RocSupport version 4.0

Verification Manual

RocSupport Verification Problem #1

1.1 Introduction

This problem was taken from Vrakas and Anagnostou (2013) [1] as an examination of a tunnel convergence in a situation where non-infinitesimal displacement can be expected.

1.2 Problem Description

This problem considers a cylindrical excavation in a linearly elastic-perfectly plastic material that obeys the Mohr-Coulomb failure criterion with a non-associated flow rule. The medium is assumed to apply a hydrostatic compressive stress field of 20.00 MPa. Figure 1-1 shows the tunnel convergence, equal to the radial wall displacement, u_a, divided by the initial radius of the tunnel, a_o, for different values of the support pressure, σ_a.

1.3 Parameters

Parameter	Value
Young's Modulus (E)	2000.00 MPa
In-situ Stress Field (σ_0)	20.00 MPa
Cohesion (c)	0.25 MPa
Poisson's Ratio (v)	0.3
Friction Angle (ϕ)	20 degrees
Dilation Angle (ψ)	5 degrees

1.4 Results

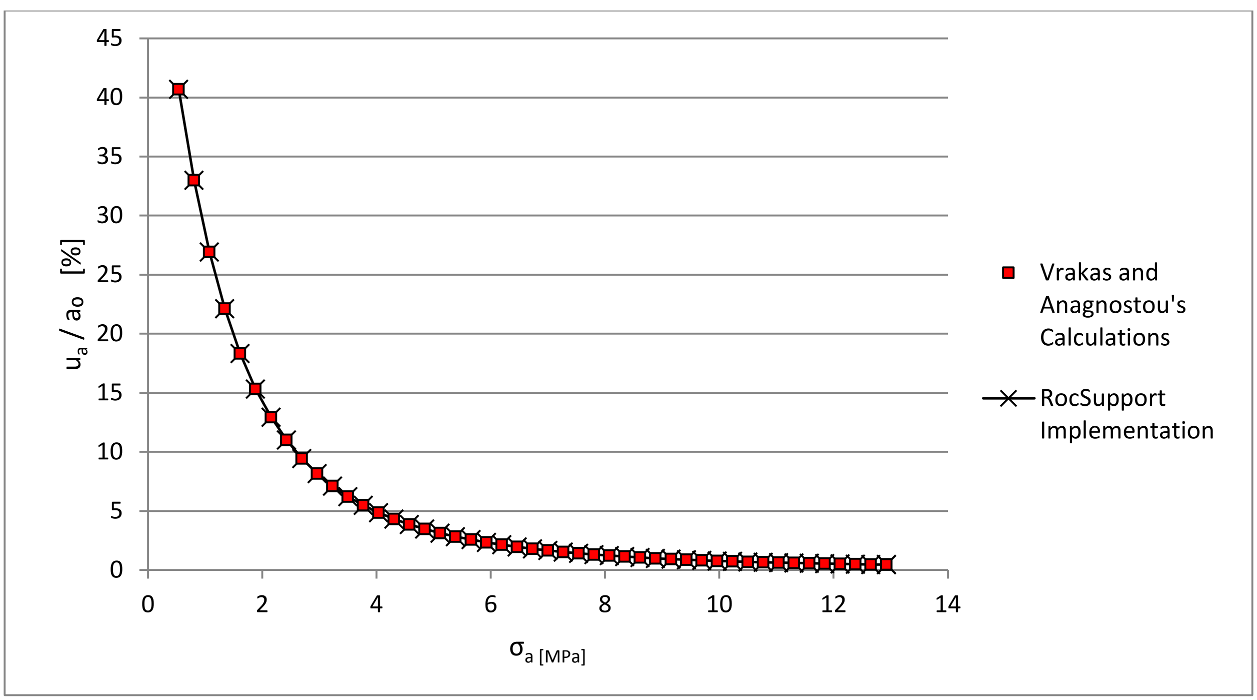

Figure 1-1 Comparison of Vrakas and Anagnostou's calculations and the Rocsupport implementation of their solution for problem 1, showing close agreement.

RocSupport Verification Problem #2

2.1 Introduction

This problem was taken from Vrakas and Anagnostou (2014) [2], where it is used as a summary of their solution for tunnel convergence for various values of the input parameters.

2.2 Problem Description

This problem considers a cylindrical excavation in a linearly elastic-perfectly plastic material that obeys the Mohr-Coulomb failure criterion with a non-associated flow rule. The medium is assumed to apply a hydrostatic compressive stress field.

By performing Caquot's transformation [3] and normalizing by the Young's modulus (as shown in eq. 1), the number of input parameters is reduced :

$$\widetilde{\sigma} = \frac{1}{E}\left(\sigma + \frac{\sigma_D}{\frac{1 + sin\varphi}{1 - sin\varphi} - 1} \right) \qquad (1)$$

where E is the Young's modulus, ϕ is the friction angle, σ_D is the unconfined compressive strength, σ is the untransformed stress and $\widetilde{\sigma}$ is the transformed stress.

Figures 2-1 and 2-2 show the normalized ground response curve for various values of the friction angle ϕ , and the transformed initial stress $\tilde{\sigma}_0$.

2.3 Parameters

Parameter	Value
Poisson's Ratio (v)	0.3
Dilation Angle (ψ)	max(0°, ϕ - 20°)

2.4 Results

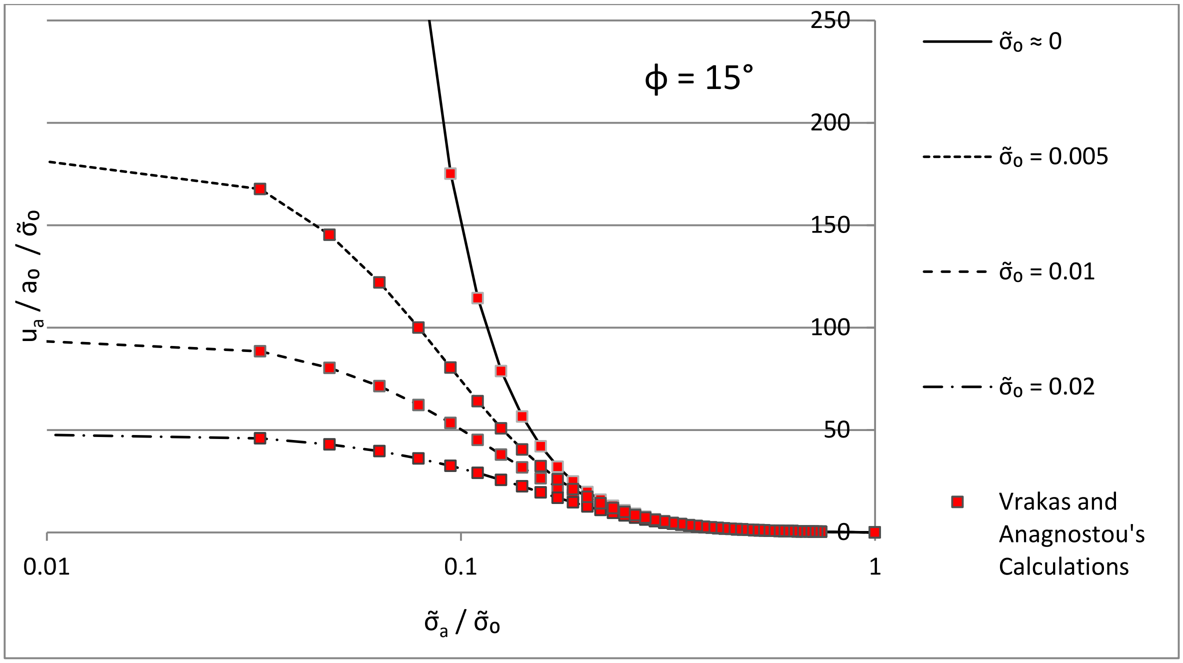

Figure 2-1 Comparison of Vrakas and Anagnostou's calculations and the Rocsupport implementation of their solution for various values of transformed stress with ϕ = 15° , showing close agreement.

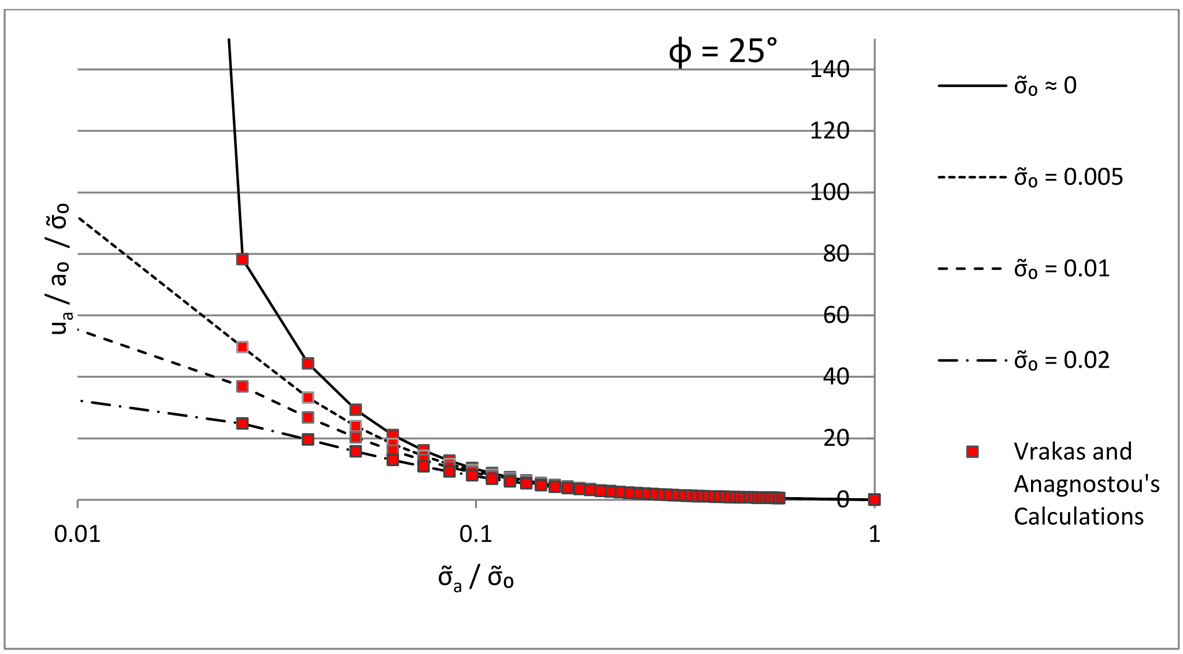

Figure 2-2 Comparison of Vrakas and Anagnostou's calculations and the Rocsupport implementation of their solution for various values of transformed stress with ϕ = 25° , showing close agreement.

RocSupport Verification Problem #3

3.1 Introduction

This problem was taken from Vrakas and Anagnostou (2014) [2]. It compares the results of finite-strain and infinitesimal solutions for tunnel convergence for a problem with a significant final wall displacement. The problem uses material properties corresponding to the Sedrun section of the Gotthard Base Tunnel in Switzerland, which passes through heavily squeezing ground.

3.2 Problem Description

This problem considers a cylindrical excavation in a linearly elastic-perfectly plastic material that obeys the Mohr-Coulomb Failure Criterion with a non-associated flow rule. The medium is assumed to apply a hydrostatic compressive stress field of 22.5 MPa. Figure 3-1 shows the tunnel convergence, equal to the radial wall displacement, u_a, divided by the initial radius of the tunnel, a_o, for different values of the support pressure, σ_a, with the results Vrakas and Anagnostou's finite strain method compared against the classical small-strain solution.

3.3 Parameters

Parameter	Value
Young's Modulus (E)	2000.00 MPa
In-situ Stress Field (σ_0)	22.5 MPa
Cohesion (c)	0.25 MPa
Poisson's Ratio (v)	0.25
Friction Angle (ϕ)	23 degrees
Dilation Angle (ψ)	3 degrees

3.4 Results

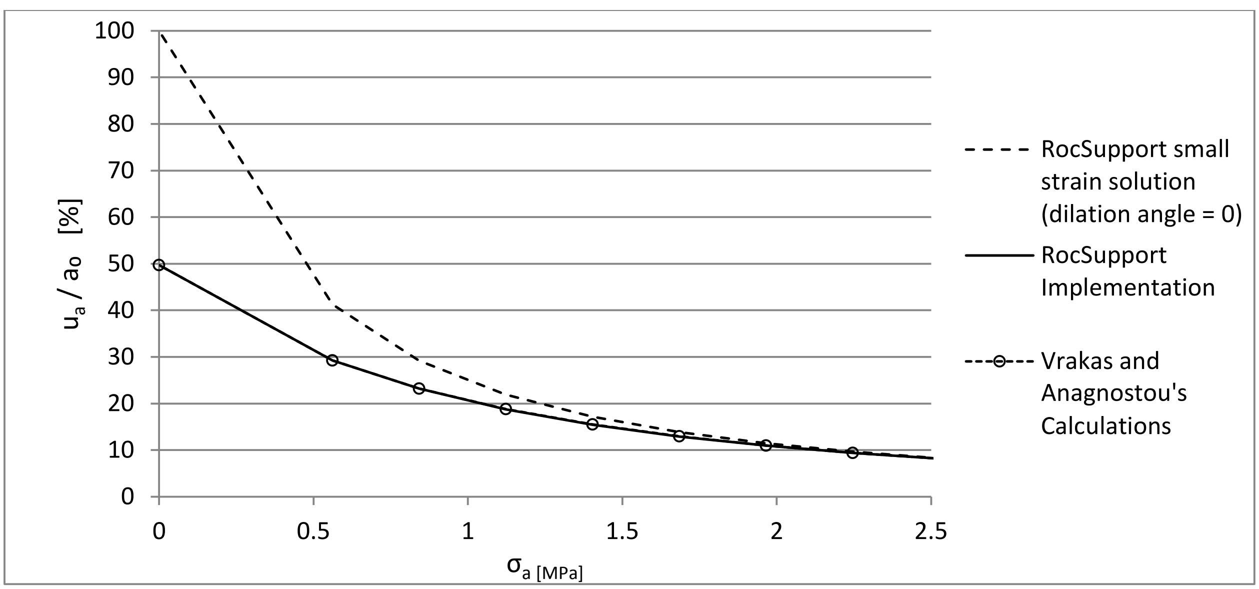

Figure 3-1 Comparison of Vrakas and Anagnostou's calculations and the Rocsupport implementation of their solution with the classical small-strain solution.

RocSupport Verification Problem #4

4.1 Introduction

This problem is taken from Lee and Pietruszczak, 2008, for the validation of their numerical solution when compared to the analytical solution put forward by Carranza-Torres in 2004. In particular, it examines the ground reaction curve generated for a Generalized Hoek-Brown medium with gradual strain-softening.

4.2 Problem Description

This problem considers a cylindrical excavation in material that obeys the Generalized Hoek-Brown failure criterion with a non-associated flow rule. The material is assumed to undergo strain-softening of the three Hoek-Brown parameters as a linear function of the plastic deviatoric strain. A critical value of plastic deviatoric strain is selected which marks the transition between the strain-softening regime and the residual regime.

$$\eta = \varepsilon_\theta^p - \varepsilon_r^p$$

$$\omega(\eta) = \begin{cases} \dfrac{\omega^p - \omega^r}{\eta^*}\eta, & 0 < \eta < \eta^* \\ \omega^r & \eta \geq \eta^* \end{cases}$$

where ω represents one of mb, s, or a.

The medium is assumed to apply a hydrostatic compressive stress field of 15.00 MPa. Figure 4-1 shows radial wall displacement, u_a, for different values of the support pressure, σ_a (the "ground reaction curve"), as calculated using the Carranza-Torres solution and the Lee and Pietruszczak solution for various values of the critical deviatoric plastic strain, the parameter that controls the extent of the strain-softening regime.

4.3 Parameters

Parameter	Value
Tunnel Radius (R)	2 m
Young's Modulus (E)	5700 MPa
In-situ Stress Field (σ_a)	15.0 MPa
Peak and Residual Intact Compressive Strength (σ_{cp}, σ_{cr})	30.0 MPa, 30.0 MPa
Poisson's Ratio (v)	0.25
Peak and Residual Hoek-Brown mb parameter (m_p, m_r)	1.7,0.85
Peak and Residual Hoek-Brown s parameter (s_p, s_r)	0.0039,0.0019
Peak and Residual Hoek-Brown a parameter (a_p, a_r)	0.55,0.6
Dilation Angle (ψ_p, ψ_r)	0 degrees

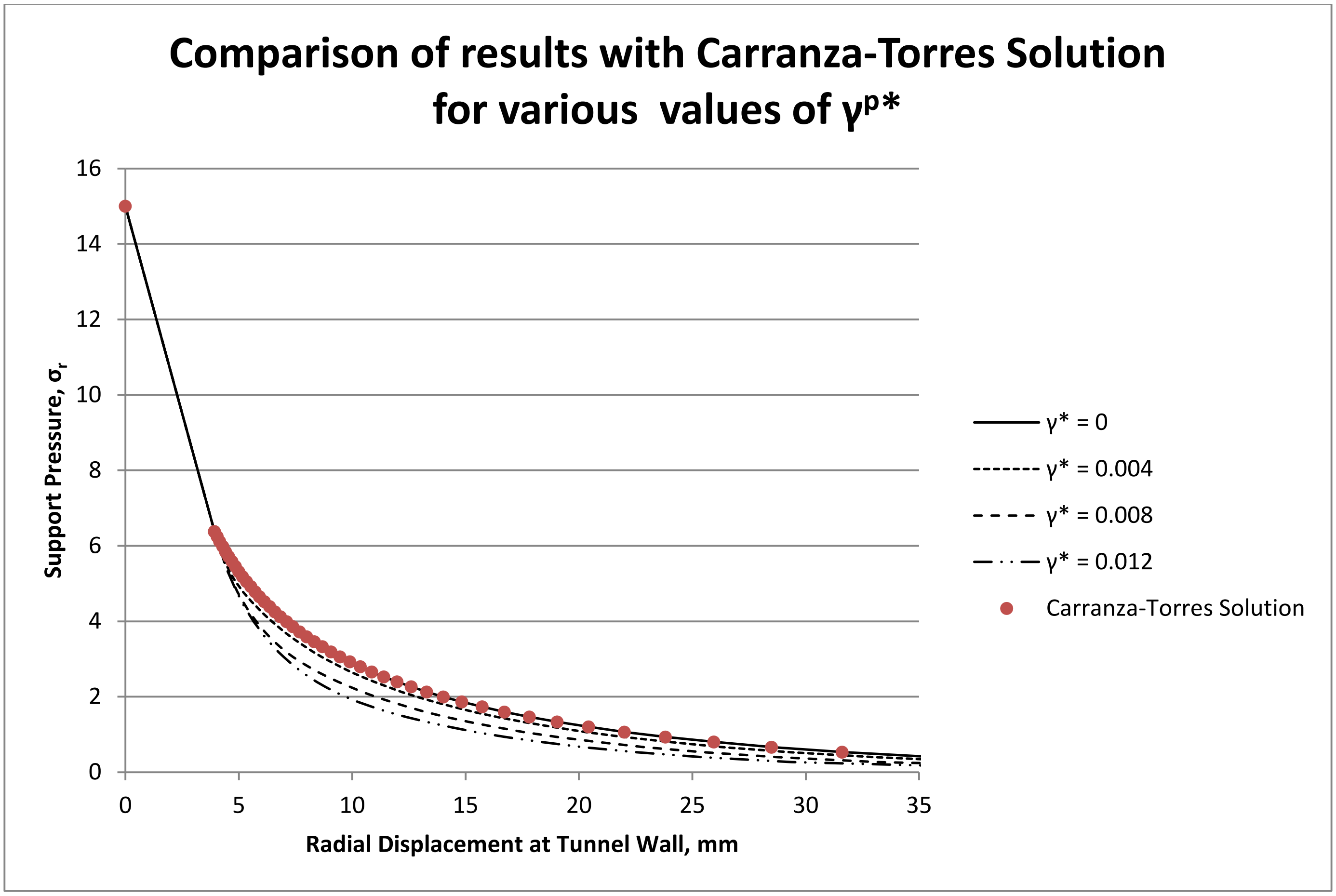

Figure 4-1 Comparison of RocSupport Implementations of the Carranza-Torres solution and of the Lee and Pietruszczak solution for various γ^{p*}, showing agreement in the brittle case.

4.4 Results

It is observed that the results of the Lee and Pietruszczak solution are in close agreement with the Carranza-Torres solution in the case of $\gamma^{p*} = 0$, which corresponds to a perfectly brittle material, with no strain-softening regime. As expected, increasing the value of the critical deviatoric plastic strain in the Lee and Pietruszczak solution decreases the extent of the radial displacement for the same value of support pressure.

RocSupport Verification Problem #5

5.1 Introduction

This problem was taken from $Phase^2$ verification example 2. It compares the results of two analytical solutions, one large-strain (Vrakas-Anagnostou) and one infinitesimal-strain (Duncan-Fama) with the results of a finite element analysis in $Phase^2$ at various values of cohesion, in-situ stress and dilation angle.

5.2 Problem Description

This problem considers a cylindrical excavation in a linearly elastic-perfectly plastic material that obeys the Mohr-Coulomb failure criterion with a non-associated flow rule. The medium is assumed to apply a hydrostatic compressive stress of either 20.00 MPa or 30.00 MPa. The dilation angle was allowed to vary between 0 and 30 degrees. Table 1.3 displays the relevant problem parameters, and results are displayed in Table 1.4 and figures 5-1 to 5-4.

5.3 Parameters

Parameter	Value
Young's Modulus (E)	10000.00 MPa
In-situ Stress Field (σ_a)	20.00 MPa, 30.00 MPa
Cohesion (c)	3.45 MPa, 5 MPa
Poisson's Ratio (v)	0.2
Friction Angle (ϕ)	30 degrees
Tunnel Radius (r)	1 m

5.4 Results

Cohesion (MPa)	In-Situ Stress (MPa)	Solution	Avg. Plastic Zone Radius (m)
3.45	30.00	Duncan-Fama	1.74
		Vrakas & Anagnostou	1.71
		Phase 2	1.71
	20.00	Duncan-Fama	1.47
		Vrakas & Anagnostou	1.47
		Phase 2	1.47
5.00	30.00	Duncan-Fama	1.49
		Vrakas & Anagnostou	1.48
		Phase 2	1.47
	20.00	Duncan-Fama	1.29
		Vrakas & Anagnostou	1.28
		Phase 2	1.27

Radius of the plastic zone is independent of dilation angle in the Phase2 analysis and the Duncan-Fama solution, but decreases with dilation angle for Vrakas-Anagnostou. Average values of this radius for the two analytical solutions were generally in close agreement, and practically equal to the values given by Phase 2.

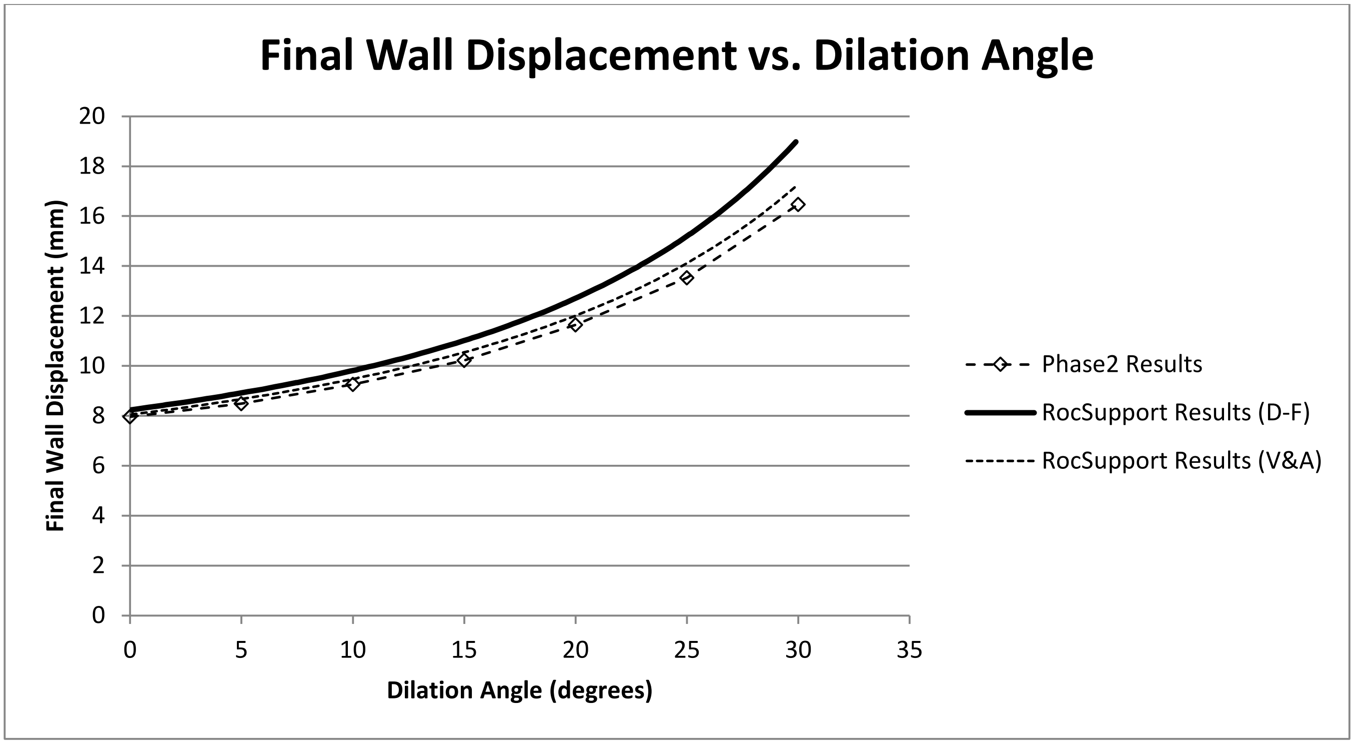

Figure 5-1 Comparison of results from Vrakas and Anagnostou solution, Duncan-Fama solution and Phase2 numerical results for 3.45 MPa cohesion and 30.0 MPa in-situ stress.

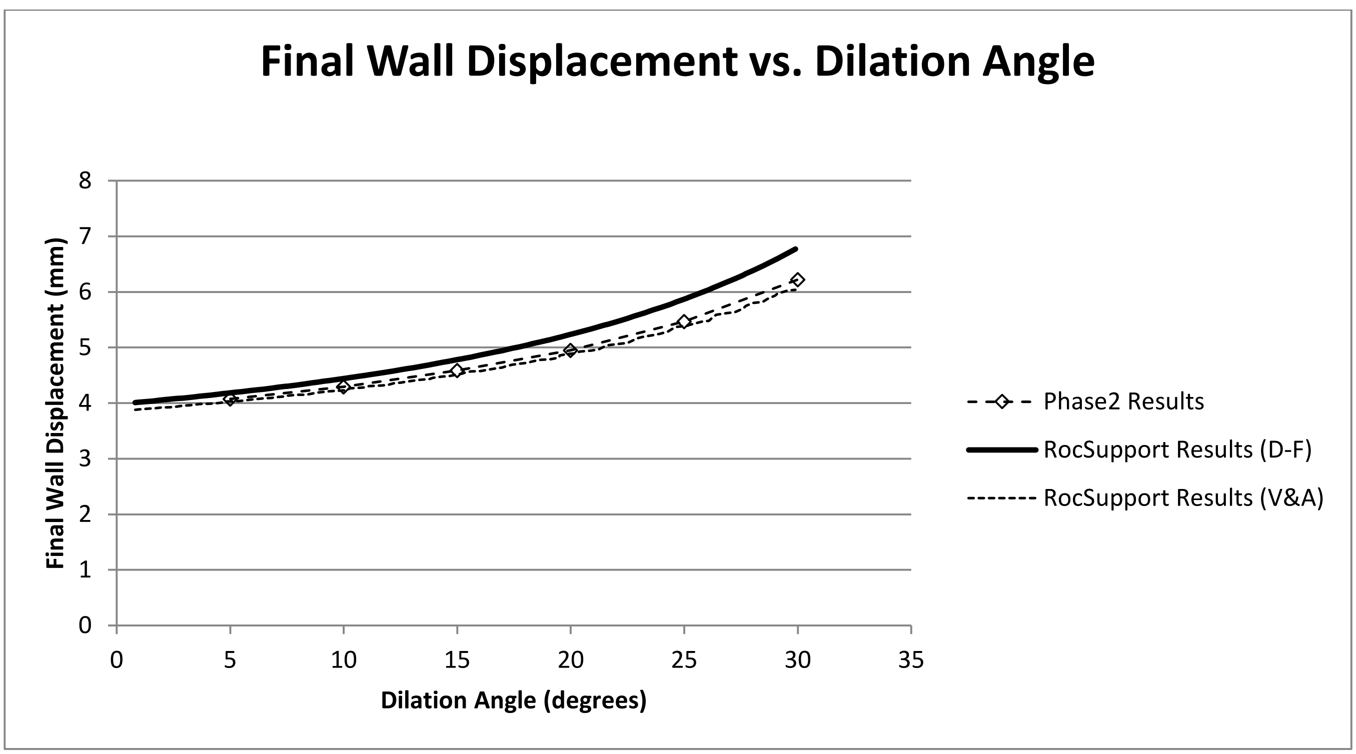

Figure 5-2 Comparison of results from Vrakas and Anagnostou solution, Duncan-Fama solution and Phase2 numerical results for 3.45 MPa cohesion and 20.0 MPa in-situ stress.

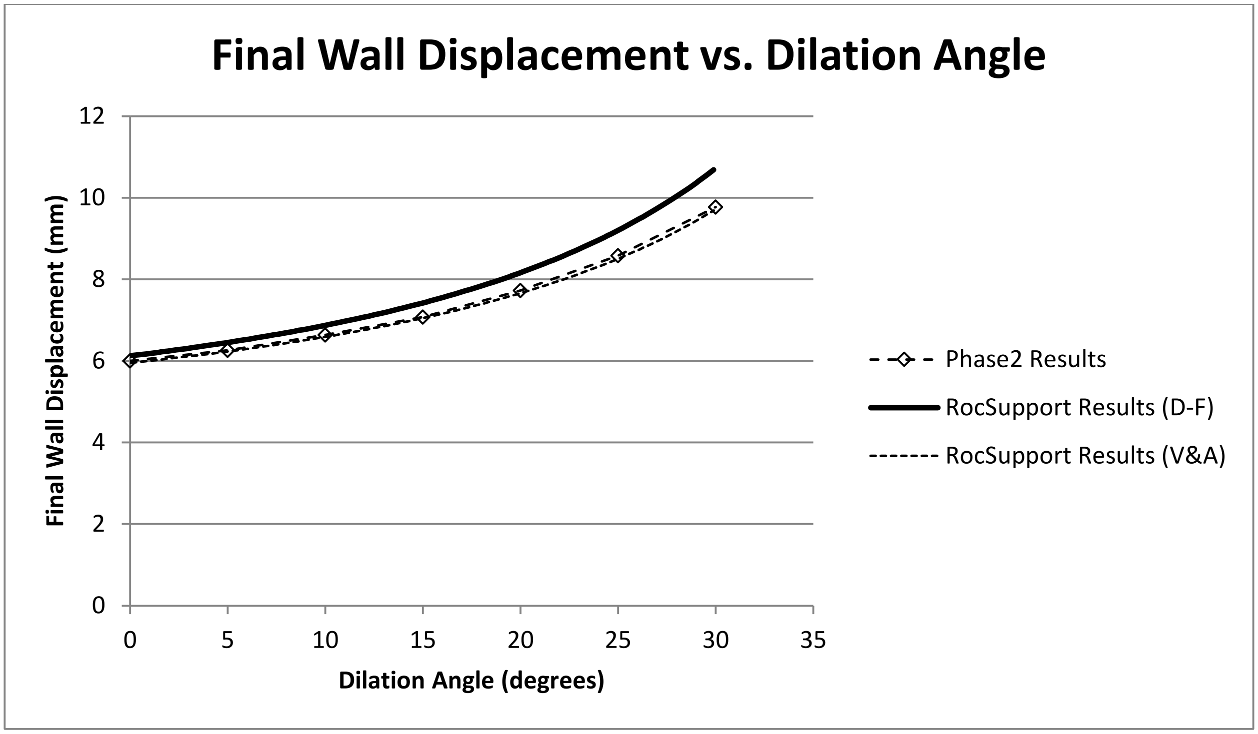

Figure 5-4 Comparison of results from Vrakas and Anagnostou solution, Duncan-Fama solution and Phase2 numerical results for 5 MPa cohesion and 30.0 MPa in-situ stress.

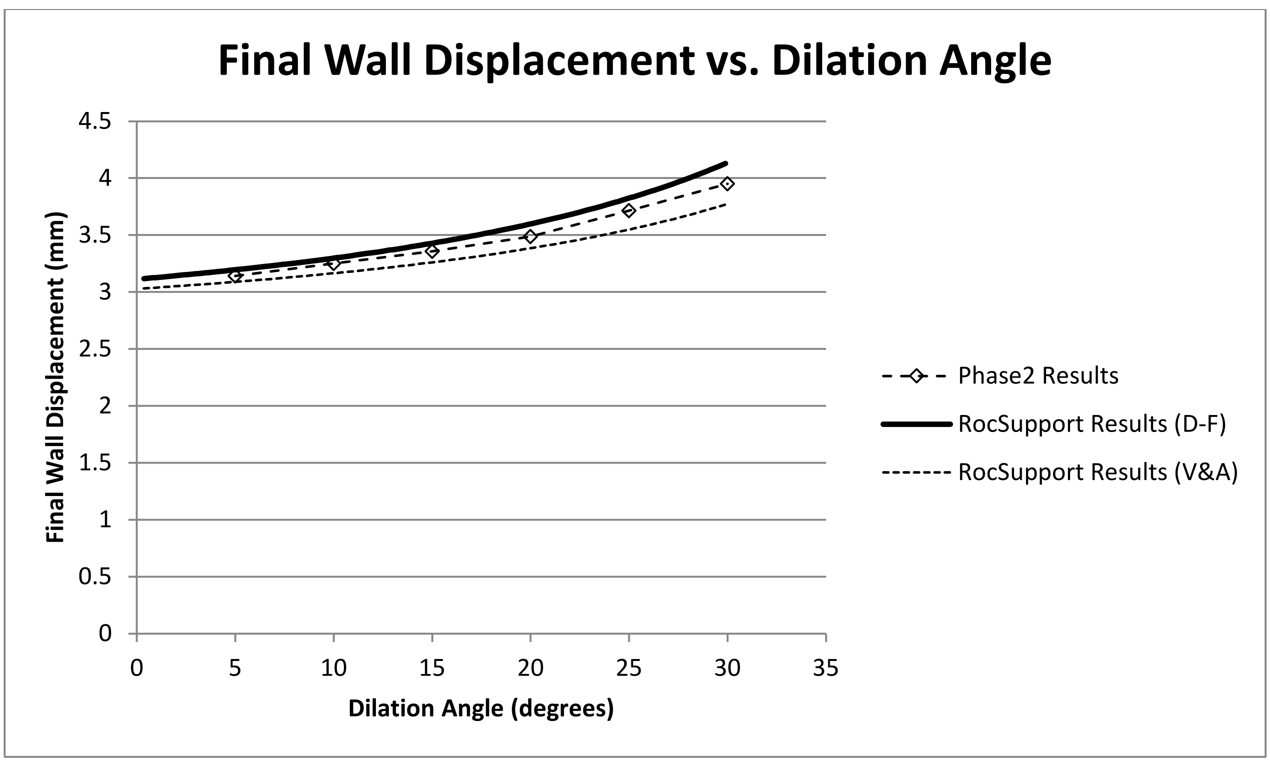

Figure 5-3 Comparison of results from Vrakas and Anagnostou solution, Duncan-Fama solution and Phase2 numerical results for 5 MPa cohesion and 20.0 MPa in-situ stress.

The results of the Phase2 analysis are generally in good agreement with the results of the Vrakas-Anagnostou analysis. The results of the Duncan-Fama analysis match the other two sets of results closely for small dilation angles and tunnel convergences, but differ from the numerical solution significantly (up to 15%) for large dilation angles and tunnel convergences, suggesting the model's assumption of infinitesimal strain may not be appropriate for the problem parameters.

Note on Calculations

Vrakas and Anagnostou's calculations are taken from a spreadsheet made available to RocScience Inc. by Prof. Georg Anagnostou and Dr. Apostolos Vrakas based upon the model presented in Vrakas and Anagnostou, 2013 [1]. Input parameters were changed by RocScience staff to replicate the problems from Vrakas and Anagnostou, 2014 [2].

Values for the RocSupport Implementation were calculated directly in RocSupport 4.

References

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