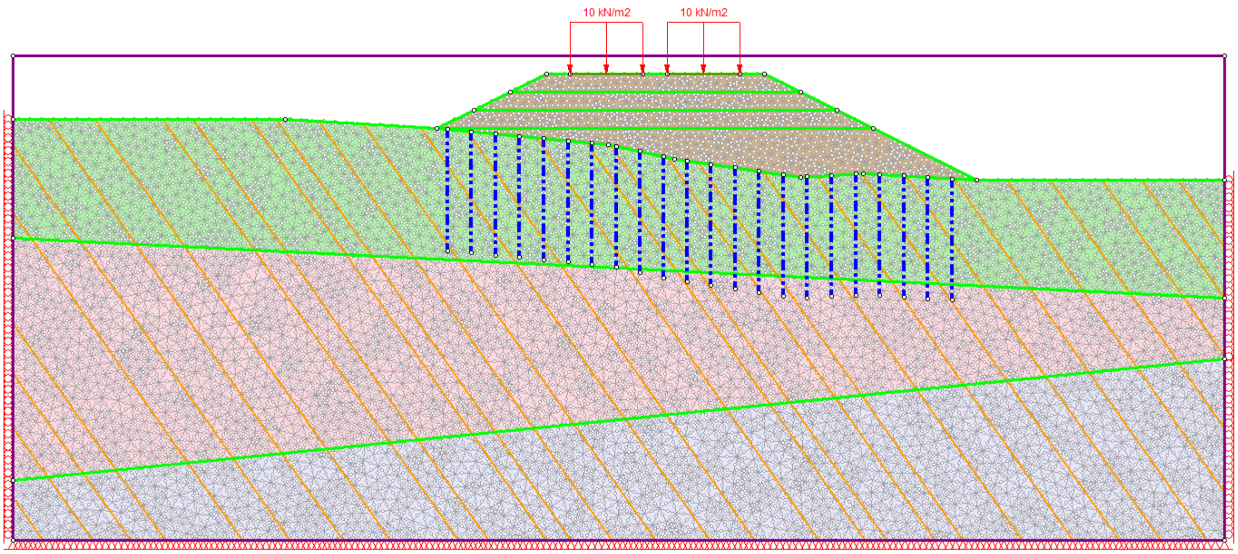


Figure 1: RS2 Model Geometry with XFEM Joints

13.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 compares displacement results at stage 7 and Figures 6 & 7 compares displacement results at the final stage.

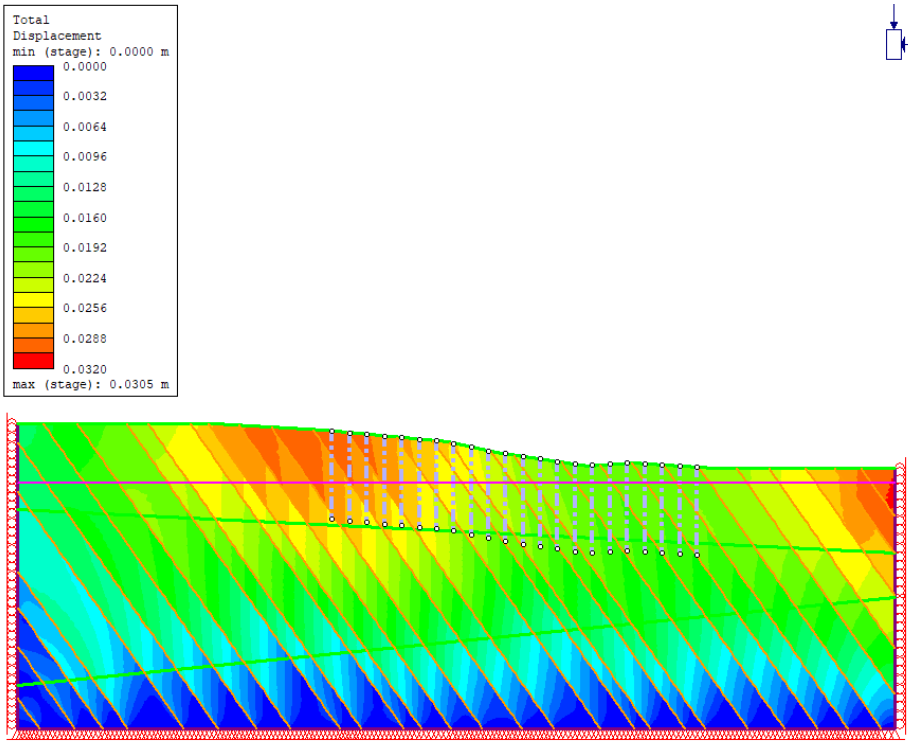


Figure 2: Solid Displacement at Initial Stage: FEM Joints

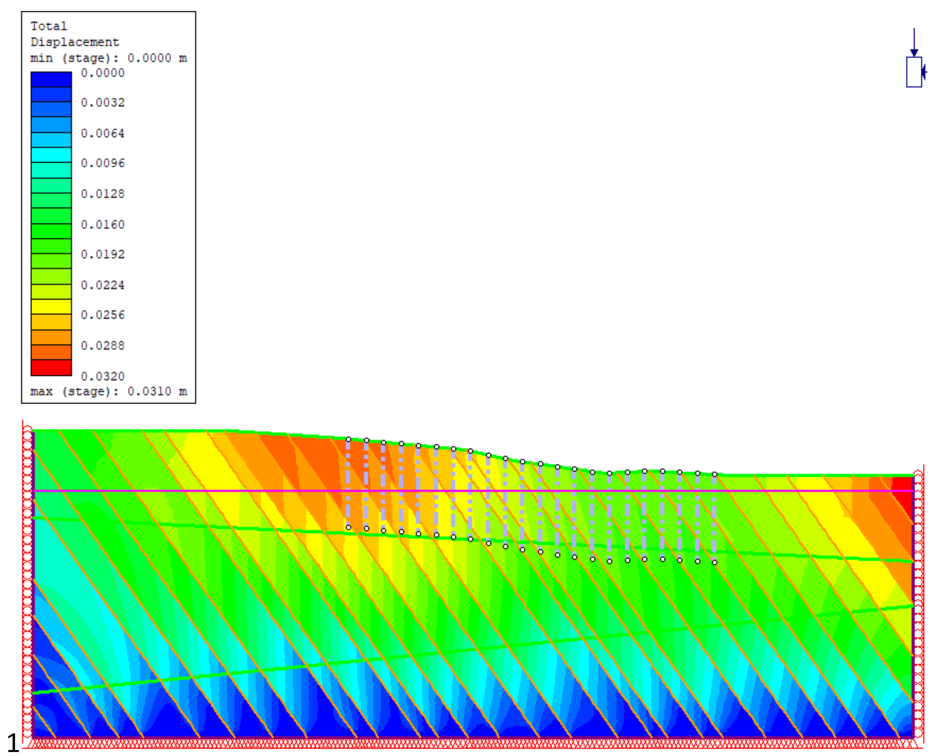


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

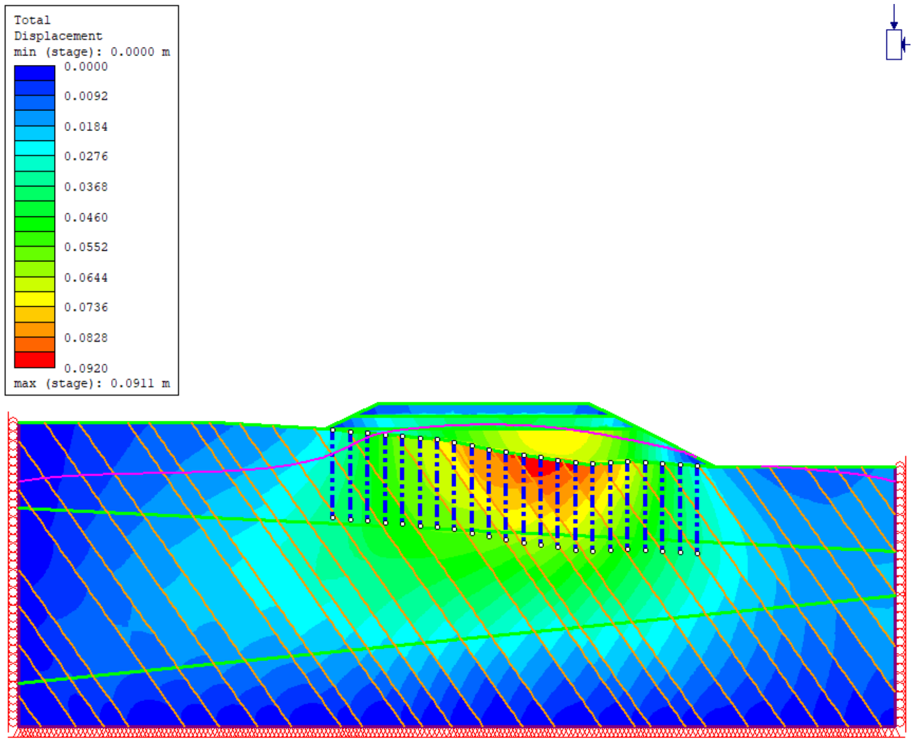


Figure 4: Solid Displacement at Stage 7: FEM Joints

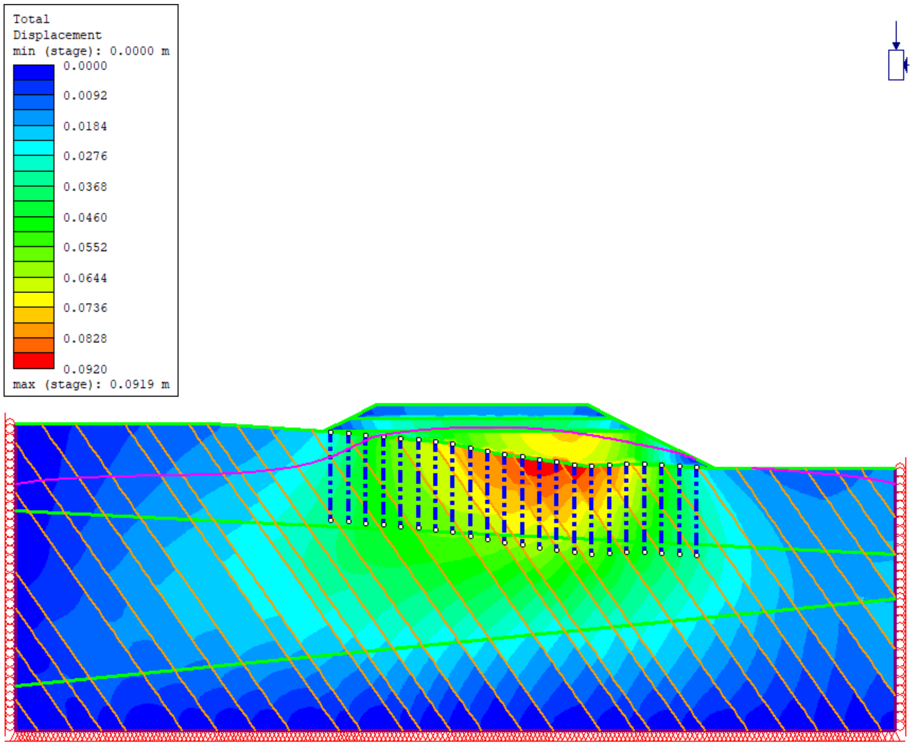


Figure 5: Solid Displacement at Stage 7: XFEM Joints

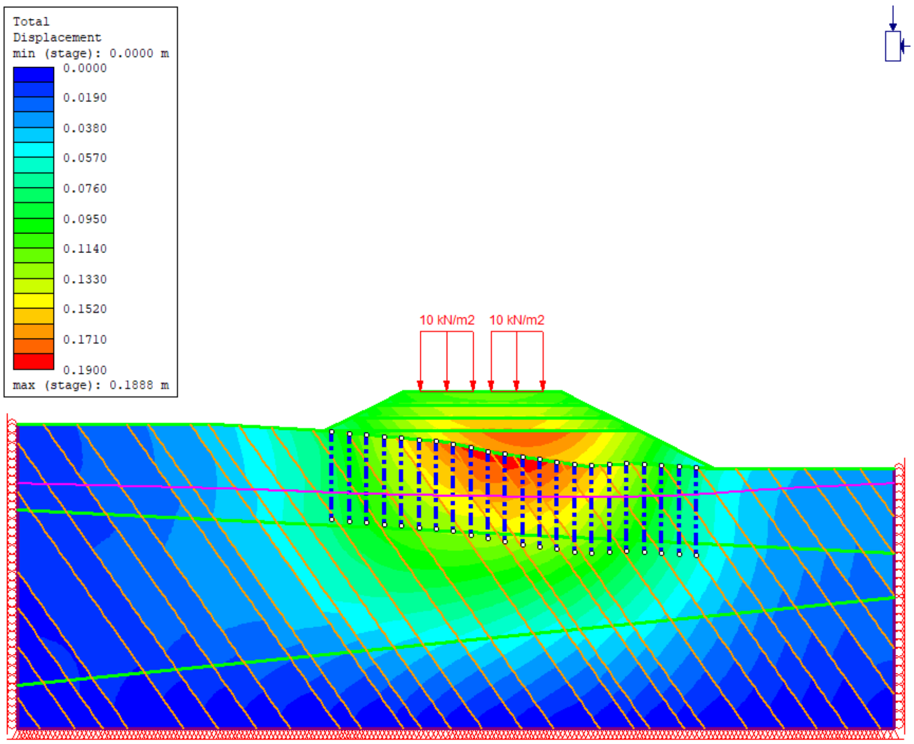


Figure 6: Solid Displacement at Stage 14: FEM Joints

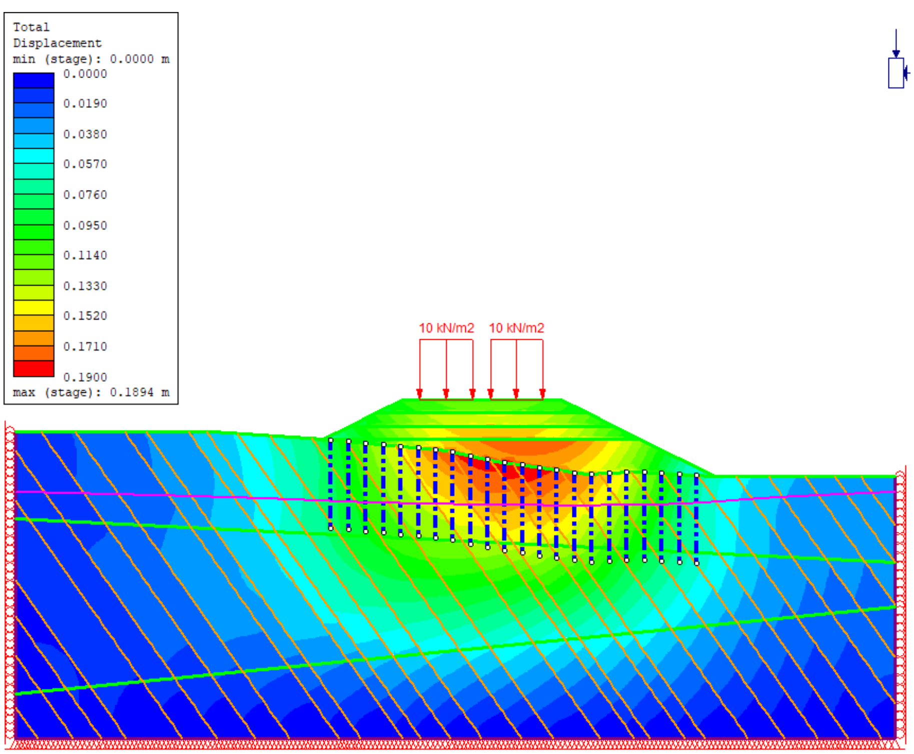


Figure 7: Solid Displacement at Stage 14: XFEM Joints

14 DYNAMIC SLOPE STABILITY

14.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints under dynamic loading conditions. This example compared with the explicit joint method in RS2 software by Rocscience Inc.

14.2 PROBLEM DESCRIPTION

This model is built from the model in the Dynamic Slope Analysis (Part D) RS2 tutorial and it simulates the seismic loading of a slope using earthquake data from the 1985 Mexico City Earthquake. As shown in the tutorial, the earthquake data has been deconvoluted and filtered.

The model has a slope of 2/3 and during the initial stage, has fix in x-displacement at the left and right and fully fixed at the bottom boundary conditions assigned. In the dynamic stages, the left and right boundaries are assigned the transmit boundary condition with the bottom boundary assigned the absorb boundary condition. The dynamic earthquake load is applied as velocity on the bottom boundary at dynamic stages.

14.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

ϕ' (deg.)	E (kPa)	γ (kN/m3)	υ	c (kPa)	Tensile Strength (kPa)	Material Model
38	100,000	19	0.4	5	5	Mohr Coulomb Plastic

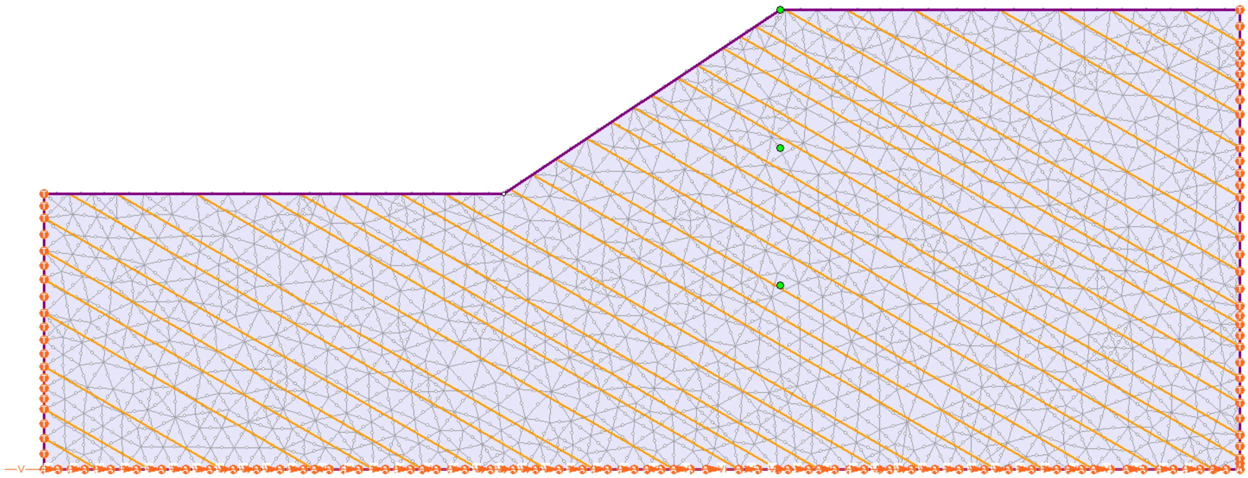


Figure 1: RS2 Model Geometry with XFEM Joints

14.4 Results

Figures 2 & 3 compares the displacement results at the initial stage using both XFEM and FEM joints with similar mesh densities. Figures 4 & 5 demonstrates the agreement between XFEM and FEM jointed models at dynamic time query locations for both displacement and velocity.

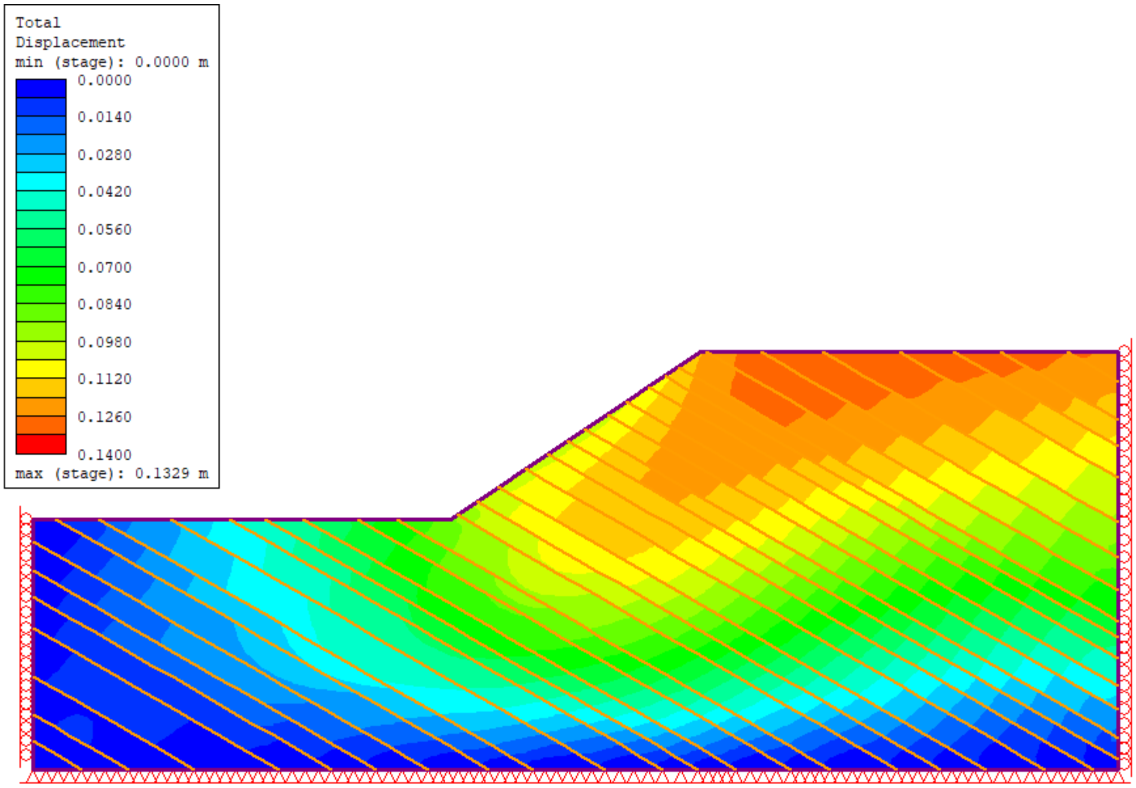


Figure 2: Solid Displacement at Initial Stage: FEM Joints

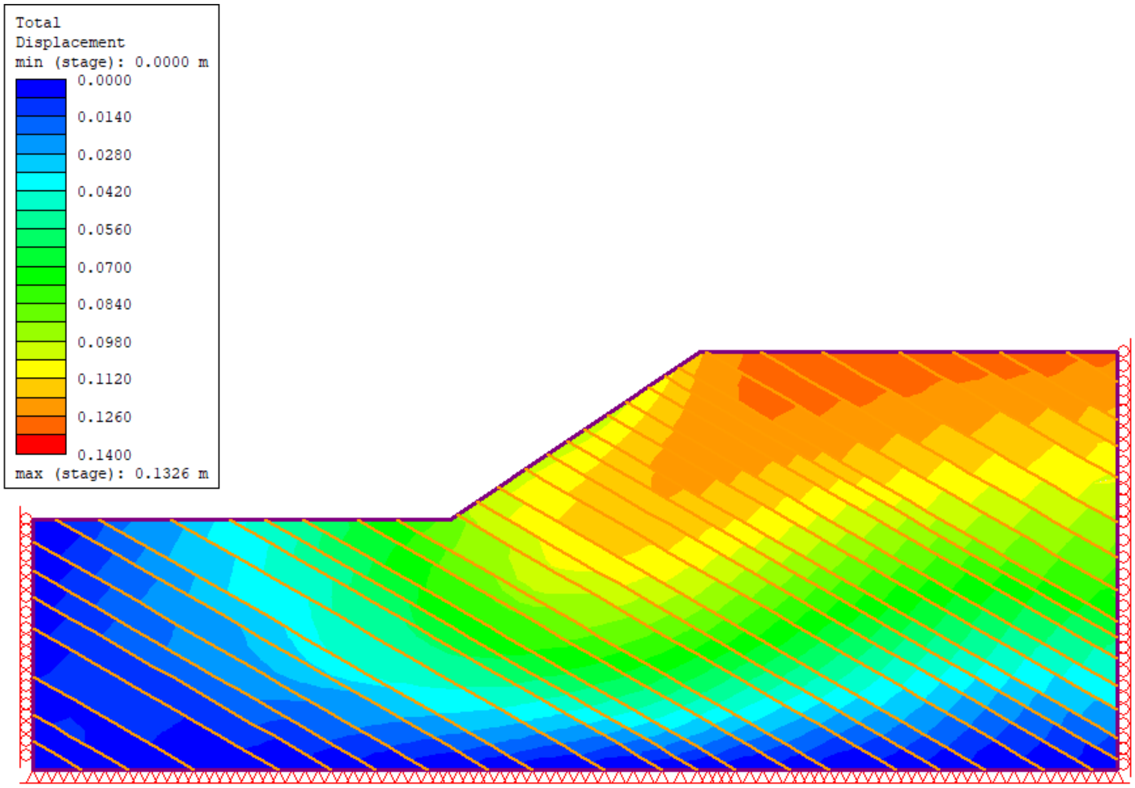


Figure 3: Solid Displacement at Initial Stage: XFEM Joints

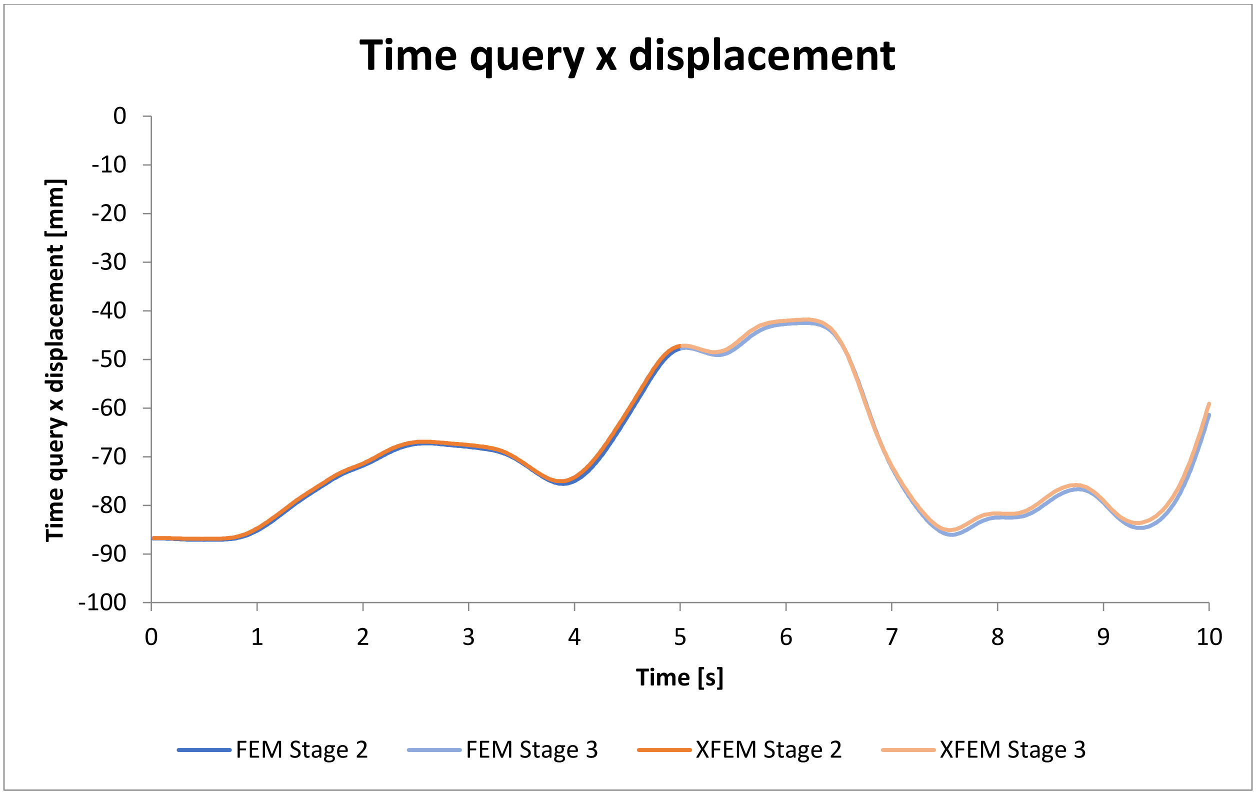


Figure 4: Time Query 15m Below Ground Surface: X-Displacement

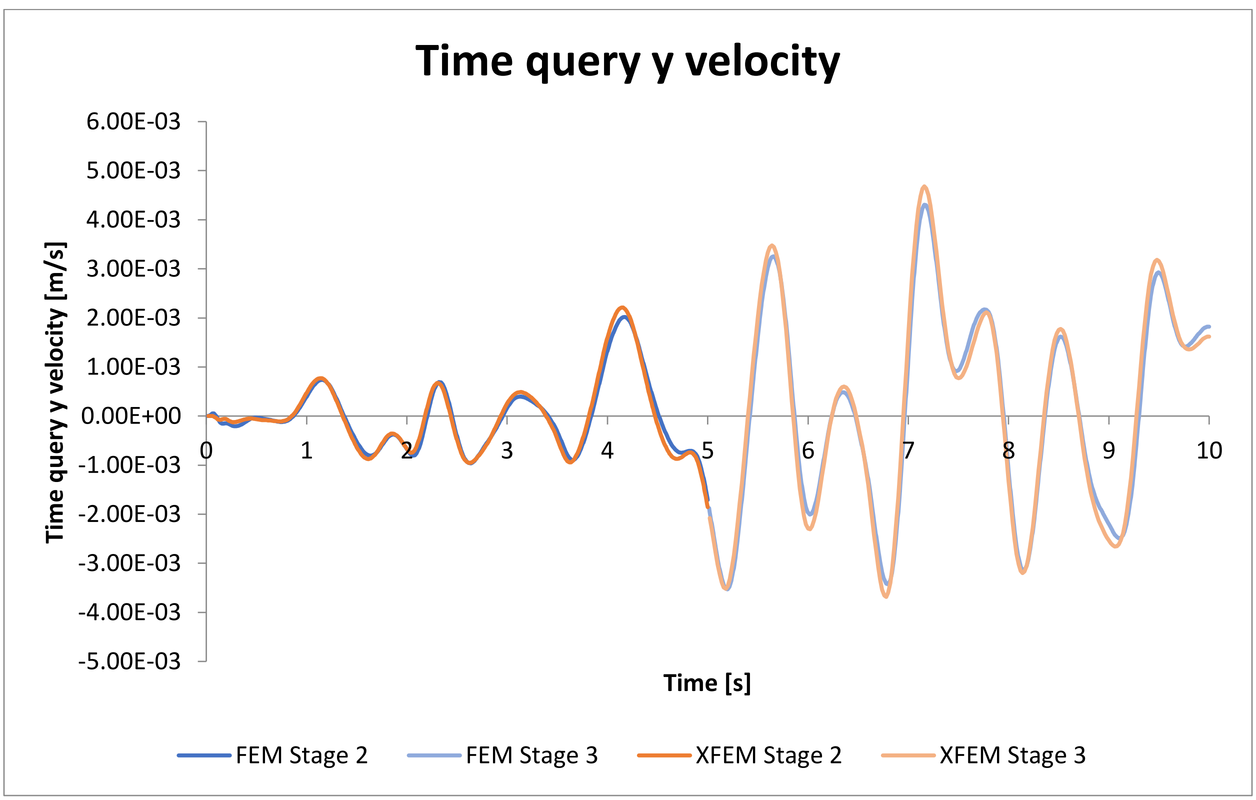


Figure 5: Time Query 15m Below Ground Surface: Y-Velocity

15 HARMONIC SHEAR WAVE

15.1 INTRODUCTION

This verification is picked from "RS2 dynamic verification" to check the shear wave propagation in a homogenous media, crossed by XFEM joint in the middle.

15.2 PROBLEM DESCRIPTION

A joint boundary is used to simulate the discontinuity in the middle of the media with elastic material. four joint boundary cohesions are assigned to four model to simulate the non-slip surface (2.5MPa) and slip surface (0.02MPa, 0.1MPa and 0.5MPa). The friction angle of the joint boundaries is equal to zero. Absorb boundary condition is assigned to the top and the bottom boundaries, vertical restraints are also assigned to the two lateral sides of the model as shown in Figure 1(a). A shear wave in terms of frequency w and time t is given as sin (wt) and applied in the horizontal direction at the bottom boundary of the models. Please note that the magnitude of the shear wave needs to be doubled in this case, taking consideration of two nonreflective boundary.

15.3 GEOMETRY AND PROPERTIES

E (kPa)	γ (kN/m3)	υ
100,000	19	0.4

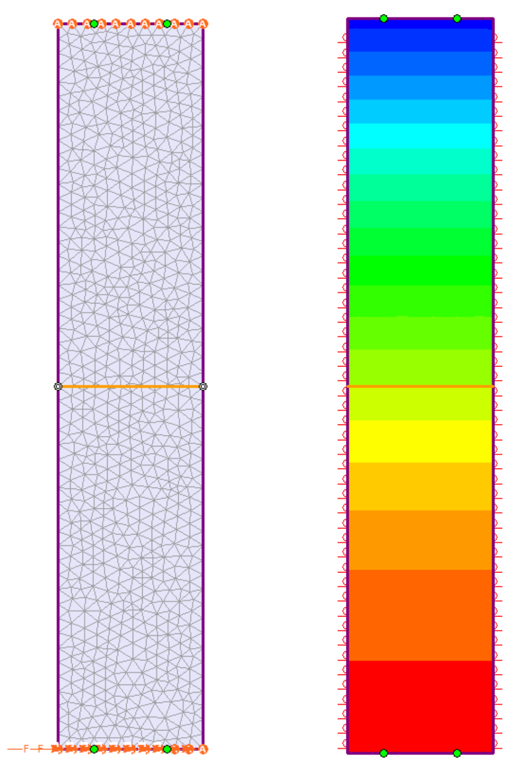


Figure 1(a) geometry of the model, (b) Horizontal displacement for non-slip case

15.4 Results

In Figure 2(a-d) the variation of horizontal displacement and velocity for a point on top and the bottom of the model is compared with RS2 explicit joint. As it can be seen, by reducing the cohesion of the joint, the amplitude of displacement and velocity for the top side is reduced. This phenomenon caused by more energy dissipation by joint.

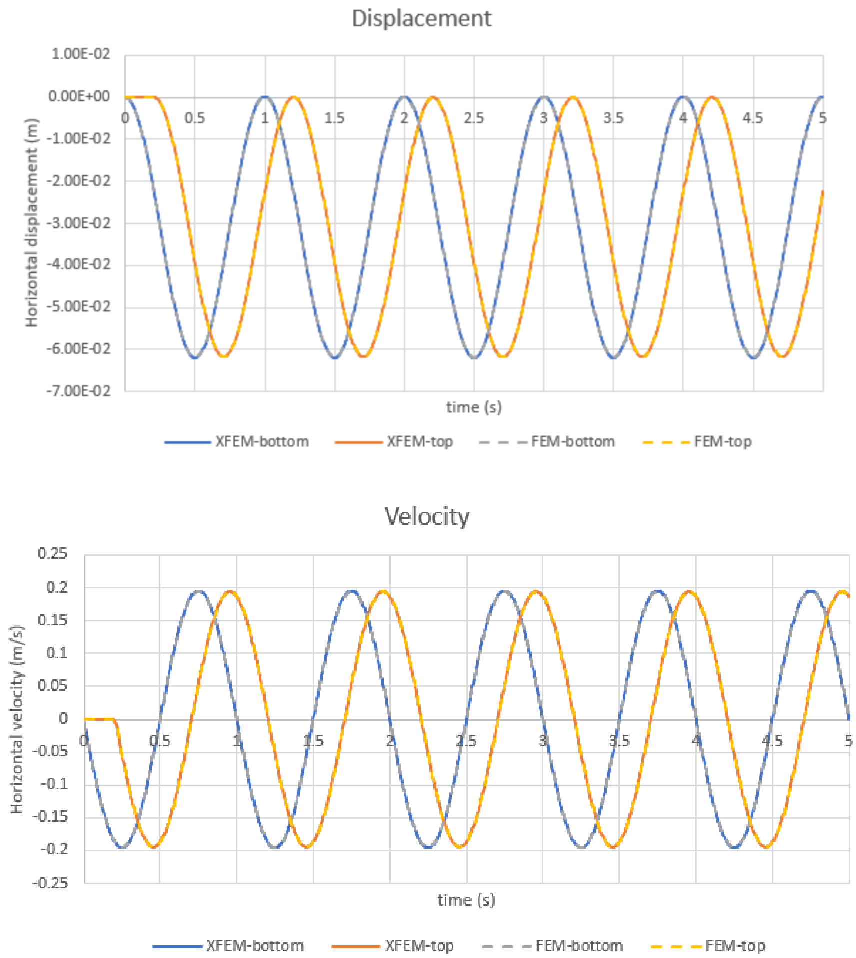


Figure 2(a) Horizontal displacement and velocity (c = 0.0 MPa)

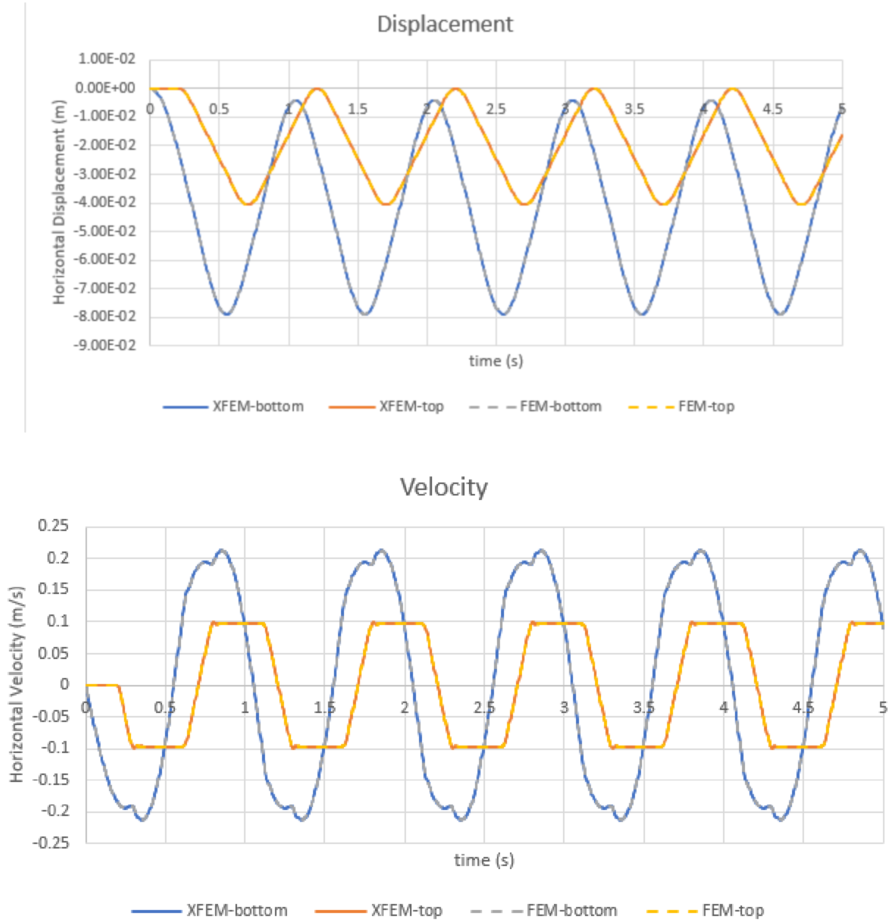
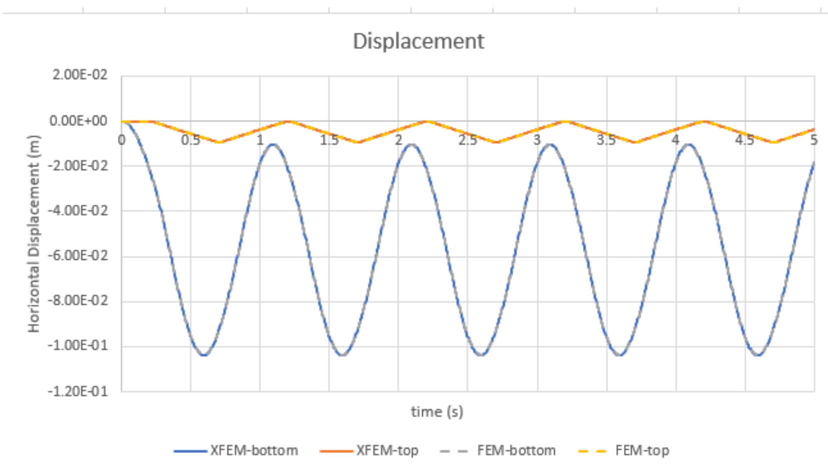


Figure 2(b) Horizontal displacement and velocity (c = 0.5 MPa)



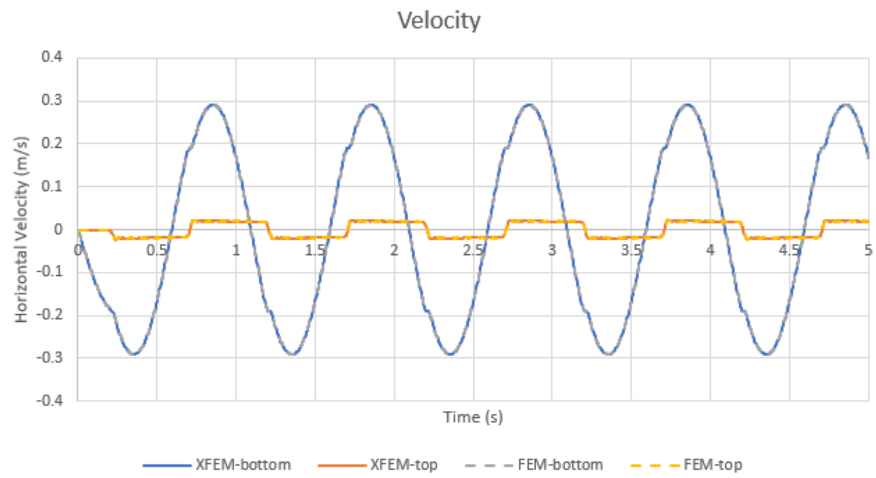


Figure 2(c) Horizontal displacement and velocity (c = 0.1 MPa)

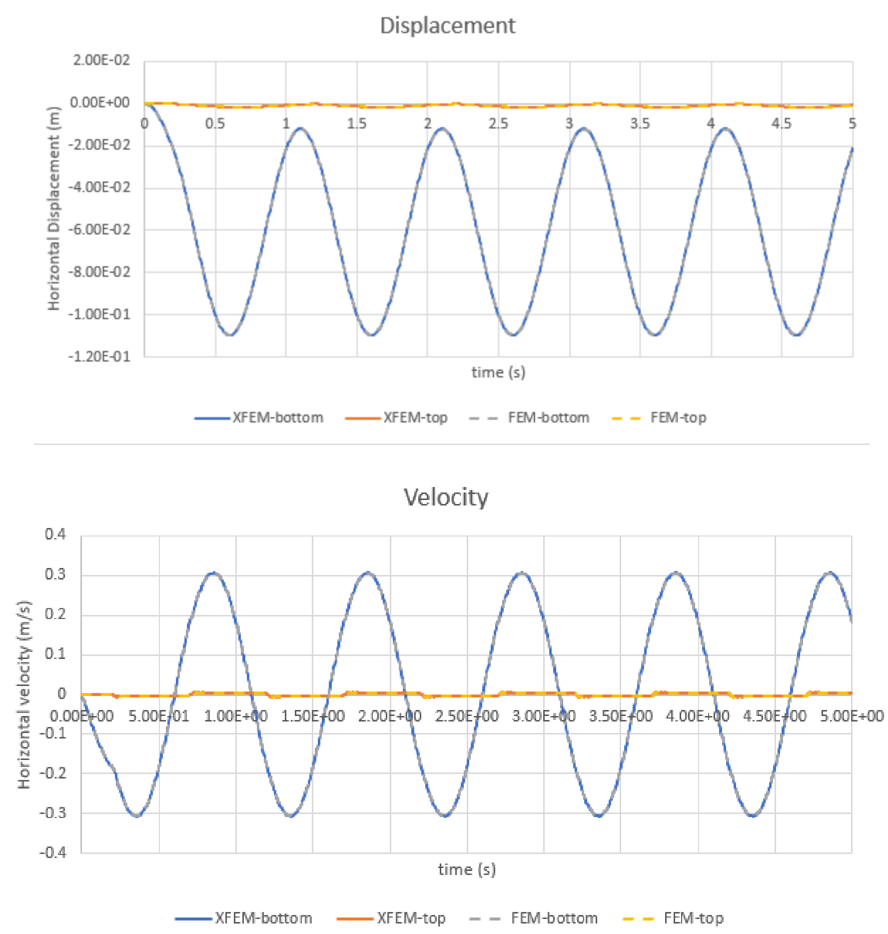


Figure 2(d) Horizontal displacement and velocity (c = 0.02 MPa)

16 JOINT-LINER INTERACTION

16.1 INTRODUCTION

This verification model is used to confirm the proper behaviour of XFEM joints when interacting with tunnel liner elements. This example compared with the explicit joint method in RS2 software by Rocscience Inc.

16.2 PROBLEM DESCRIPTION

This model is taken directly from the Joint-Liner Interaction RS2 tutorial and it simulates the behaviour of liners when joints intersect the excavation boundaries it supports. To correctly model these interactions, composite liners which include a joint at the rock-liner interface is required.

The model is a 44.8m x 44.8m square with a tunnel excavation at the center, the displacements are fixed at all boundaries. There is an initial stage followed by an excavation phase where the tunnel is excavated and a composite liner is installed.

16.3 GEOMETRY AND PROPERTIES

Table 1: Material Properties

Compressive Strength (MPa)	E (MPa)	γ (kN/m3)	mb	s	a	Material Model
25	1,645	27	0.821	0.0004	0.522	Hoek-Brown Plastic

Joint Name	Joint Color	Slip Critirion	Normal Stiffness (MPa/m)	Shear Stiffness (MPa/m)	Initial Deformation	Pressure from Groundwater Analysis	Apply Pressure to Linear Side Only	Apply Additional Pressure inside Joint	Tensile Strength (MPa <tension positive>)	Peak Cohesion (MPa)	Peak Friction Angle (degrees)	Residual Strength	Apply Stage Factors
Rock Joints		Mohr-Coulomb	100000	10000	Yes	Yes	Yes	Not Included	0	0	20	No	No

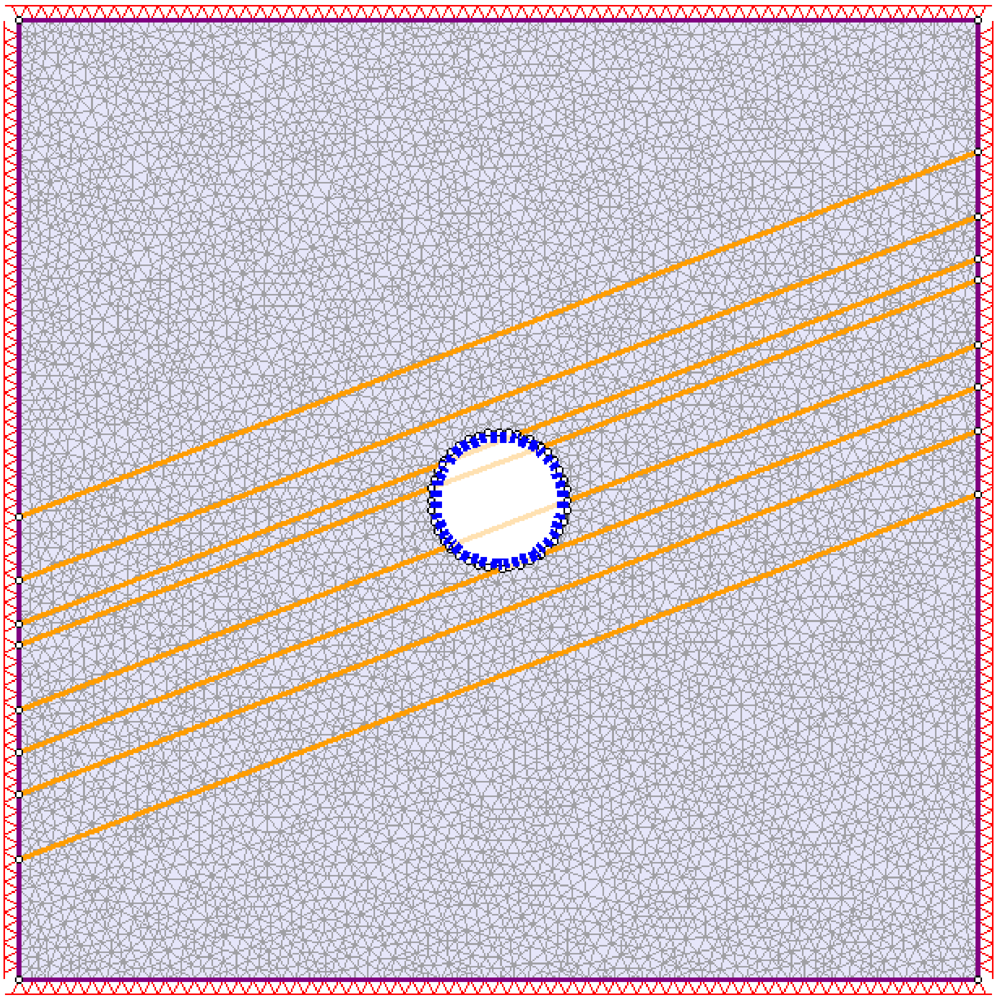


Figure 1: RS2 Model Geometry with XFEM Joints

16.4 Results

Figures 2 & 3 compares the displacement results at the excavation stage using both XFEM and FEM joints with similar mesh densities. Figures 4 through 7 compares the joint data at the excavation for the 3rd joint from the top of the model, which intersects the excavation and liner.

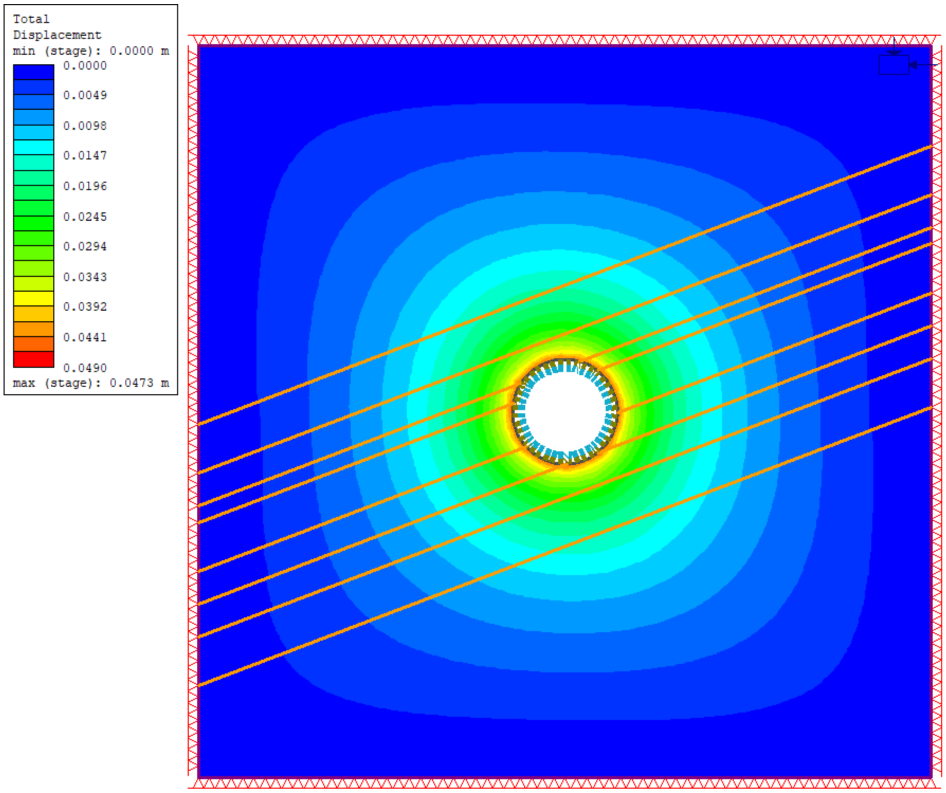


Figure 2: Solid Displacement at Excavation Stage: FEM Joints

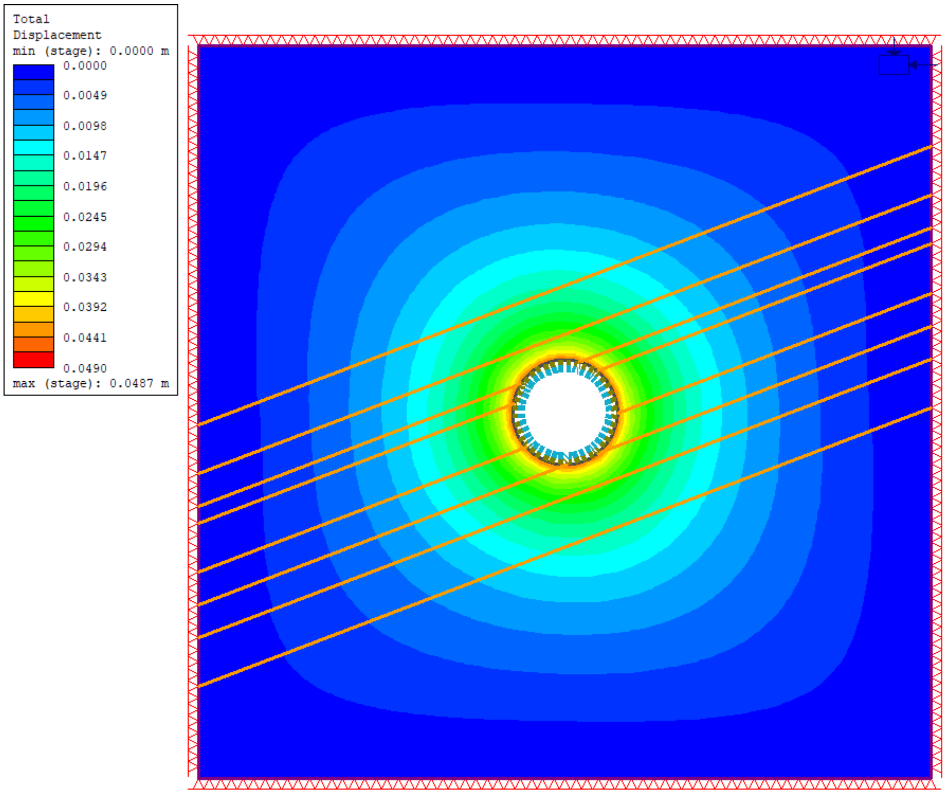


Figure 3: Solid Displacement at Excavation Stage: XFEM Joints

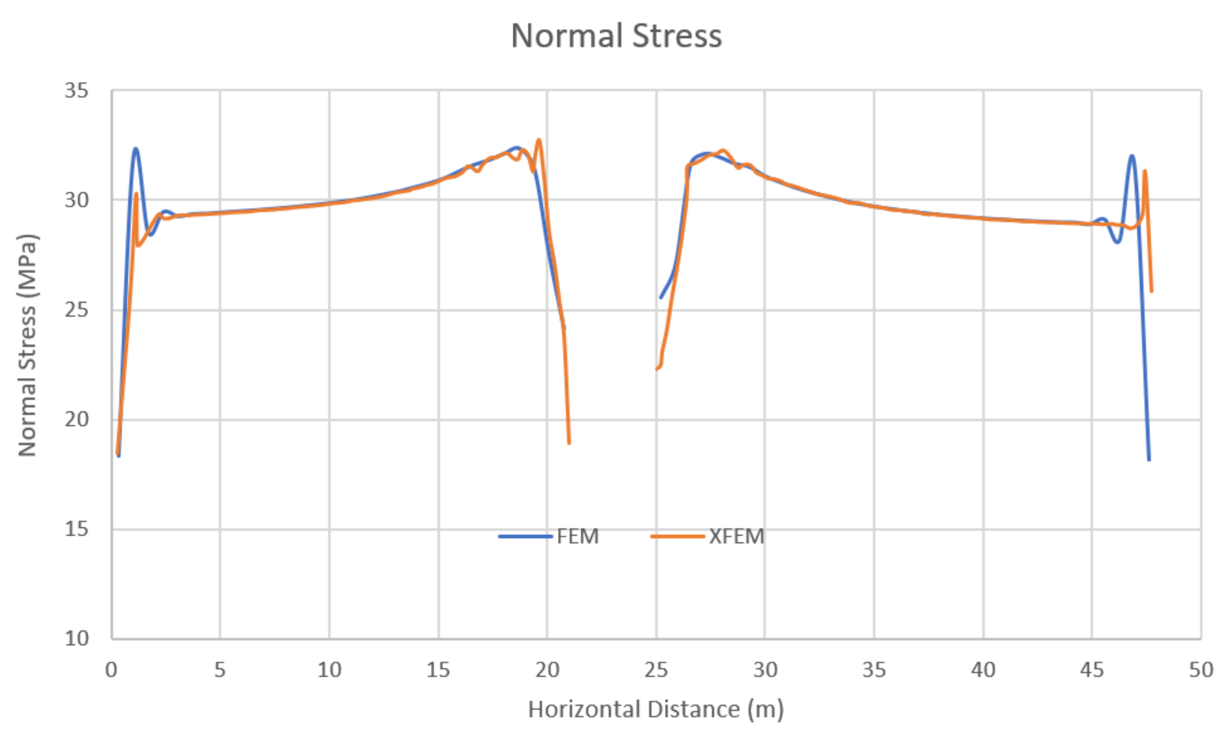


Figure 5: Normal Stress at 3th Joint from Top

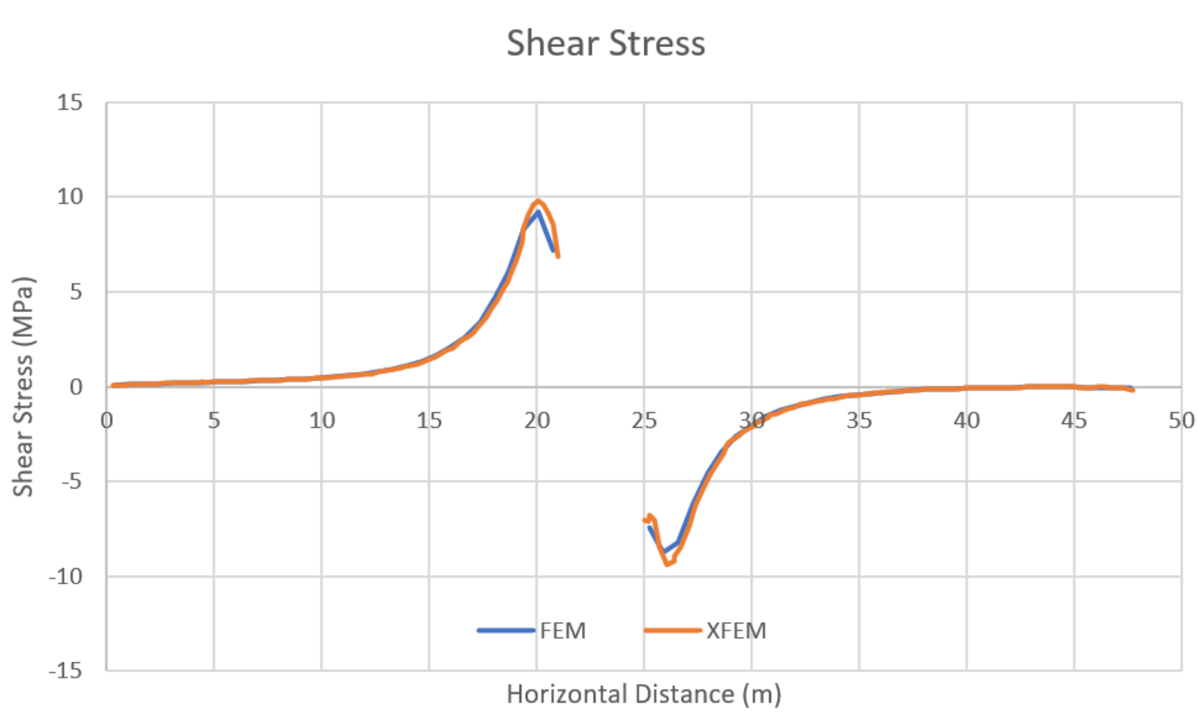


Figure 7: Shear Stress at 3th Joint from Top