POLITECNICO DI TORINO

Architect & Engineering faculty

Building Engineering

Master of Science Thesis

Slope stability analyses in bimrocks of Las Medulas cave:

Professors:

Prof. Monica Barbero

Prof. Maria Lia Napoli

Student:

Majid Delkhah

S316415

March 2025

Summary

Las Médulas is a remarkable historical and geological site in Spain, known for its complex and unique landscape shaped by ancient Roman mining activities. It is considered one of the most significant examples of large-scale Roman engineering, where hydraulic mining techniques were used to extract gold. The site consists of eroded clay formations with cavities and tunnels, creating a striking contrast of reddish terrain and lush vegetation.

This study examines the geological and mechanical behavior of Las Médulas' cave formations, with a focus on slope stability. The research adopts a stochastic approach to assess the effects of erosion and material composition on structural integrity. Various sample distributions, representative of the natural heterogeneity of the terrain, were analyzed to determine their influence on slope stability. Three different volumetric proportions of sedimentary deposits were considered, and their impact on failure mechanisms was evaluated. The study compares numerical modeling results with traditional stability analysis methods to provide insights into the economic and safety implications of excavation techniques.

The findings reveal a strong relationship between stability and material composition, demonstrating that a larger clay content makes a material more prone to collapse and erosion. The findings show that the distribution of sedimentary layers affects the failure zones, with regions with weaker material cohesiveness showing more noticeable surface instability. The study also highlights how difficult it is to draw a direct connection between the distribution of deposits, failure trends, and overall structural integrity.

Models that simply take into account homogeneous sediment understate safety considerations, according to a comparison between numerical simulations and traditional stability analysis. Even though they are helpful, traditional limit equilibrium techniques might not adequately represent the erratic failure patterns seen in heterogeneous deposits. The results highlight how crucial it is to use thorough geological models in order to improve safety evaluations and maximize conservation initiatives for Las Médulas Cave.

Table of content

Introduction

Las Médulas[1] is a remarkable historical and geological landmark known for its distinctive landscape and engineering significance. It is situated in the northwest Spanish province of León. (Description of a UNESCO World Heritage Site). Ruina montium[2], an advanced hydraulic mining technique that involved channeling large amounts of water through a network of tunnels and reservoirs to control the collapse of mountain slopes, was once the most significant gold mine in the Roman Empire. (J.C. Domergue, Les Mines de l'Empire Romain 1990). As a result, the reddish clay formations are carved with large cave systems, towering cliffs, and deep ravines, creating a spectacular environment. (Rodríguez-Pascua et al. 2017). Due to its complicated topography and persistent stability issues, Las Médulas, a UNESCO World Heritage Site, is not only a treasure trove of archaeological artifacts but also a topic of intense interest in geological and geotechnical research. (World Heritage Site, UNESCO).

Las Médulas' distinct geological makeup offers both analytical opportunities and obstacles. In (2017, Rodríguez-Pascua et al.) Rock fragments of various sizes are scattered throughout the region's mostly sandy and clayey, weakly cemented elements. J.C. Sánchez-Palencia (2000). Slope stability is impacted by this diverse composition, which leaves the region vulnerable to weathering, erosion, and even landslides. Concerns regarding structural integrity have been raised as a result of the site's stability being shaped over time by both natural and man-made causes, especially inside the caves and exposed rock formations. (Orejas, A., & Sánchez-Palencia, J. C. 2002). A comprehensive geotechnical study is necessary to ensure the site's preservation due to its historical and cultural significance. This study also offers insights into the wider implications of rock-mass stability in similar sedimentary formations. (Source: UNESCO).

Numerical modeling techniques provide an effective analytical tool for evaluating the stability of Las Médulas Cave and the surrounding rock formations. (Brown, E. T.), and Hoek, E. (1997). A popular finite element program for geotechnical and rock mechanics simulations, RS2 (previously known as Phase2) offers a thorough method for assessing stress distributions, deformation patterns, and failure causes in intricate geological environments. (2023) Rocscience Inc. Researchers can evaluate the effects of possible excavation or conservation operations, simulate different loading scenarios, and examine the impact of material heterogeneity by using RS2 on Las Médulas. Phien-wej, N., and Fuenkajorn, K. (2001). This method enables a thorough

1 Las Médulas is a spectacular landscape in Spain formed by ancient Roman gold mining using the "ruina montium" technique.

2 an ancient Roman mining technique involving the use of water to collapse mountains and access mineral resources.

comprehension of erosion's impacts, slope stability, and potential preventative measures for structural failures. (J. M. Duncan, 1996)

Figure 1: Las Medulas Cave

Historical Context

One of the most important ancient mining sites in Europe is Las Médulas, which is situated in the northwest Spanish province of León. In 1990, Domergue, C. Operating mostly from the first century BCE to the third century CE, it was the biggest and most fruitful gold mine in the Roman Empire. Wilson, A. (2002). Because it produced enormous quantities of gold that supported both imperial expansion and economic prosperity, this mining complex was vital to the Roman economy. (Oleson, J. P., Sherwood, A. N., & Humphrey, J. W. 1998) The ruina montium (literally "collapse of the mountains"), a highly advanced hydraulic system intended to fracture the landscape and make ore extraction easier, is one of the Roman engineering methods that made the location famous for its ability to harvest gold. (Gutiérrez-Alonso, G. 2016).

After the Roman conquest of Hispania, the exploitation of Las Médulas started under the reign of Emperor Augustus. (Orejas, A., & Sánchez-Palencia, F. J. 2002; Domergue, C. 1990). Recognizing the area's abundant gold reserves, the Romans created a sophisticated mining system that depended on a vast system of man-made lakes and waterways. Wilson, A. (2002) and Sánchez-Palencia, F. J. (2000) Through a network of tunnels, storage basins, and aqueducts, water was diverted from the nearby mountains. (Jiménez-Salvador, J. 2014; Gutiérrez-Alonso, G. 2016). They exposed the gold-bearing material by abruptly releasing massive amounts of water, which produced highpressure flows that eroded and crushed the sedimentary strata[3]. (Sánchez-Palencia, F. J., & Orejas, A. 2007). This technique was very successful, but it also had a significant influence on the terrain, creating the interconnecting caverns, steep cliffs, and deep gullies that now characterize the area. (Gutiérrez-Alonso, G. 2016- Orejas, A., & Sánchez-Palencia, F. J. 2002).

Thousands of workers, including Roman engineers, soldiers, and indigenous laborers—possibly even slaves—were employed in the industrial-scale mining enterprise that was Las Médulas at its height. Wilson, A. (2002); Domergue, C. (1990). The gold that was produced here was taken to Rome for coin minting and military campaign funding, making the location a crucial component of the larger Roman mining network. (Orejas, A., & Sánchez-Palencia, F. J. 2002- Duncan-Jones, R. 1994; Sánchez-Palencia, F. J. 2000). Mining operations dwindled over time as the Roman Empire's priorities changed and the gold reserves were exhausted, leading to the site's eventual abandonment. (Gutiérrez-Alonso, G. 2016- Sánchez-Palencia, F. J., & Orejas, A. 2007).

The Ruina Montium Technique

The Romans employed a sophisticated hydraulic mining method called the Ruina Montium (Latin for "collapse of the mountains") to recover gold from substantial reserves, most notably at Las Médulas. (Domergue, C. 1990; Orejas, A., & Sánchez-Palencia, F. J. 2002; Pliny the Elder). This technique, which was one of the most inventive and extensive mining operations of antiquity and demonstrated the Romans' mastery of engineering and resource extraction, was detailed by the Roman historian Pliny the Elder in his Naturalis Historia. (Wilson, A. 2002- Sánchez-Palencia, F. J. 2000).

In order to more effectively remove gold-bearing sediments, the method used water pressure to weaken and collapse entire mountain parts. There were multiple stages to the process: (Wilson, A. 2002- Domergue, C. 1990).

- Water Supply System
- Tunneling into the Mountains
- Sudden Release of Water
- Gold Separation

3 layers of rock or soil, often formed over long geological periods, that are distinguishable from one another.

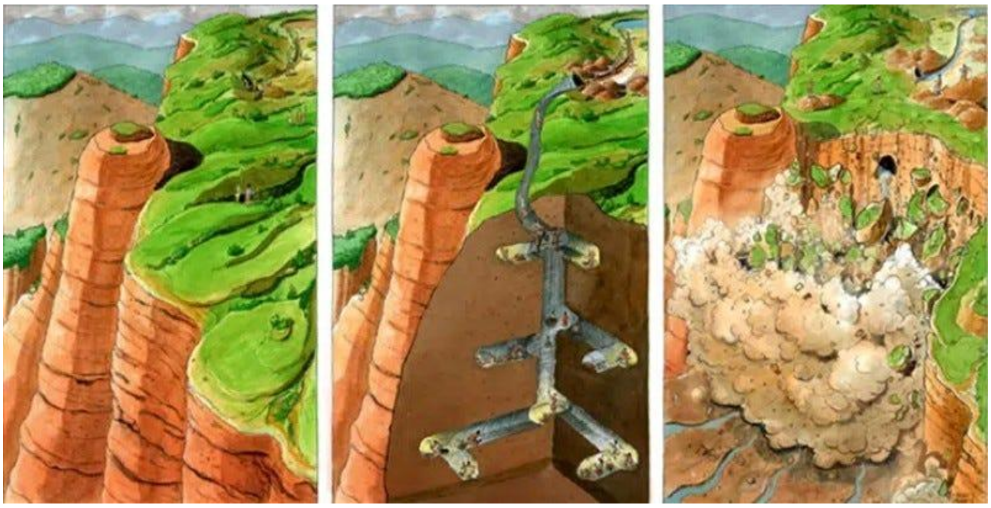


Figure 2:The Ruina Montium Technique (viajesyrutas.es)

Engineering and Environmental Impact

Although the Ruina Montium process was a very effective way to extract gold on a massive scale, it had a significant negative influence on the ecosystem. In 1990, Domergue, C. Deep cliffs, caverns, and ravines[4] were carved out during the process, significantly changing the natural environment. Many of these features may still be seen at Las Médulas today. In 1970, Lewis, P. R., and G. D. B. Jones cited Orejas, A., and Sánchez-Palencia, F. J. (2002). This striking alteration in the landscape is regarded as one of the first instances of significant environmental change brought about by human activity. (Hooke, R. L. 2000-Wilson, A. 2002).

Visiting Las Médulas

Las Médulas, a UNESCO World Heritage site in Spain, is a testament[5] to Roman ingenuity[6] and the impact of human activity on the landscape. (UNESCO World Heritage Centre. "Las Médulas." Inscribed 1997).

In addition to learning about the site's history at the Carucedo archeological museum, visitors can explore the ochre-colored cliffs and valleys via paths and views like Mirador de Orellán. Hiking trails and guided excursions provide more in-depth understanding. (Official Tourism Website of Spain).

Las Médulas' significance lies in several key areas:

Roman Engineering: It is the biggest Roman gold mine and exemplifies the sophisticated "Ruina Montium" hydraulic mining method, which uses an extensive system of reservoirs and aqueducts. (Jones, G. D. B. (1980).

4 deep, narrow valleys with steep sides, often carved by the erosive action of water over time.

5 strong evidence or proof

6 cleverness, creativity, and innovation.

Geological Formation: The distinctive red cliffs and ravines are the result of centuries of mining that drastically altered the terrain. (Orejas, A., & Sánchez-Palencia, F. J. (2002).

Human-Nature Interaction: The manipulation of the environment by ancient civilizations for resources is exemplified by Las Médulas, which raises concerns regarding sustainability. (World Heritage Center, UNESCO). Las Médulas: Assessment of Advisory Bodies (ICOMOS)." 1997)

Cultural Heritage: Roman villages and buildings shed light on the lives of those who worked there and helped to define the identity of the area. (Castilla y León Cultural Heritage).

Living Museum: Historians, archaeologists, geologists, and environmental scientists study at Las Médulas, which provides continuous insights into Roman engineering and environmental history. (Domergue, C. 1990).

Objectives and Scope of the Thesis

The purpose of this thesis is to discuss many aspects of the site's current state, the legacy of its past mining activities, and its potential preservation. The study's main goals are designed to examine the Roman past while also examining the site's future from the perspective of contemporary engineering.

Evaluate the Stability of Las Médulas Under Current Geological and Environmental Conditions

Evaluating Las Médulas' stability in the present while taking into account the environmental and geological elements that affect it is one of the main goals of this research. Although historic mining methods affected the site's landscape, natural erosion and climate forces have continued to influence it.

Geological Evaluation: This entails comprehending the soil composition, erosion trends, and structural soundness of the surviving cliffs, caverns[7], and ravines. Rainwater infiltration, rock weathering, and seismic activity have all contributed to the degradation and alteration of these formations over time. The purpose of this investigation is to find any indications of geotechnical instability, including possible landslides, and to determine how the old mining method itself affects these circumstances.

7 large underground chambers formed by natural processes, often featuring impressive stalactites and stalagmites.

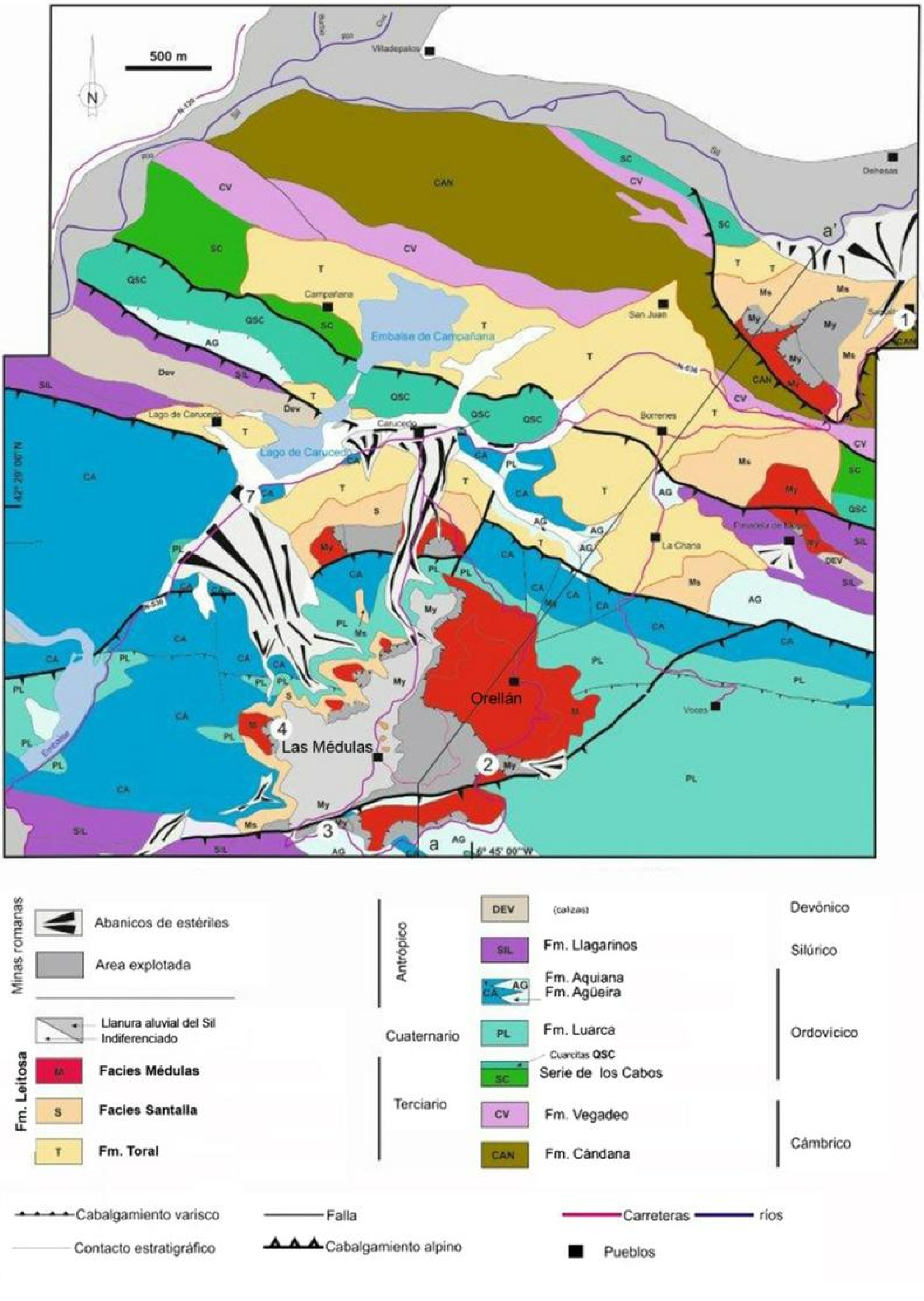


Figure 3: Geological map

Scope of the Study: A Blend of History and Modern Engineering

This study's comprehensive focus includes both the historical relevance of Las Médulas and the use of contemporary engineering and geotechnical techniques. This thesis aims to close the gap between historical inventiveness and current technical developments by examining the site using modern scientific instruments.

Contemporary Applications: The study will then model the long-term impacts of historic mining methods and how they still affect the land now using contemporary geotechnical analysis to assess the site's current state. Future preservation plans are informed by this blending of the past and current.

Methodology Overview

The study makes use of Rocscience RS2, a finite element program that is frequently used in geotechnical engineering for modeling and analyzing soil and rock behavior under various situations, in order to accomplish the goals stated in the thesis. In (2023, Rocscience Inc). The program is especially helpful for assessing the stability of structures like Las Médulas, which were molded by historic mining operations, and for modeling intricate geotechnical processes. Brown, E. T., and Hoek, E. (1997). The methodology's goals are to reproduce the Ruina Montium technology, evaluate the site's stability thoroughly, and suggest contemporary preservation tactics. (Orejas, A., & Sánchez-Palencia, F. J. 2002).

Collecting Geological and Historical Data Relevant to Las Médulas

In order to comprehend the site's current condition and the past processes that produced it, the methodology's initial step is to collect geological and historical data. The basis for modeling and analysis is this data:

Geological Data: This contains details about the types of rocks, soil composition, erosion patterns, and structural elements present at Las Médulas. (Orejas, A., & Sánchez-Palencia, F. J. Eds. 2006). Important details including the location and depth of the gold-bearing[8] strata, the local rock mechanics, and any geotechnical data from earlier research will be gathered. (P. Higueras and others, 2010). This information aids in faithfully capturing the site's physical attributes in the model.

Historical Data: Rebuilding the Ruina Montium method requires an understanding of the history of the mining operations at Las Médulas. (Orejas, A., & Sánchez-Palencia, F. J. 2002). In order to learn more about how the Romans employed hydraulic mining to

8 materials or geological formations that contain gold, either in visible particles or embedded within the rock.

extract gold, historical documents, archaeological discoveries, and research on Roman engineering techniques will all be examined. (Pliny the Elder, 1952; 77 AD). By giving the modeling process context, this historical data guarantees that the hydraulic and mechanical motions replicated in the model are accurate representations of antiquated techniques.

Constructing a 2D Finite Element Model

The study then uses Rocscience RS2 to create a 2D finite element model based on the geological and historical data that was gathered. The simulated using finite element modeling (FEM)[9], a potent computer method. Several essential elements are involved in this step:

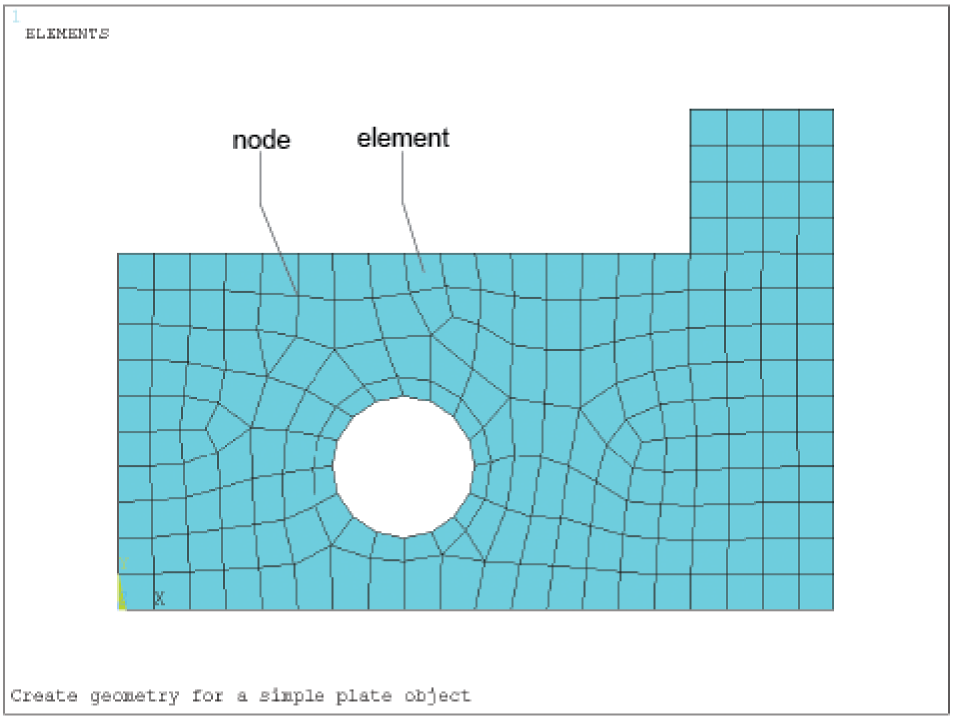


Figure 4: Constructing a 2D Finite Element Model

Analyzing Stress Distributions, Failure Mechanisms, and Safety Factors

Following the construction of the finite element model, a thorough investigation will be conducted to evaluate the stability of the Las Médulas site in both its historical and current contexts. This stage entails:

Stress Distribution: The model will examine the distribution of stress in the soil and rocks.

9 a numerical technique for solving complex engineering and physical problems by breaking down structures into smaller, simpler parts called finite elements.

Failure Mechanisms: The investigation will determine the failure processes that could result in landslides or cave-ins today by examining the model's output. This entails modeling the potential for instability. In addition to highlighting places most at risk of failure, the investigation will shed light on why some parts of Las Médulas are more susceptible to erosion than others.

Safety Factors[10]: The site's safety factor, a crucial metric in geotechnical engineering that gauges a system's likelihood of failure, will be computed. Stability is indicated by a safety factor more than one, and instability is suggested by values less than one. This research will assist in determining whether specific site components need to be intervened to stop more deterioration or collapse.

Proposing Stabilization Measures Based on Findings

The thesis will suggest stabilizing strategies to improve the site's resilience and maintain its structural integrity based on the analysis's findings. These actions will take into account both current geotechnical procedures and the results of the modeling process:

Structural Stabilization: Techniques like slope stabilization, soil anchoring, or reinforcement of the cave structures to stop additional erosion or collapse are some ideas for strengthening areas that are prone to failure.

Preservation Efforts: Additionally, the study will make recommendations for how to lessen the effects of contemporary tourism and environmental changes on the location. These suggestions will cover strategies for reducing visitor-induced physical deterioration as well as environmental monitoring techniques to evaluate how the site's circumstances have changed over time.

Bridging Ancient and Modern Engineering

This approach combines modern geotechnical principles with ancient Roman engineering, providing a rare chance to comprehend how historical activities shaped the site and how modern methods might conserve it. The work applies geotechnical modeling and finite element analysis to preserve a cultural and geological monument in a scientific manner. A thorough and in-depth picture of the site's condition is provided.

10 multipliers applied to calculated stresses or loads in engineering to ensure structures or components remain safe under unexpected conditions or uncertainties.

Geology of Las Médulas

A key component of Las Médulas' historical Roman mining and current preservation initiatives is its geology, which is located in the El Bierzo area of León Province in northwest Spain (Sánchez-Palencia & Orejas, 2006). The terrain of the site was created by volcanic activity that deposited tuff, a soft, porous rock, and breccia, a more durable mixture of angular fragments, during the Tertiary period (65–2.6 million years ago) within the Hercynian[11] Mountain range (Higueras et al., 2010). The Romans used the Ruina Montium hydraulic technique to exploit gold-bearing alluvial strata that were exposed by tectonic processes and erosion (Higueras, P., et al. 2010). This process produced the site's famous ochre cliffs, deep gullies, and caverns, demonstrating how humans have altered nature by eroding tuff and collapsing hillside. (Sánchez-Palencia, F. J., & Orejas, A. (Eds.). 2006). By creating weak areas for water-driven rock displacement, the stratigraphy—which includes tuff, pumice, breccia, and clay—as well as structural elements like faults, fractures, and mining tunnels made this process easier. (Higueras, P., et al. (2010).

The geology of Las Médulas was significantly changed by the Ruina Montium technique, which displaced large rock masses, weakened interior systems, and left behind a scarred landscape that is still changing due to erosion. Jones, G. D. B., and Lewis, P. R. (1970). Understanding these effects and addressing persistent geological issues are the main goals of preservation efforts today. World Heritage Center, UNESCO. Stability is threatened by erosion and landslides brought on by rainfall and tourists, and constant monitoring is necessary to stop further deterioration of groundwater flow through tuff and breccia. (P. Higueras and others, 2010). By addressing soil compaction, rock disintegration, and possible slope failures, modern research attempts to maintain the site's geological integrity and guarantee that Las Médulas continues to be a testament to both Roman engineering and natural processes. (UNESCO World Heritage Centre).

11 a geological period and mountain-building event (orogeny) that took place during the late Paleozoic Era, primarily affecting Europe and parts of North America.

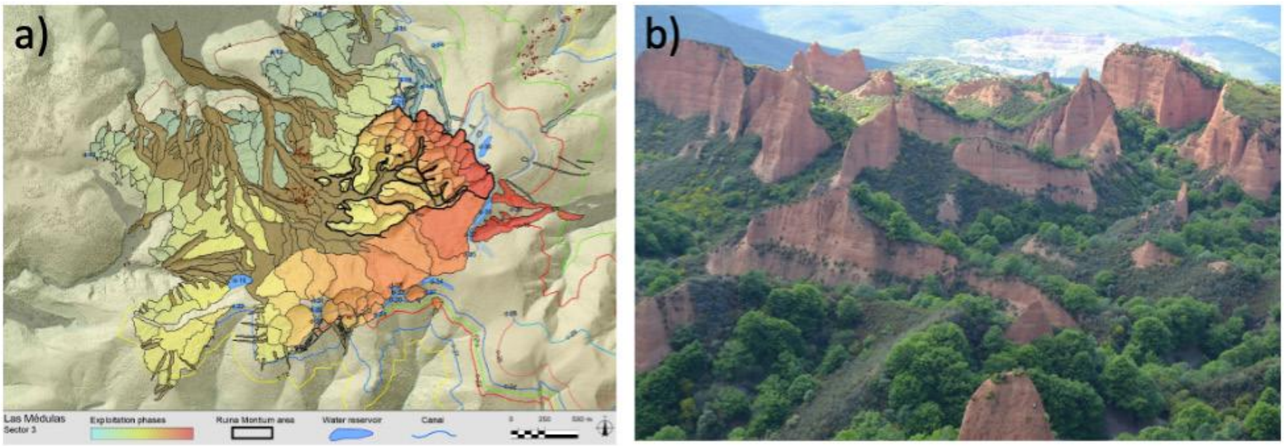


Figure 5: General view of the place

Studies on Soil Structure Stability

The aim of stability analysis of bimrocks is to assess the mechanical behavior and stability of these heterogeneous materials in geotechnical projects such as tunneling, slope stability, and foundation design. (Medley, E. 1994).

Main Objectives of analyses:

- Evaluate mechanical behavior and failure mechanisms.
- Predict stability and potential risks like block sliding and matrix shearing.
- Determine engineering properties such as shear strength and elastic modulus.
- Optimize design and stabilization methods to enhance structural safety.
- Mitigate geological hazards like landslides and sudden settlements.

Structurally Complex Rock Mass

In engineering, the study of diverse rock formations is essential, especially for slope stability, excavation, and tunnels. Brown, E. T., and Hoek, E. (1997). Agglomerates[12] need their mechanical properties to be defined methodically because they are made up of strong blocks inside a weaker matrix. (Medley, E. W. 1994).

Scholars like Medley and Lindquist have been studying complex formations like the Franciscan Complex in California and comparable deposits in Italy since the 1960s. Medley, E. W., and Lindquist, E. S. (1998). Block size, orientation, matrix strength, and

12 geological formations composed of fragments or clasts of varying sizes that have been cemented together by a fine-grained matrix.

block-matrix interaction are important considerations while researching these structures. (Medley, E. W., & Lindquist, E. S. 1995).

Bimrocks (Block-in-Matrix Rocks)

The term was first used by Raymond (1984), but Medley (1994) reinterpreted it to emphasize geotechnical behavior. (L. A. Raymond, 1984). Rock pieces embedded in a finer matrix, usually sandstone or limestone in clay, form bimrocks. (E. W. Medley, 1994). Block-matrix contrast, bond strength, and block proportion all affect their strength. (Medley, E. W., & Zekkos, D. 2011).

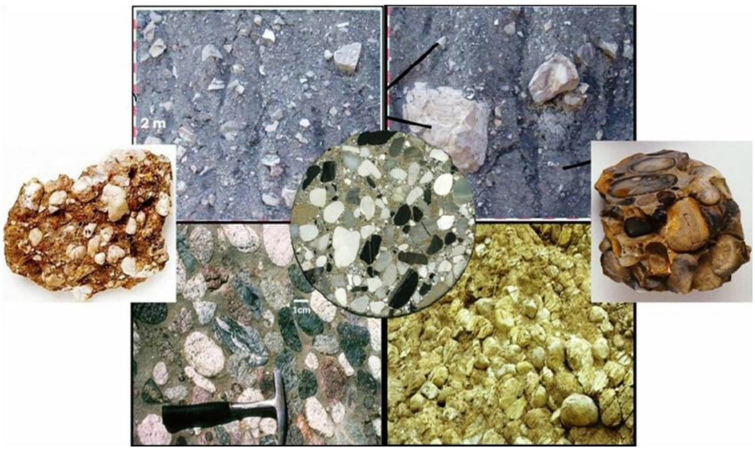


Figure 6: Block-in-Matrix Rocks

Slope Stability in Bimrocks

Blocks' impact on landslide formation must be evaluated in slope stability investigations. (Goodman, R. E., & Lindquist, E. S. 1994). Conventional techniques presume a uniform deposit; nevertheless, studies indicate that the existence of blocks improves stability. Sanz, P. F., and Medley, E. W. (2004). Block volume has a considerable impact on the safety factor, according to studies (e.g., Medley & Sanz, 2004), necessitating thorough characterisation.

Factors Influencing Failure Surfaces

Key elements affecting failure surface tortuosity include:

- Block proportion and size
- Block orientation and distribution
- Matrix strength

Failure surfaces avoid stronger blocks, which raises the safety factor as block volume rises, according to research by Medley and Sanz (2004).

Numerical Methods for Slope Stability

Barbero et al. (2006) investigated slope stability under various block proportions and orientations using finite difference modeling (FLAC). (Barbero, M., Ferrer, M., & Azañón, J. M. 2006) Their conclusions.

- Higher block volume (>20%) increases slope stability
- Elliptical blocks improve resistance more than circular ones
- Low block volume (<20%) behaves like a pure matrix
- Block orientation effects require further study

Analysis of slope stability in bimrocks: models' implementation

---

Numerical Analysis of Slope Stability at Las Médulas Cave Using RS2

Methodology

Ellipses were created using MATLAB in order to model the geotechnical behavior of the Las Médulas slopes. After experimenting with both the polyline and ellipse commands in AutoCAD to add rocks to the models, it was determined that the ellipse command should be used because RS2 had some problems with the polyline command. Using AutoCAD, they can create heterogeneous models and rocks by using the ellipse command and separate layers for distinct model components. The layers are made up of ellipses representing rocks, excavation, material boundaries, and external limits. The models should be exported as DXF files after geometry creation so they may be easily imported into the RS2 program and used for modeling and analysis.

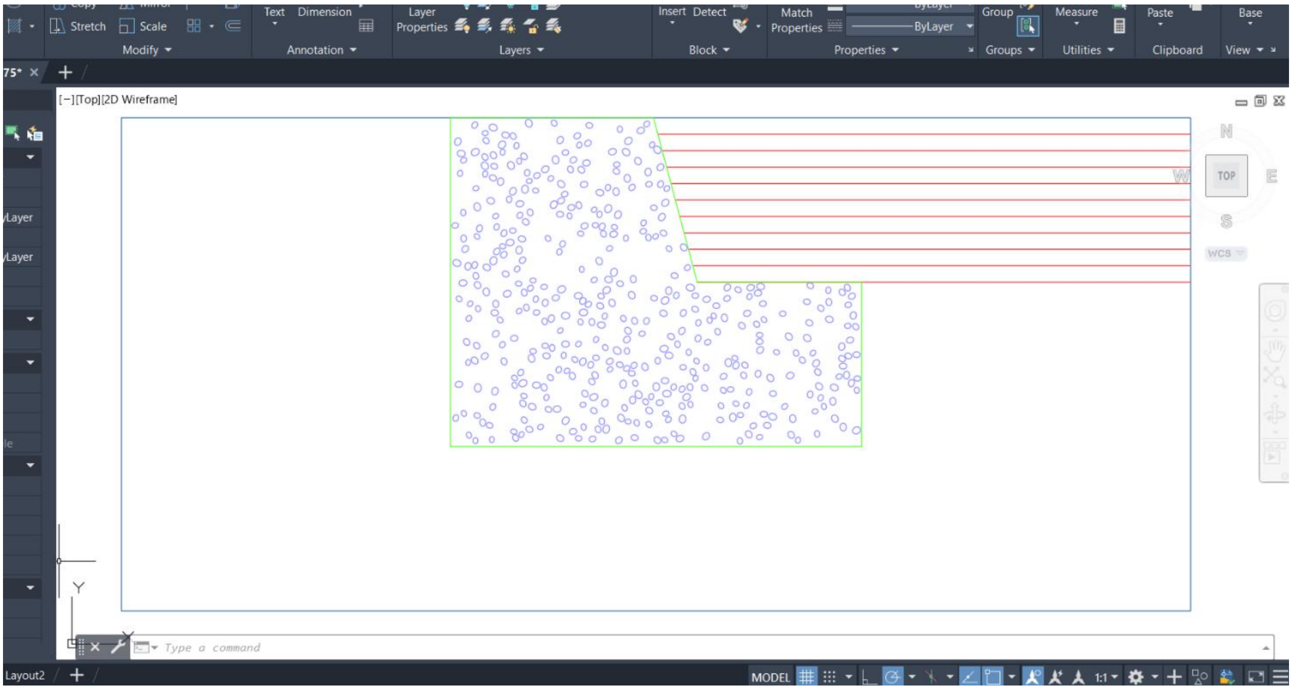


Figure 7: Model in AutoCADfor exporting divers layers as DXF file

Every layer on RS2 needs to be selected as having distinct materials and bounds. Define the layers first, followed by the material attributes. Following that, give the material characteristics to each layer and material independently. If there is a problem with rocks, RS2 might not identify all of the rocks as closed borders; in this case, it is necessary to verify that they are not and add vertexes or materials to fix the issue. Assigning stages is also crucial; this is done in stages, which are listed below:

1- Elastic
2- Elastoplastic
3- Excavations

The vertexes should therefore be more centered on the materials, Materials must be allocated to various levels for every stage, and this should be done for every stage. Mesh creation comes next, followed by. RS2 will then examine the entire model.

Obstacles:

The most significant and significant problem during the process was the permissible diameter of the rocks that RS2 could operate with; in actuality, RS2 does not accept rocks with small diameters, and it was limited by the model's height.

In order to resolve the issue, the limit diameter for each model should be established, and rocks smaller than the limit must be removed.

The diameter and proportion for each model are shown in the tables below:

Diameters of the rocks

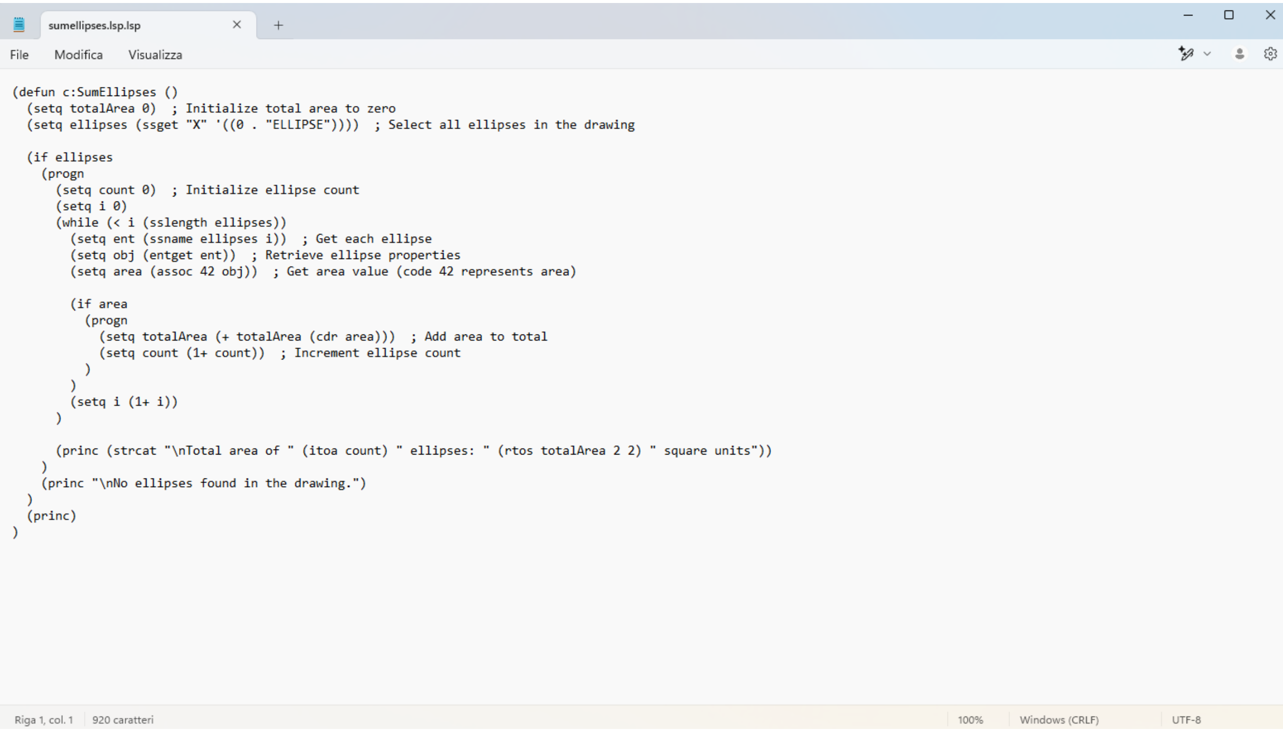
Diameters of the Rocks which RS 2 accepted to load and Analyze are shown below:

	VBP 40%			VBP 30%			VBP 20%			VBP 10%		
Height	H=10m			H=10m			H=10m			H=10m		
Slope Angle	60	75	90	60	75	90	60	75	90	60	75	90
Diameter	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm	≥40cm
Height	H=20m			H=20m			H=20m			H=20m		
Slope Angle	60	75	90	60	75	90	60	75	90	60	75	90
Diameter	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm	≥70cm

Table 1: Allowable diameters of the rocks

Calculation of areas and proportion

The command "sumellipses" is used in AutoCAD to calculate models. As seen in the picture below, a code is written and uploaded to AutoCAD using the "appload" command. "Sumellipses" may then be used to assist us add up the areas of all ellipses.




```
(defun c:SumEllipses ()
  (setq totalArea 0)  ; Initialize total area to zero
  (setq ellipses (ssget "X" '((0 . "ELLIPSE"))))  ; Select all ellipses in the drawing

  (if ellipses
    (progn
      (setq count 0)  ; Initialize ellipse count
      (setq i 0)
      (while (< i (sslength ellipses))
        (setq ent (ssname ellipses i))  ; Get each ellipse
        (setq obj (entget ent))  ; Retrieve ellipse properties
        (setq area (assoc 42 obj))  ; Get area value (code 42 represents area)

        (if area
          (progn
            (setq totalArea (+ totalArea (cdr area)))  ; Add area to total
            (setq count (1+ count))  ; Increment ellipse count
          )
        )
        (setq i (1+ i))
      )

      (princ (strcat "\nTotal area of " (itoa count) " ellipses: " (rtos totalArea 2 2) " square units"))
    )
    (princ "\nNo ellipses found in the drawing.")
  )
  (princ)
)
```

Figure 8: Sumellipses command written to upload in AutoCAD

Rocks proportion of each model

	H=10m							
Height	VBP 40%		VBP 30%		VBP 20%		VBP 10%	
Slope Angle	60	75	60	75	60	75	60	75
area proportion	2601.24/14847.17	2682.92/14847.17	1916.37/11535.93	2676.64/11535.93	1313.19/7407.88	1350.88/7407.88	2337.34/3826.46	2450.44/3826.46
	0,175201065	0,18070245	0,166121847	0,232026373	0,17726934	0,182357166	0,610836125	0,640393471
Height	H=20m							
Slope Angle	60	75	60	75	60	75	60	75
area proportion	4052.65/38352.56	2664.07/38352.56	1646.19/12289.91	3003.36/12289.91	3179.29/8293.8	1878.67/8293.8	2463.01/4096.64	955.04/4096.64
	0,105668305	0,069462638	0,133946465	0,244376078	0,383333333	0,226514987	0,601226859	0,233127636

Table 1: Proportion of the rocks

The analysis focused on three key parameters:

- Maximum Shear Strain[13] – to evaluate deformation patterns under shear stress.
- Total Displacement[14] – to assess overall movement and stability.
- Yielded Elements[15] – to identify zones where the material strength is exceeded,

Mechanical Properties of the materials:

The features of the matrix and rocks are shown below:

Parameter	Matrix	Blocks
γ [kN/m^3]	23	26
c [kPa]	400	4000
φ [°]	34	45
σt [kPa]	0,09	1,9
E [MPa]	2900	8000
v [-]	0,3	0,25

Table 3: Mechanical properties of the matrix & rocks

13 The maximum deformation in a material caused by shear forces, indicating the material's ability to withstand shear stress before failure.

14 refers to the overall movement of a point or object from its original position to its final position, considering both magnitude and direction.

15 Yielded elements are parts of a material or structure that have undergone plastic deformation due to stresses exceeding the material's yield strength.

The SRF of various VBP for various slope angles and two distinct heights is displayed in the figures below:

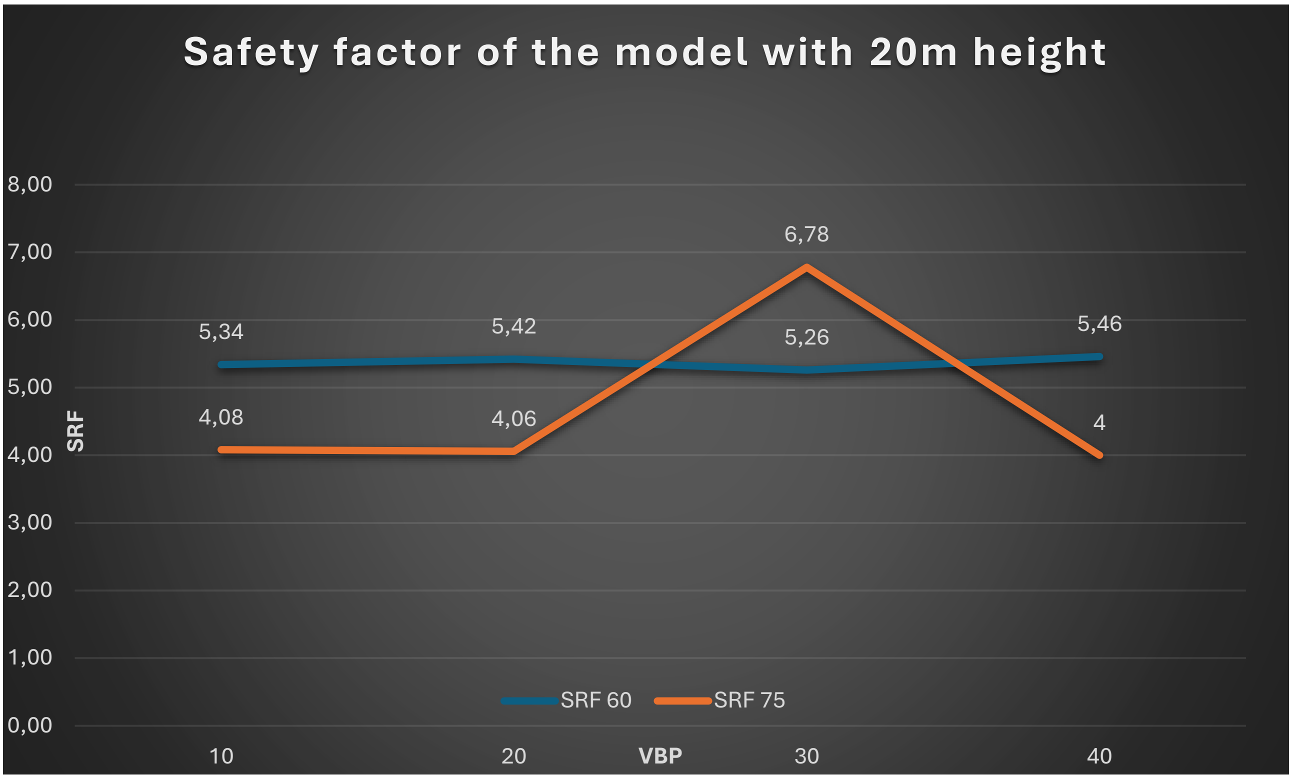


Figure 9: SRF of the model in different VBP H20

Figure 10: SRF of the model in different VBP H10

Using RS2, the geotechnical stability analysis looked at how changes in slope angle and Volumetric Block Proportion (VBP) affected the failure processes at Las Médulas Cave. In order to evaluate the effects of various conditions on shear strain, displacement, and structural yielding, the study took into account two slope heights (10 m and 20 m), two slope angles (60° and 75°), and four distinct VBPs (10%, 20%, 30%, and 40%).

Maximum Shear Strain Distribution

Significant variations in stress distribution according to slope angle and VBP were found by the shear strain analysis:

- Steeper slopes (75°) exhibited the highest shear strain, particularly at the base, where stress concentration was most intense.
- Higher VBP values (30%-40%) resulted in a more widespread shear strain distribution, indicating increased heterogeneity in mechanical behavior.
- Lower VBP models (10%-20%) had more localized shear zones, suggesting that a stronger matrix-dominated structure provides better resistance to failure.

Interpretation:

A more complex failure process results from the redistribution of stress around the larger blocks because of the rock mass becoming less homogeneous as VBP rises. This implies that to reduce the likelihood of shear failures, slope reinforcing should concentrate on high-VBP zones.

Total Displacement Analysis

The results of the total displacement revealed distinct patterns according to block proportion, height, and slope angle:

- Displacement increased with greater slope angles and height, with 20m slopes exhibiting significantly higher displacements than 10m slopes.
- The highest displacement occurred at the crest of the slopes, particularly in 90° models, indicating that steep slopes are less stable.
- Higher VBP values (40%) resulted in greater total displacement, suggesting that an increased number of large blocks weakens overall slope stiffness, making the terrain more susceptible to movement.

Yielded Elements Analysis (Failure Zones)

Finding areas where the rock mass had surpassed its strength limits and caused plastic deformation or failure was the main goal of the yielded elements analysis:

- Steeper slopes (75°) and greater heights (20m) showed the highest number of yielded elements, confirming these conditions are more prone to structural failure.
- Higher VBP (30%-40%) resulted in more widespread yielding, especially at the toe of the slope, where stress accumulation was highest.

Interpretation:

Since overall cohesiveness is weakened by the block-matrix interaction, higher VBP results in increased instability. Yielded zones are in fact developing inside the matrix component.

Final Conclusions and Engineering Implications

The RS2 analysis sheds important light on the stability of the slopes in Las Médulas by emphasizing how block proportion, slope angle, and height affect erosion and failure mechanisms. The main conclusions are:

Influence of VBP on Stability

- Higher VBP (30%-40%) seem to reduces overall stability, increasing displacement, stress redistribution, and failure risk. However, since the real VBP of the models was reduced for RS limitations, the matrix properties should have been increased to account for the presence of small rock blocks, not modelled.

Impact of Slope Angle on Stability

- Because steeper slopes undergo higher stress concentrations, greater yielding, and increased displacement, 60° slopes are noticeably more stable than 75° slopes.
- Slopes over 60° should be the main focus of analyses and eventually of reinforcement.

Effects of Slope Height on Failure Potential

- Because of increased stress building and gravitational pressures, 20-meter slopes are more likely to deform and yield than 10-meter slopes.
- Taller slopes should be given priority in mitigation methods, particularly in cases where slope angles exceed 60°.

Failure Surface Behavior and Tortuosity

- More convoluted failure surfaces are produced by larger block proportions, which raises the safety factor but complicates failure prediction.
- To take failure route variations into consideration, slope stabilizing techniques must be developed using site-specific block distributions.

Appendix

Results of the models

H10:

VBP 10:

Models of 60, 75 degrees of slope angles:

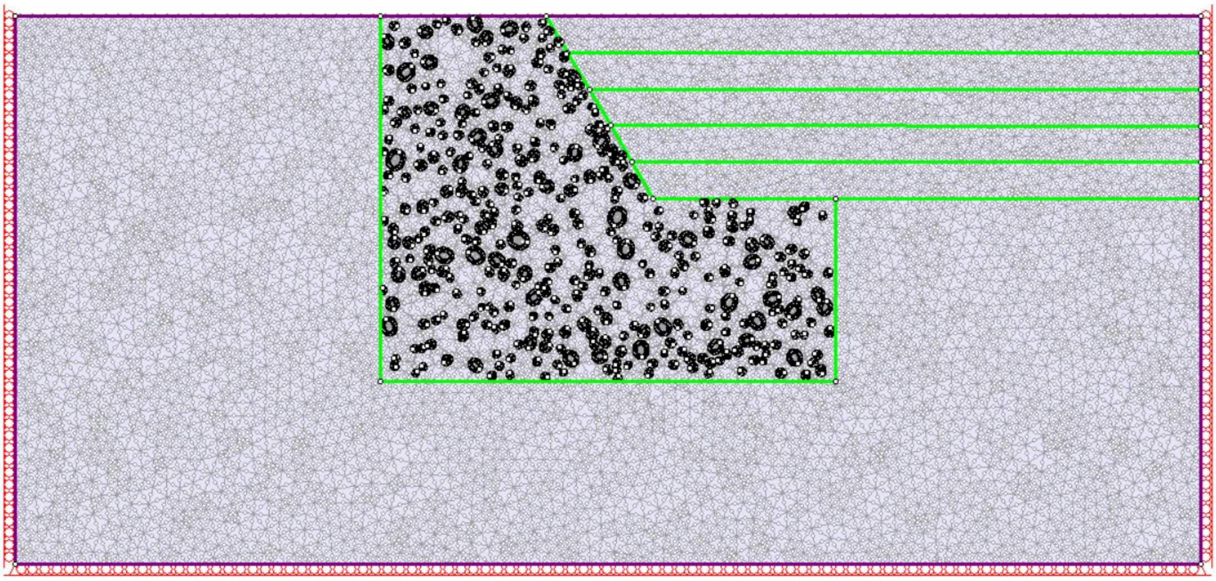


Figure 11: 60 degree model VBP 10

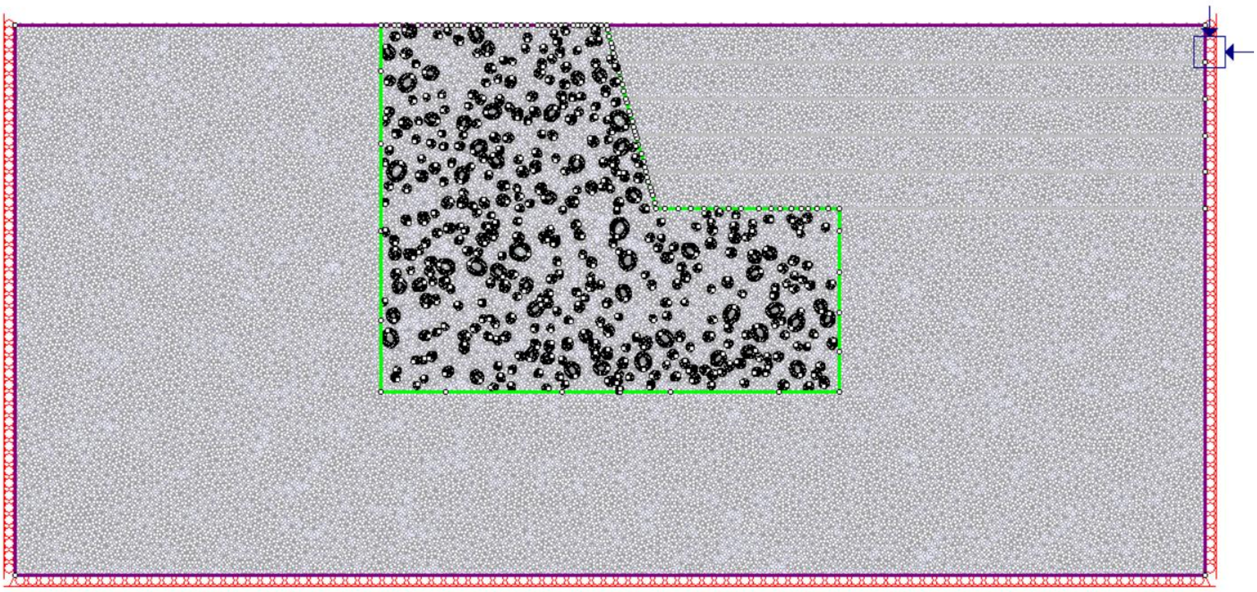


Figure 12: 75-degree model VBP 10

Maximum shear strain:

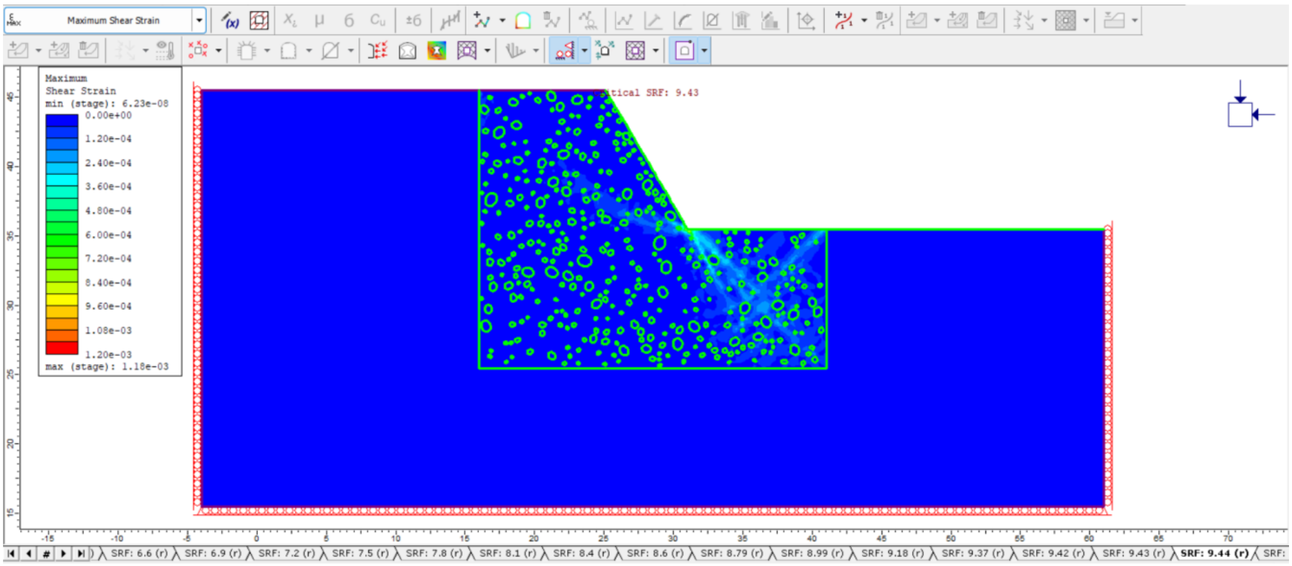


Figure 13: Maximum Shear Strain H10 VBP 10-60

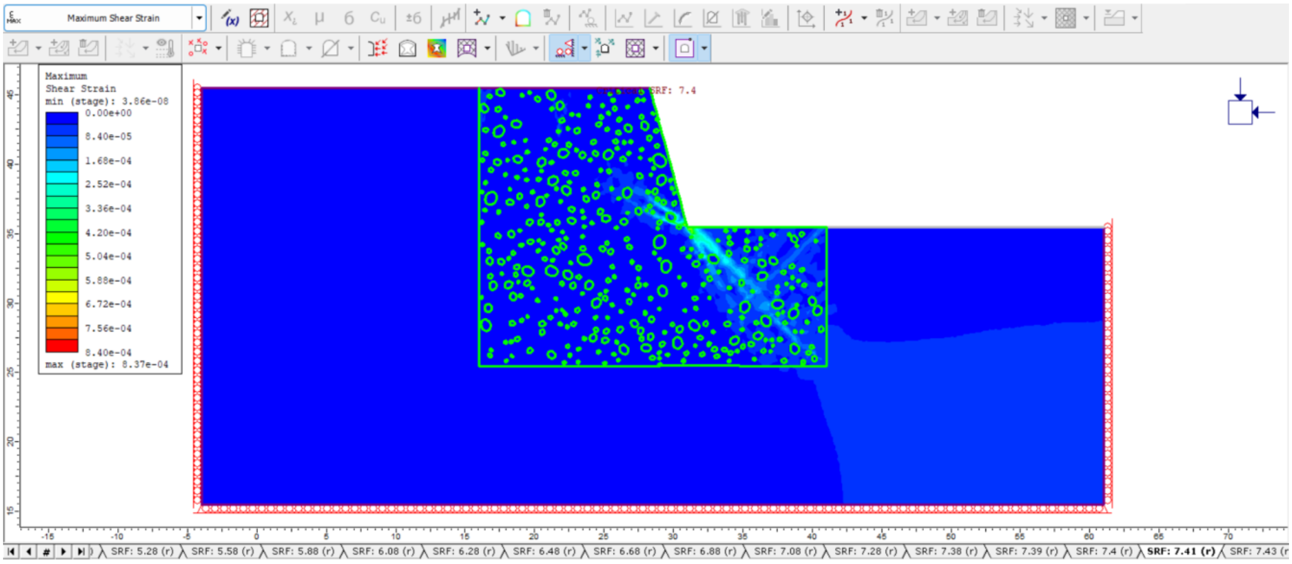


Figure 14: Maximum Shear Strain H10 VBP 10-75

Yielded elements:

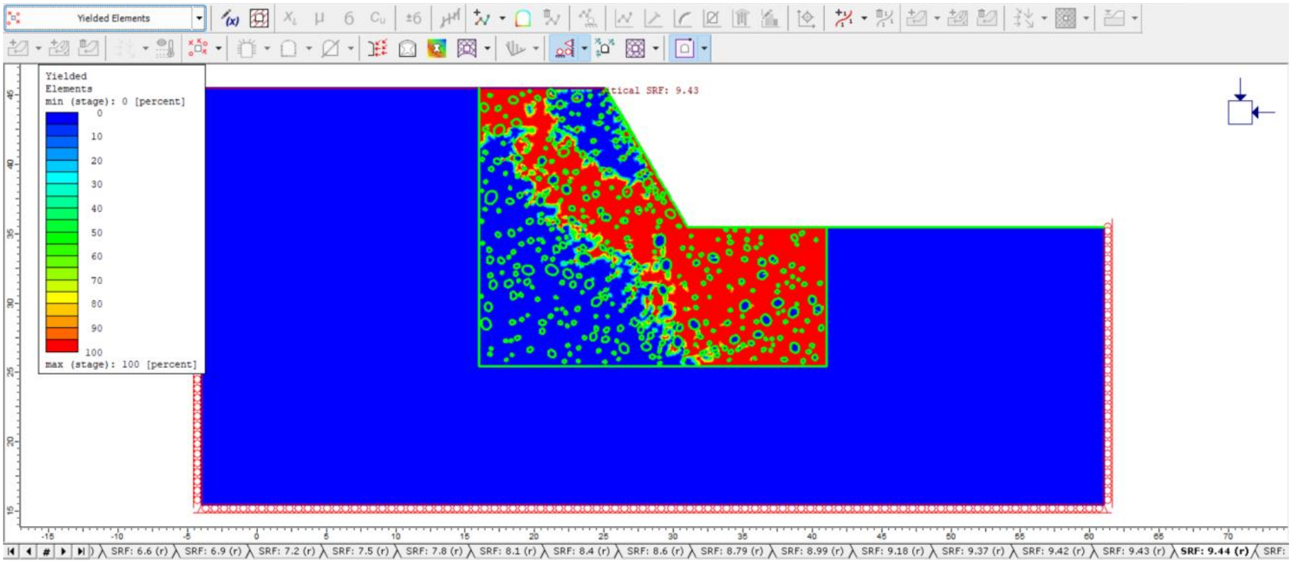


Figure 15 : Yielded elements H10 VBP 10-60

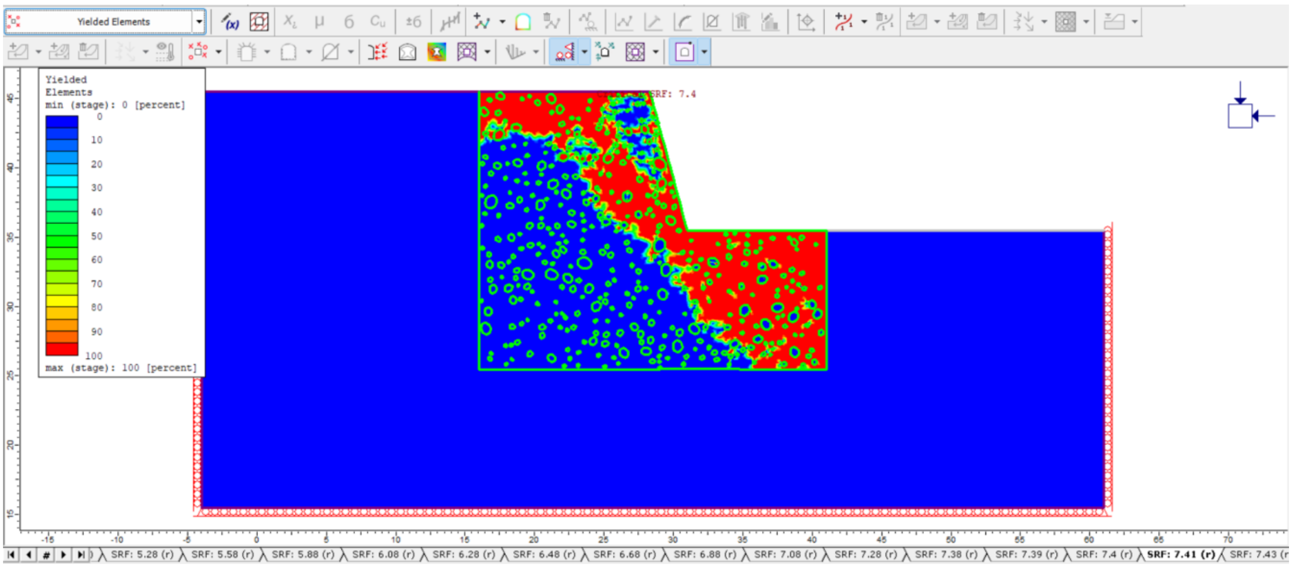


Figure 16: Yielded elements VBP 10 h10-75

Total displacement:

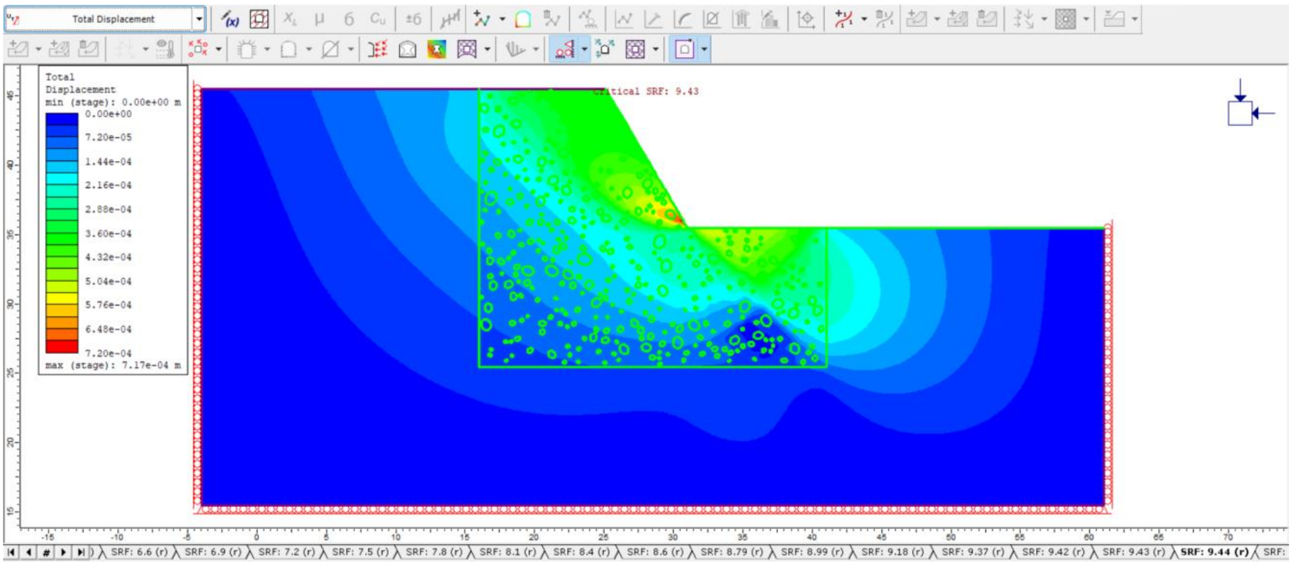


Figure 17: Total displacements. h10-vbp10-60

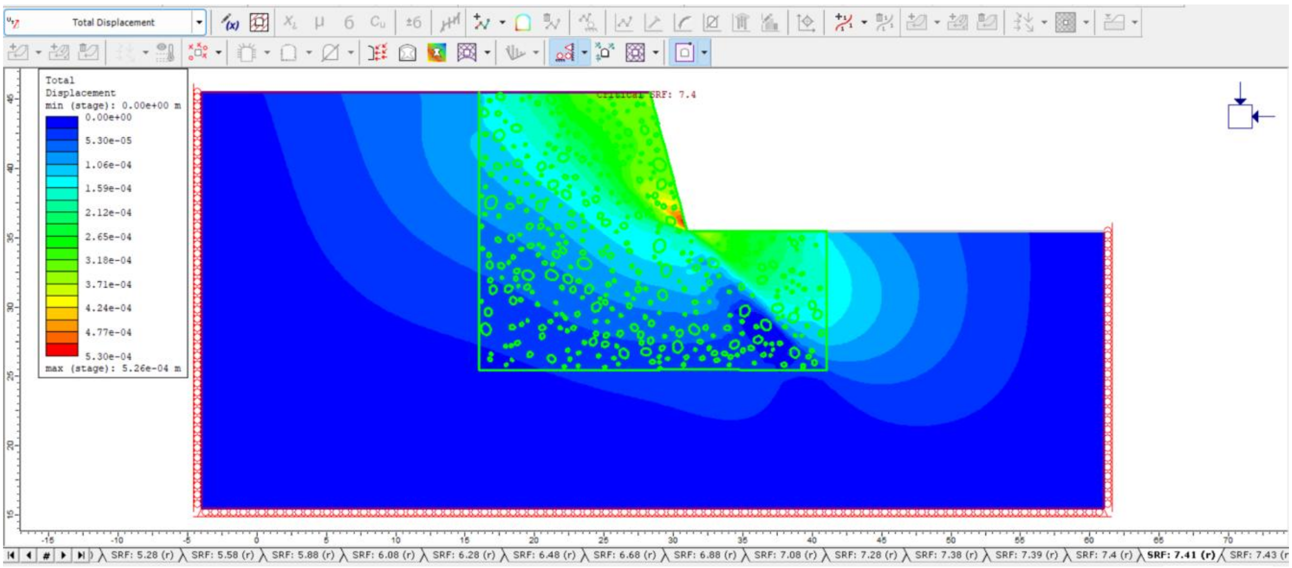


Figure 18: Total displacements. h10-vbp10-75

VBP 20:

Models of 60, 75 degrees of slope angles:

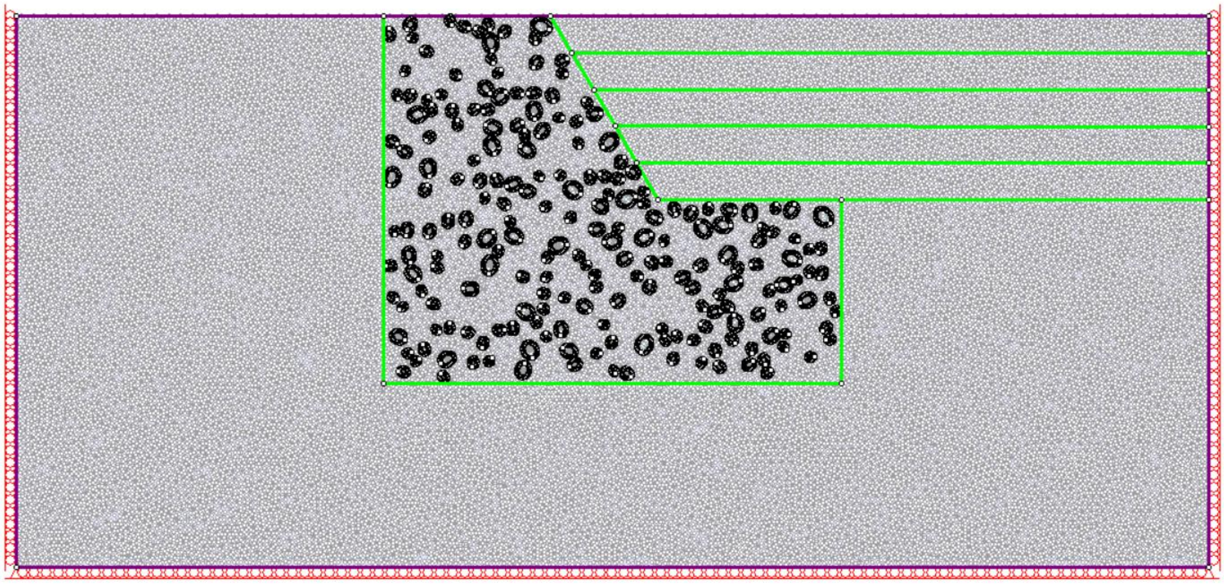


Figure 19: Model h10-vbp20-60

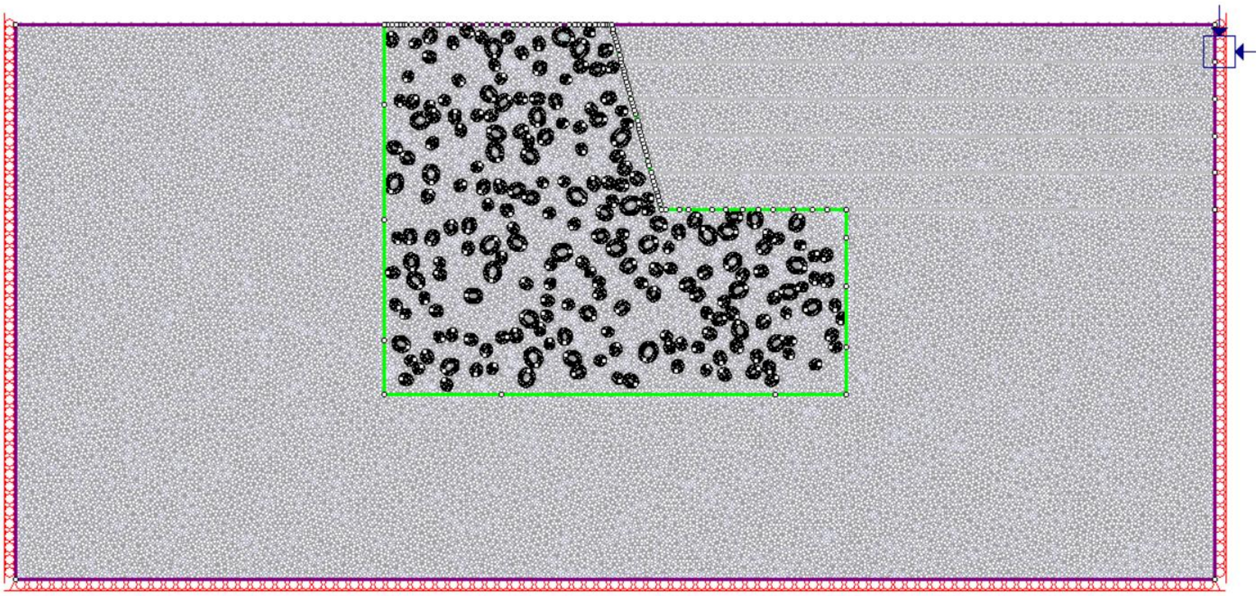


Figure 20: Model h10-vbp20-75

Maximum shear strain:

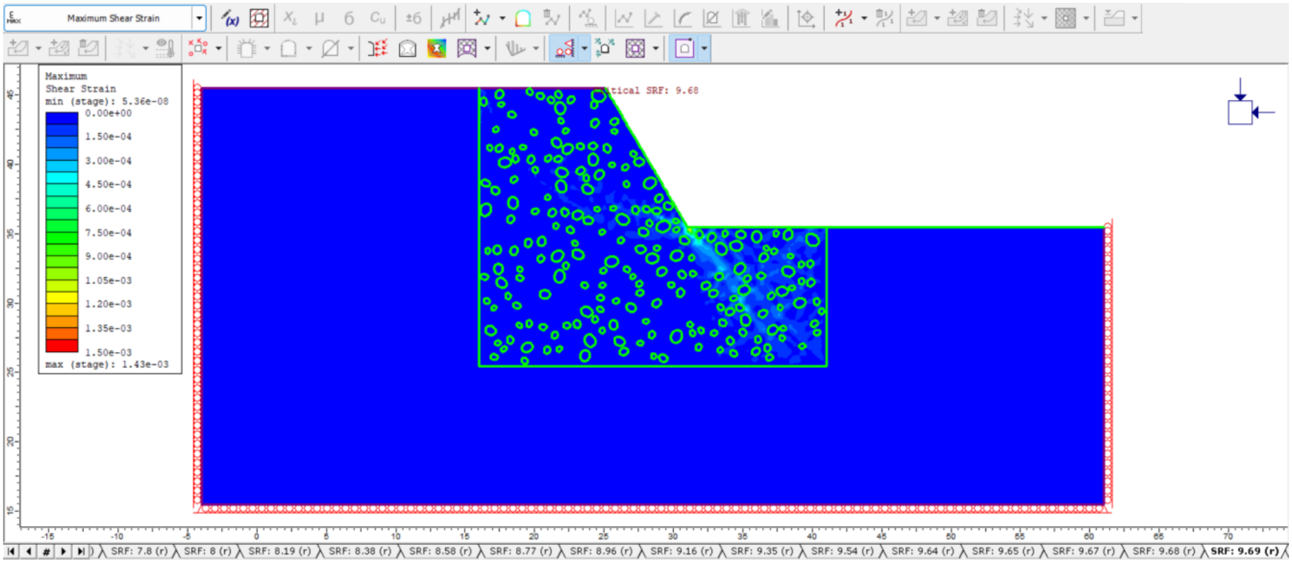


Figure 21: Maximum shear strain h10-vbp20-60

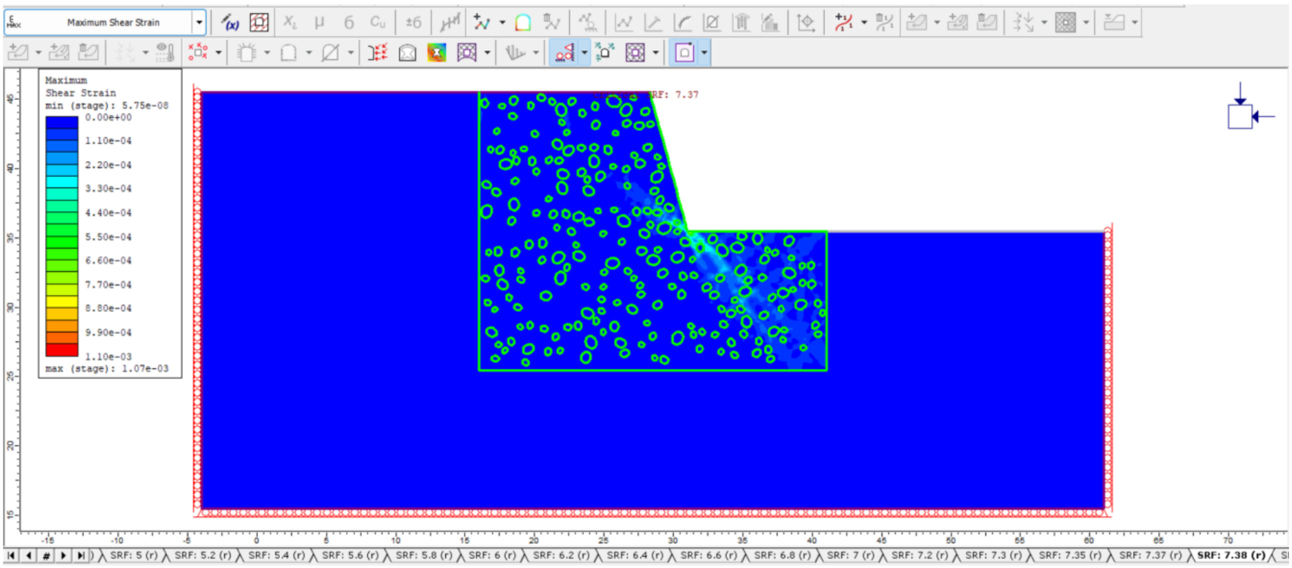


Figure 22: Maximum shear strain h10-vbp20-75

Yielded elements:

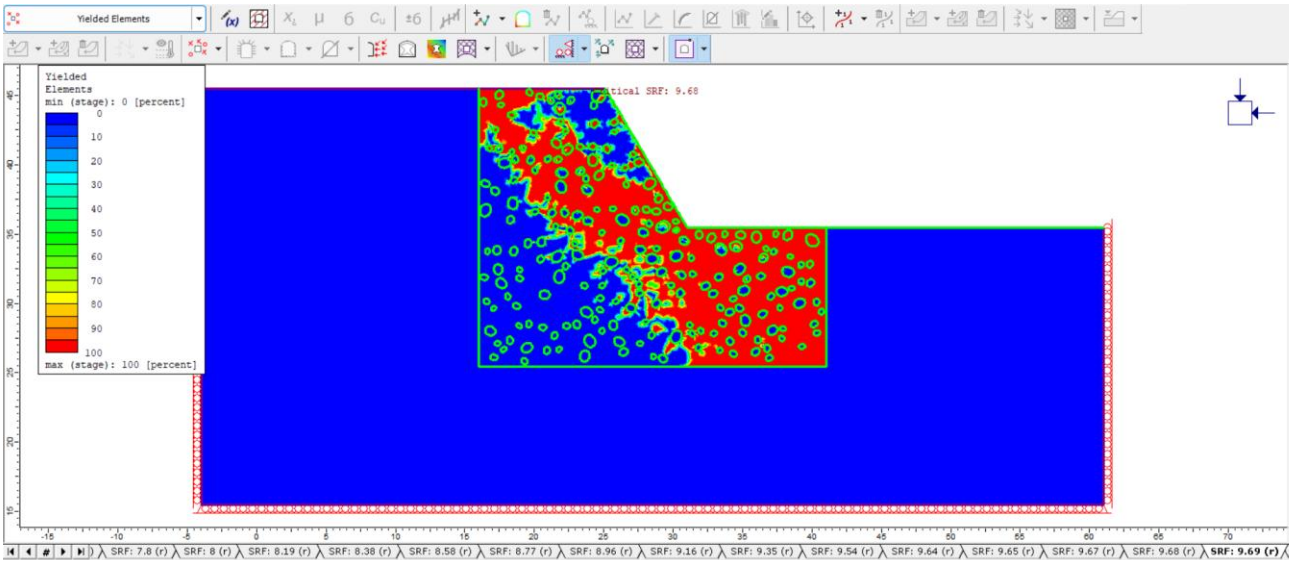


Figure 23: Yielded elements h10-vbp20-60

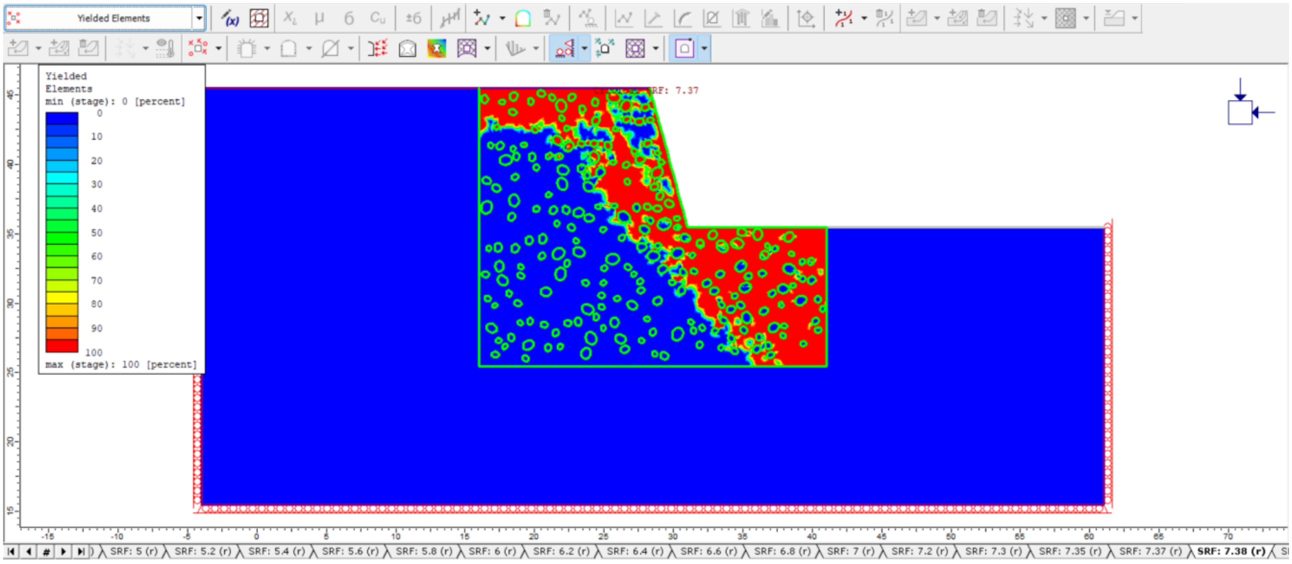


Figure 24: Yielded elements h10-vbp20-75

Total displacement:

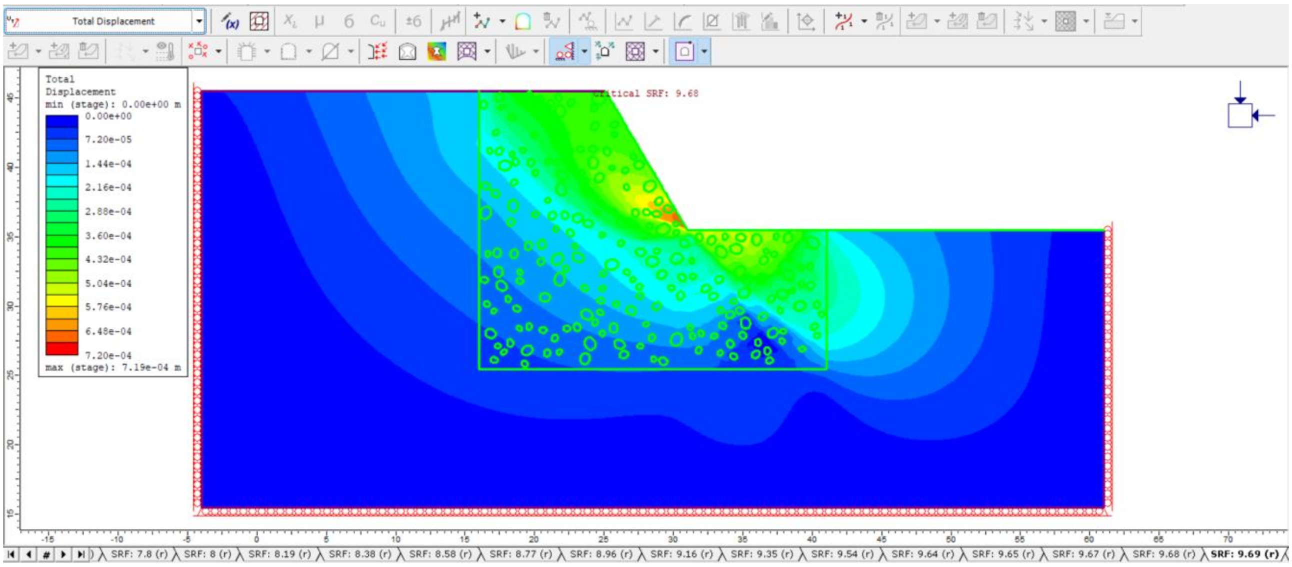


Figure 25: Total displacement h10-vbp20-60

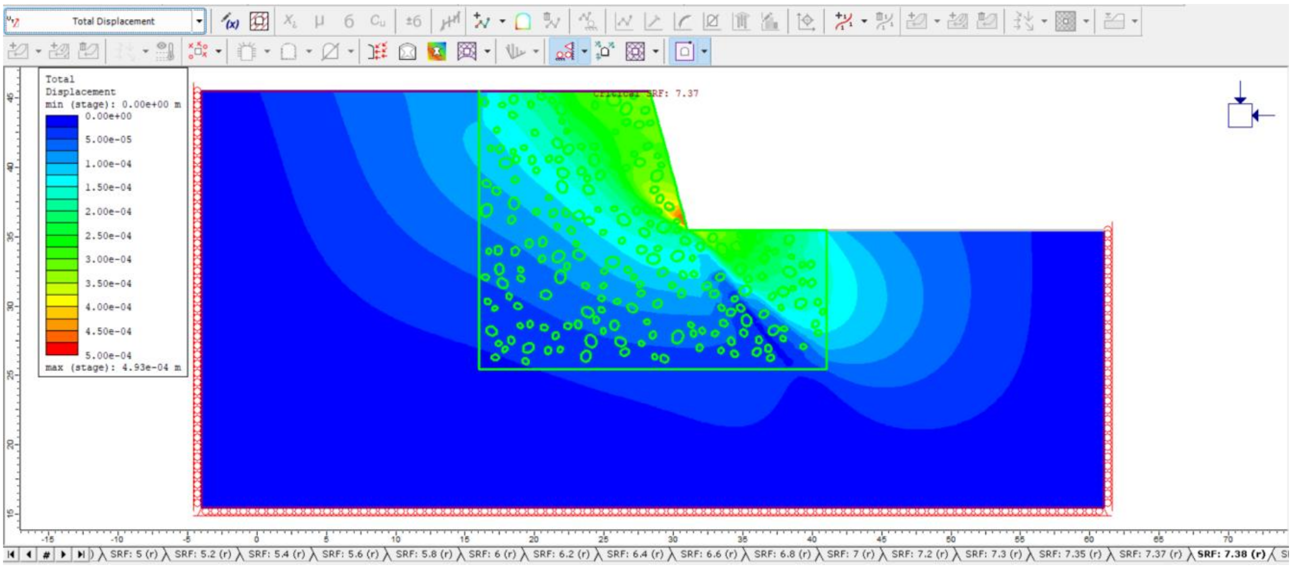


Figure 26: Total displacements h10-vbp20-75

VBP 30:

Models of 60, 75 degrees of slope angles:

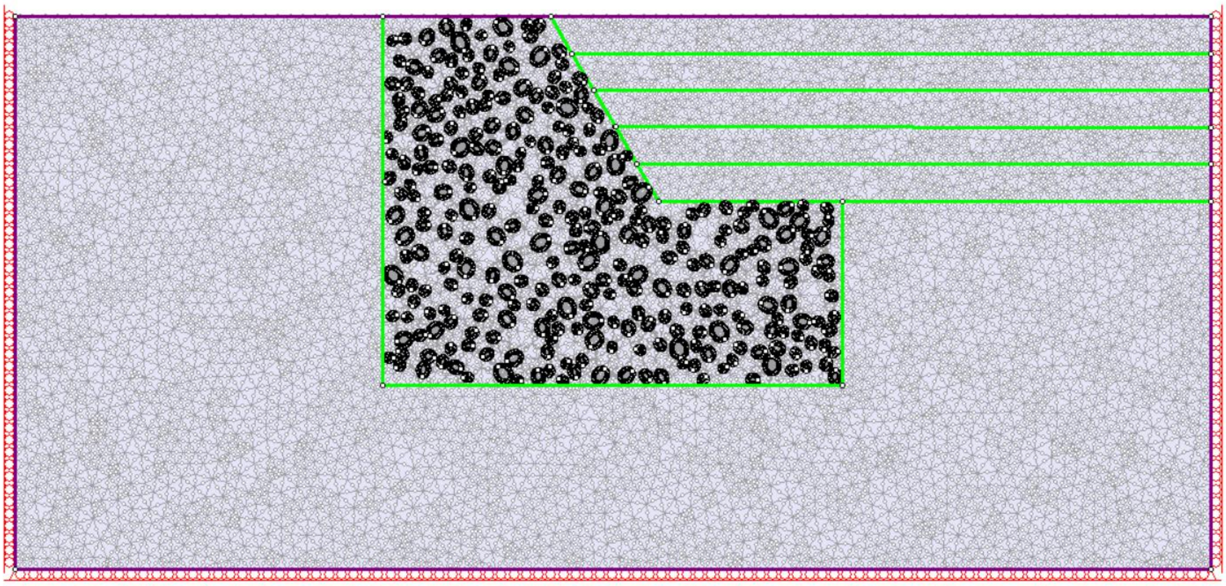


Figure 27: Model h10-vbp30-60

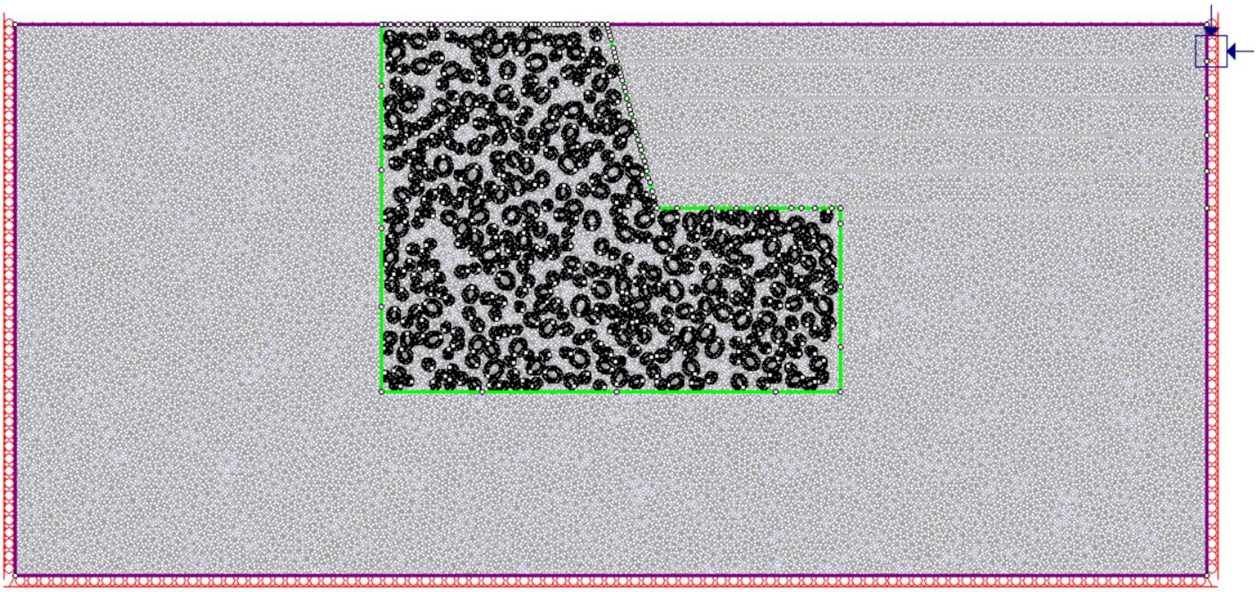


Figure 28: Model h10-vbp30-75

Maximum shear strain:

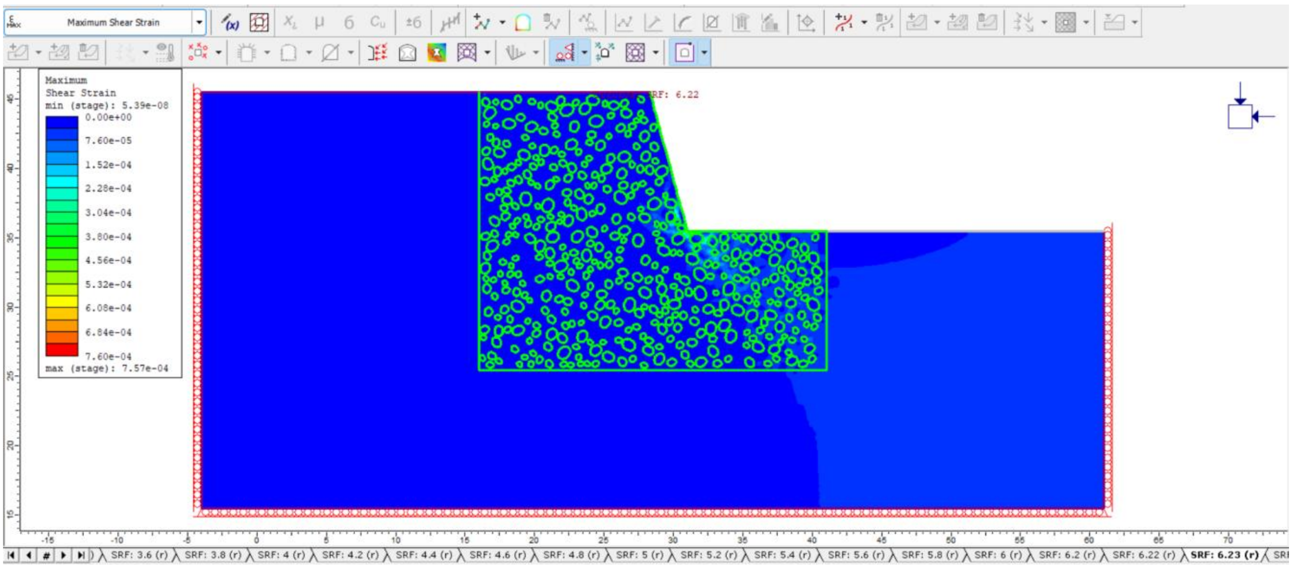


Figure 29: Maximum shear Strain h10-vbp30-75

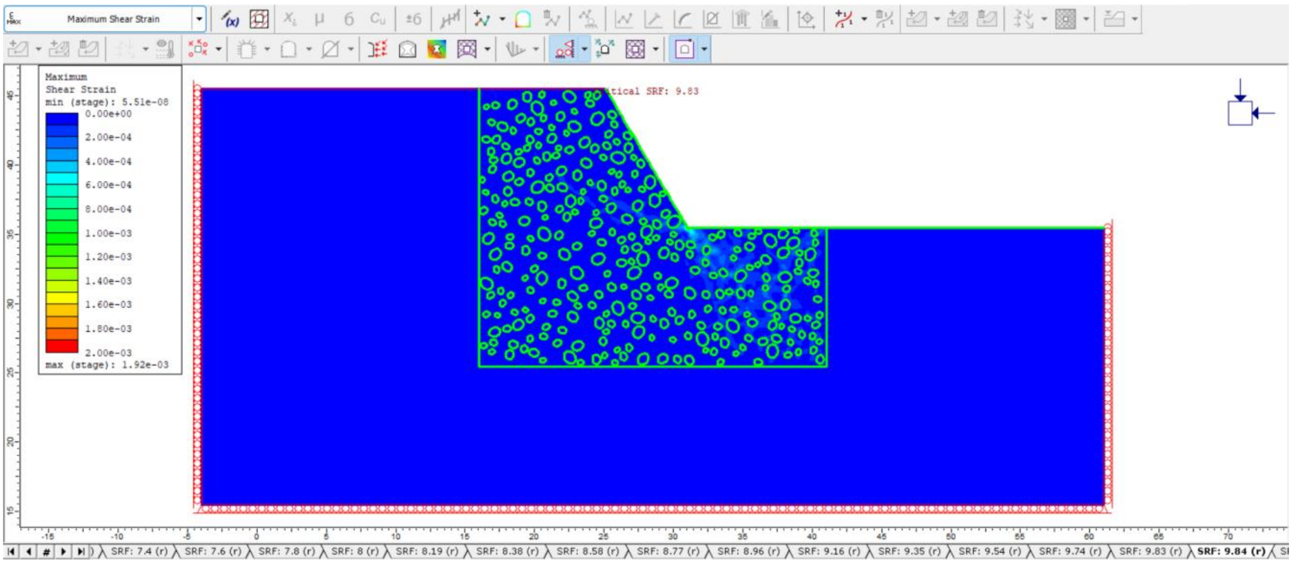


Figure 30: Maximum shear Strain h10-vbp30-60

Yielded elements:

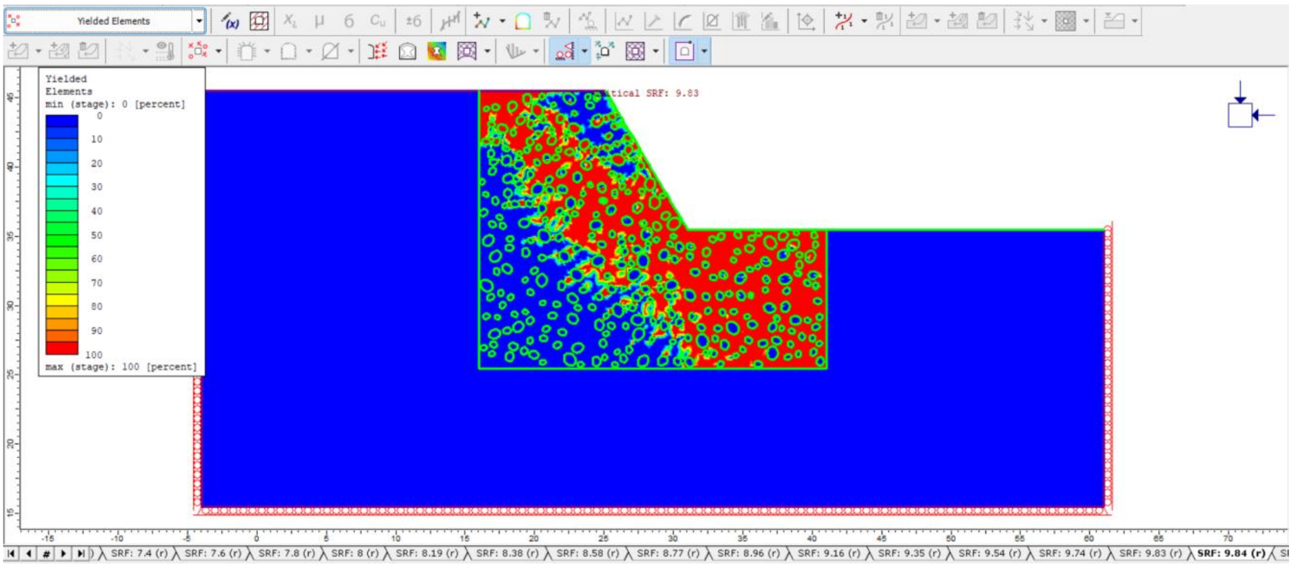


Figure 31: Yielded elements h10-vbp30-60

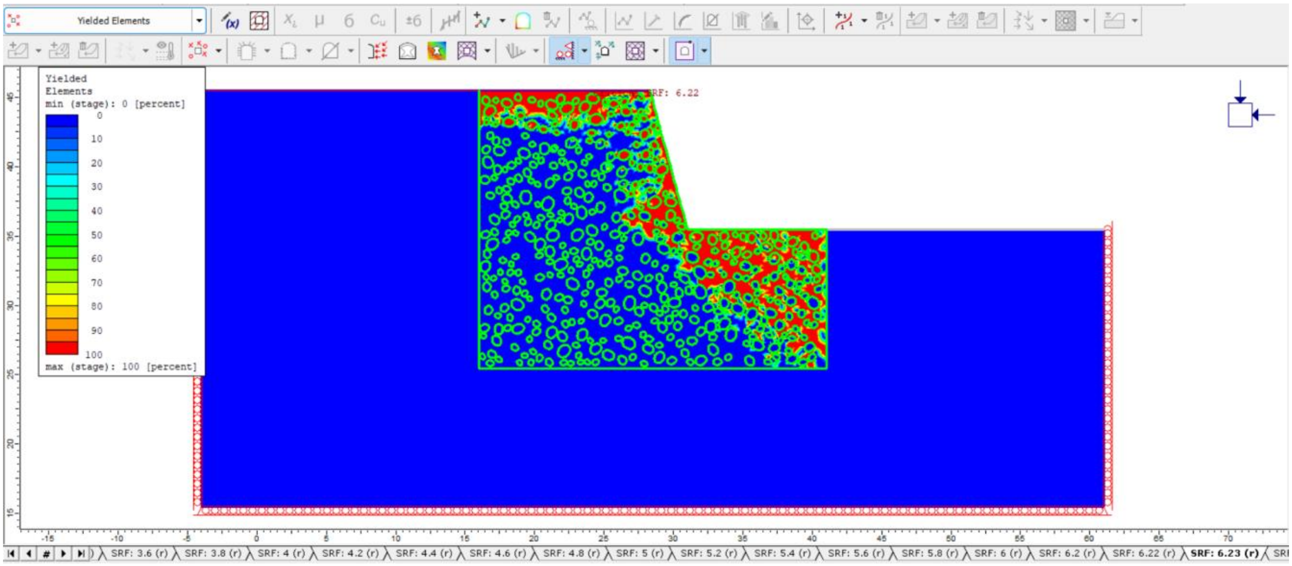


Figure 32: Yielded elements h10-vbp30-75

Total displacement:

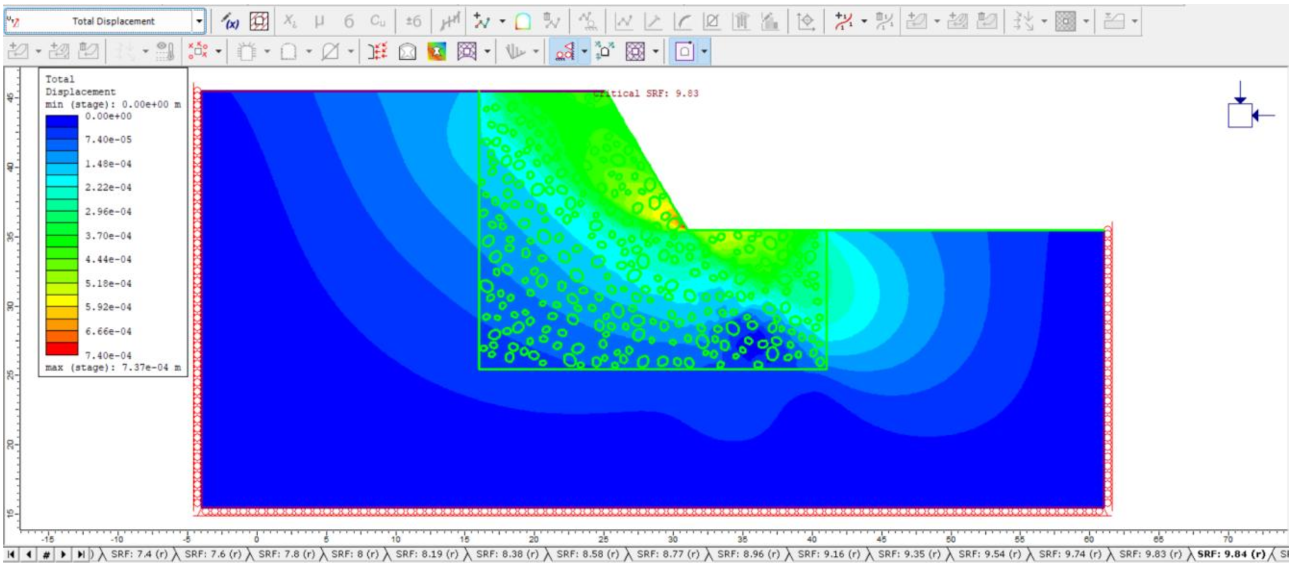


Figure 33: Total displacement h10-vbp30-60

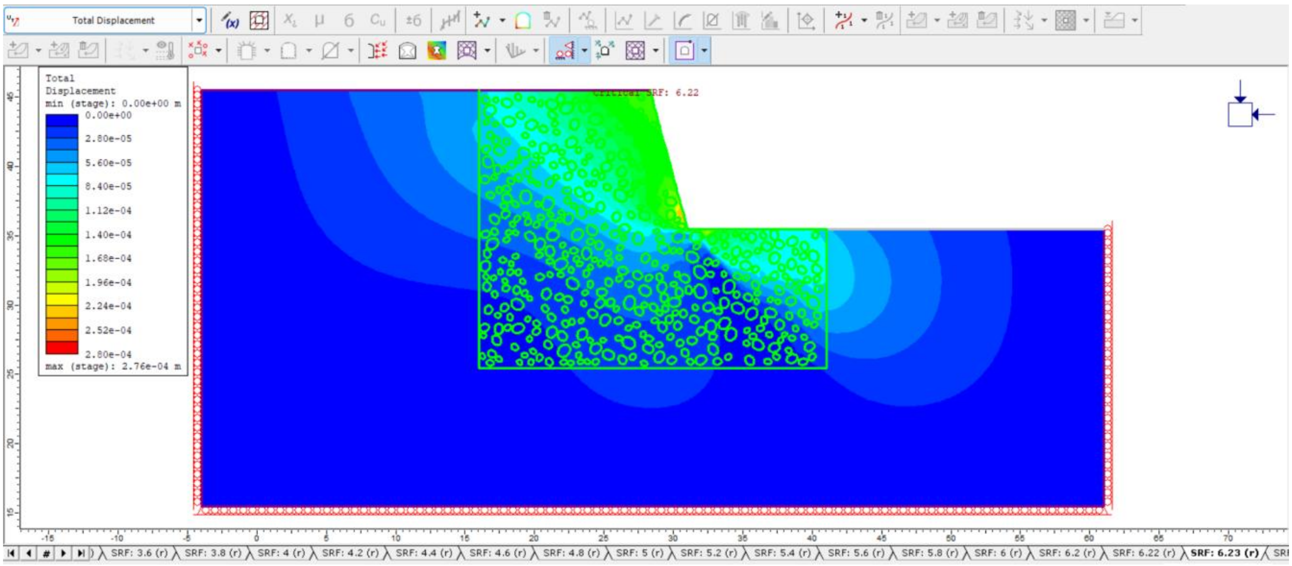


Figure 34: Total displacement h10-vbp30-75

VBP 40:

Models of 60, 75 degrees of slope angles:

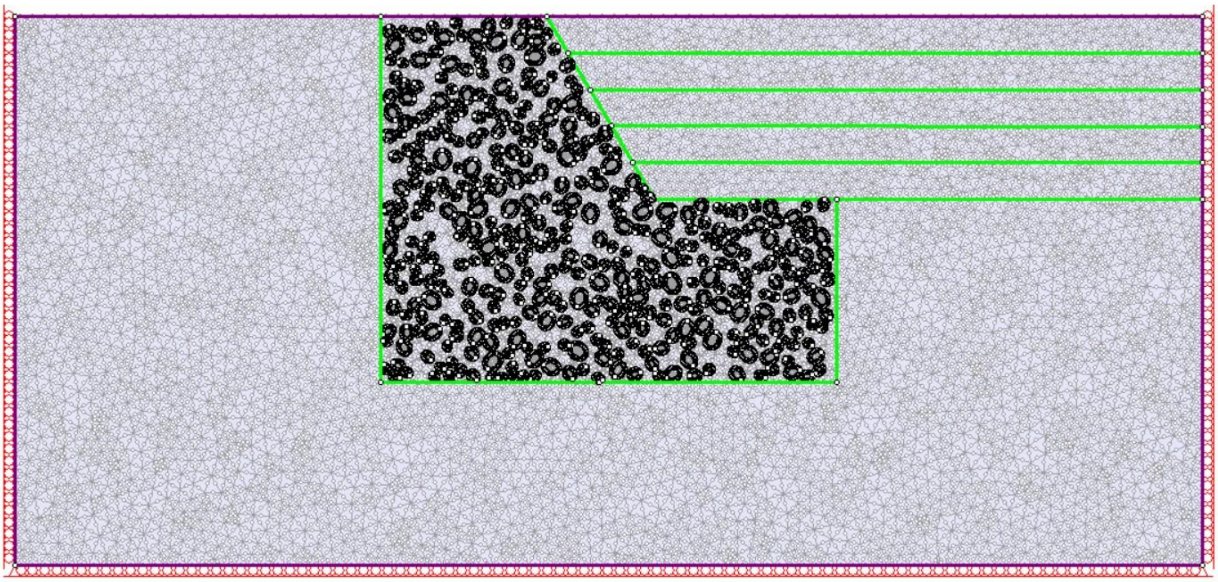


Figure 35: model h10-vbp40-60

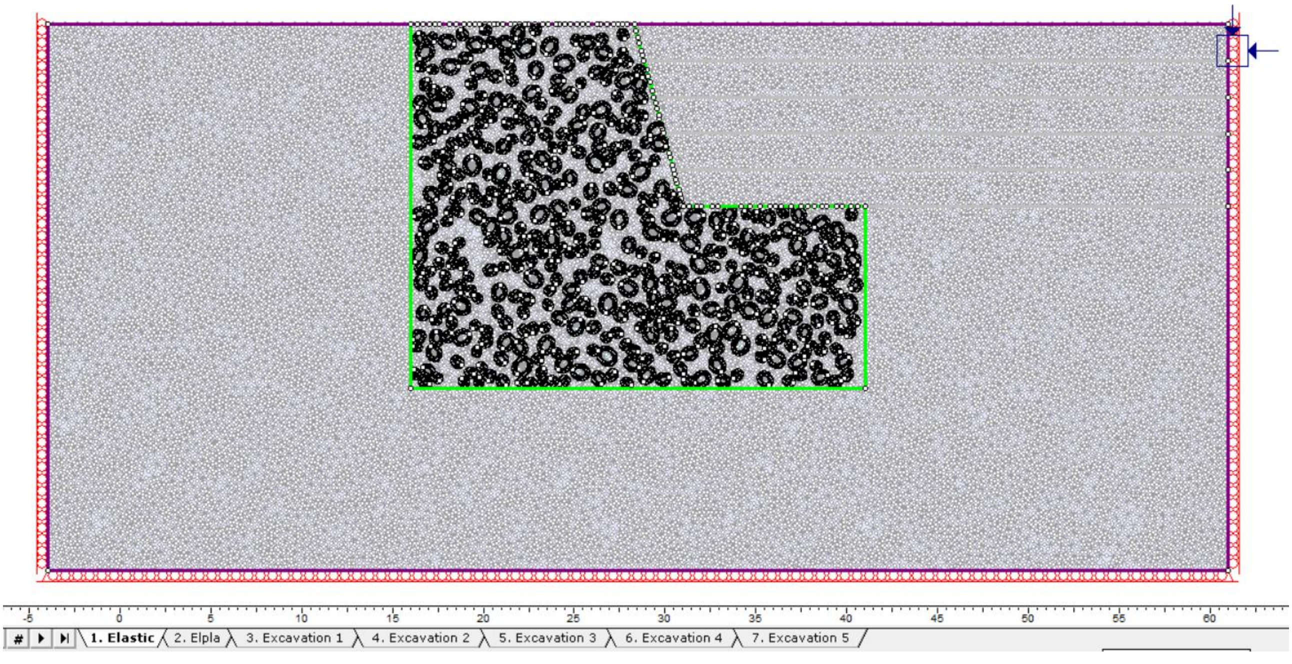


Figure 36: model h10-vbp40-75

Maximum shear strain:

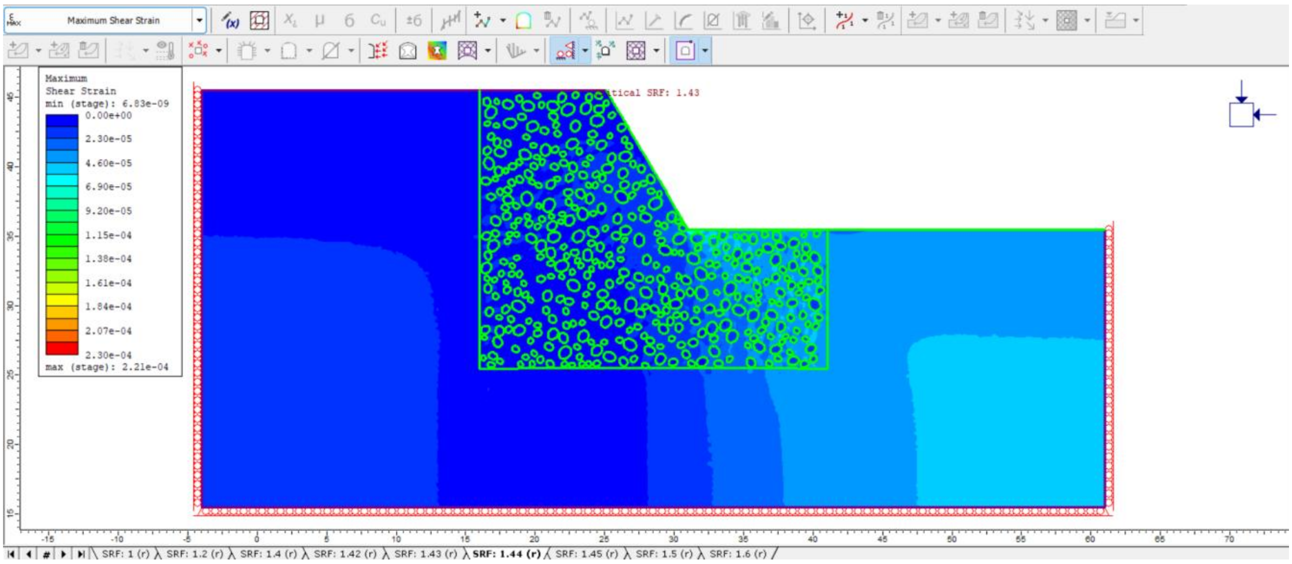


Figure 37:: maximum shear strain h10-vbp40-60

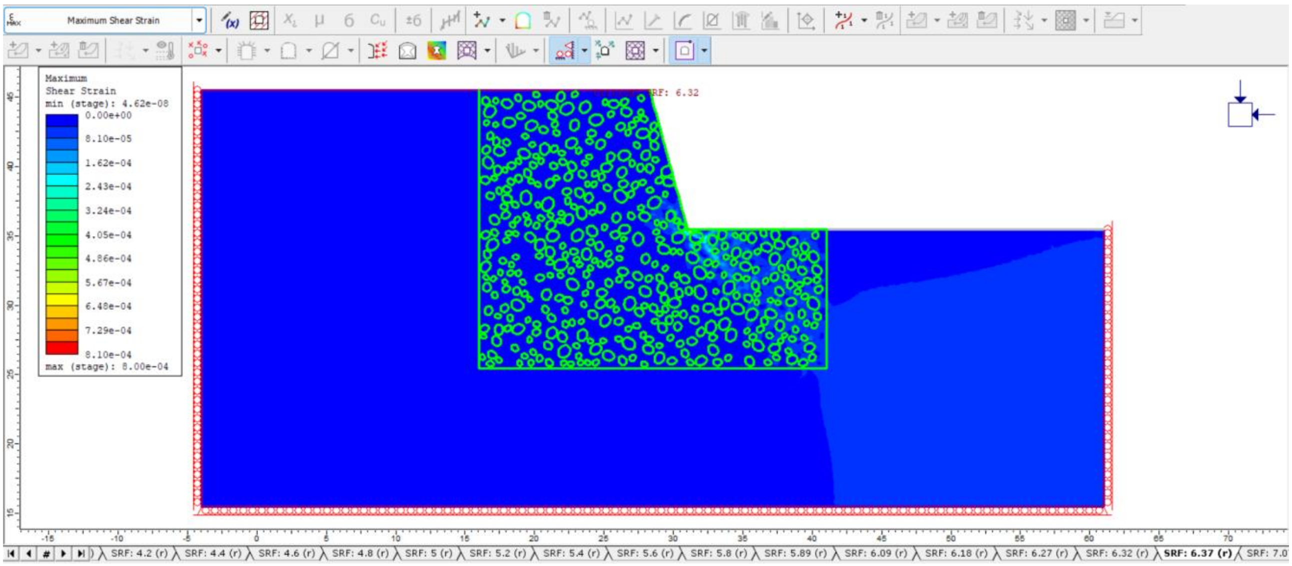


Figure 38: Maximum shear strain h10-vbp40-75

Yielded elements:

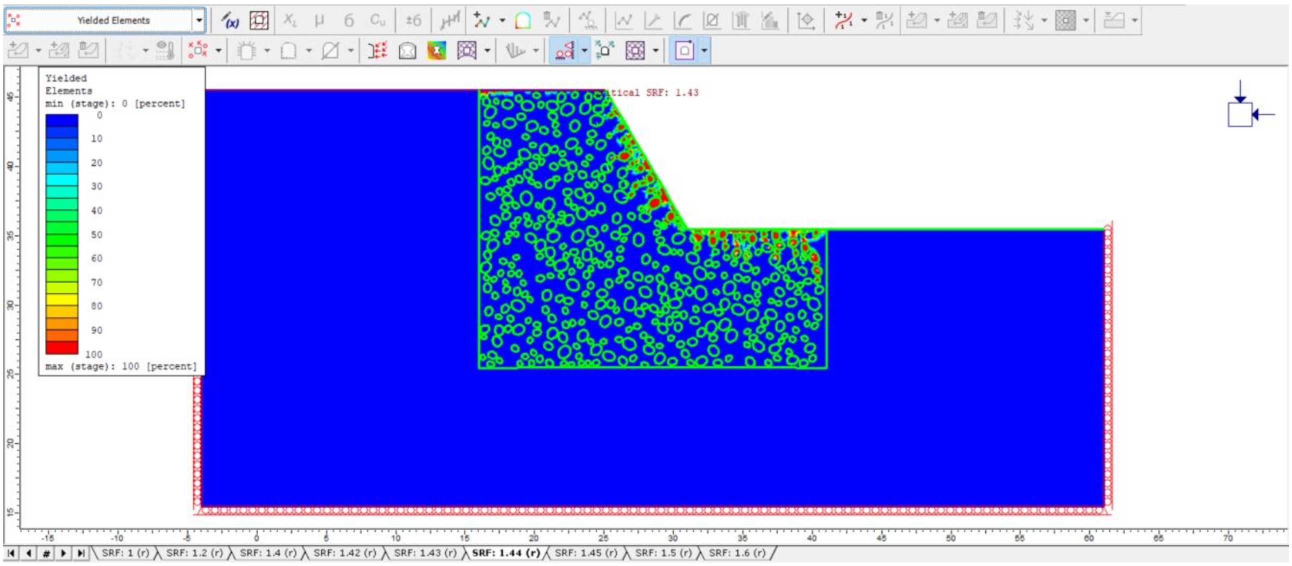


Figure 39: yielded elements h10-vbp40-60

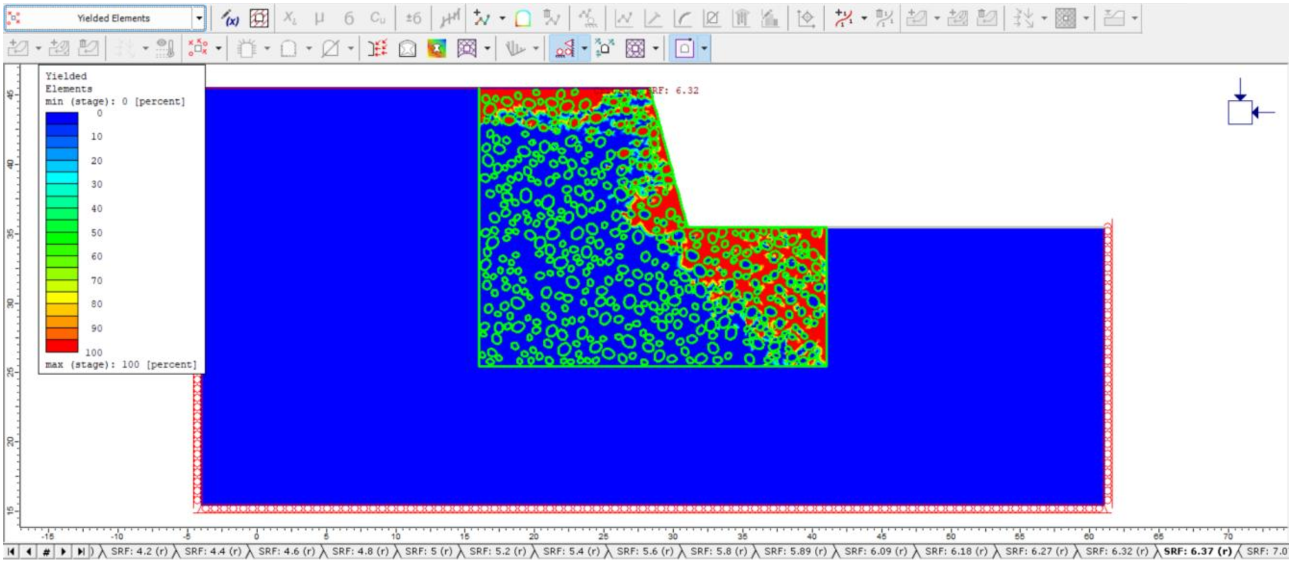


Figure 40: yielded elements h10-vbp40-75

Total displacement:

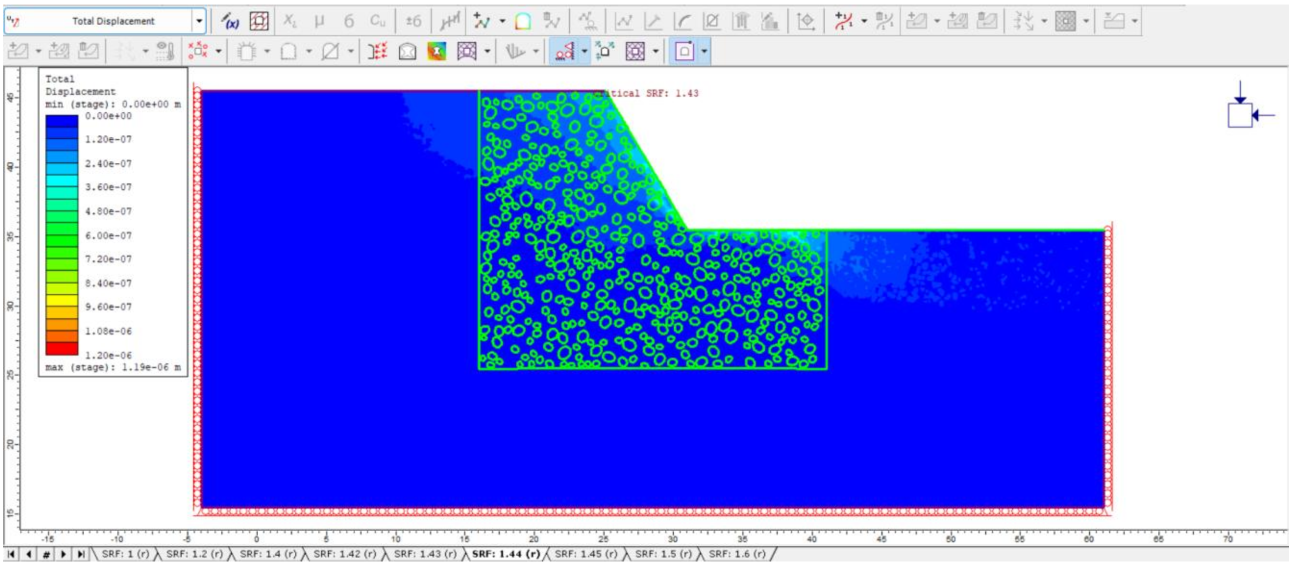


Figure 41: Total displacement h10-vbp40-60

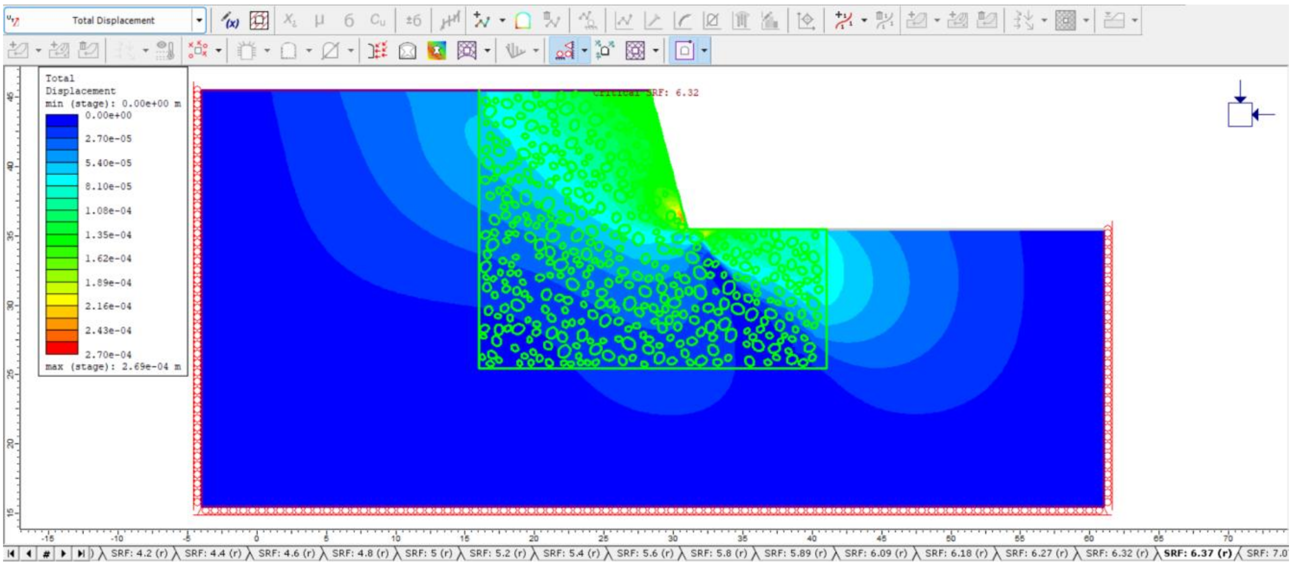


Figure 42: Total displacement h10-vbp40-75

VBP 10:

Models of 60, 75 degrees of slope angles:

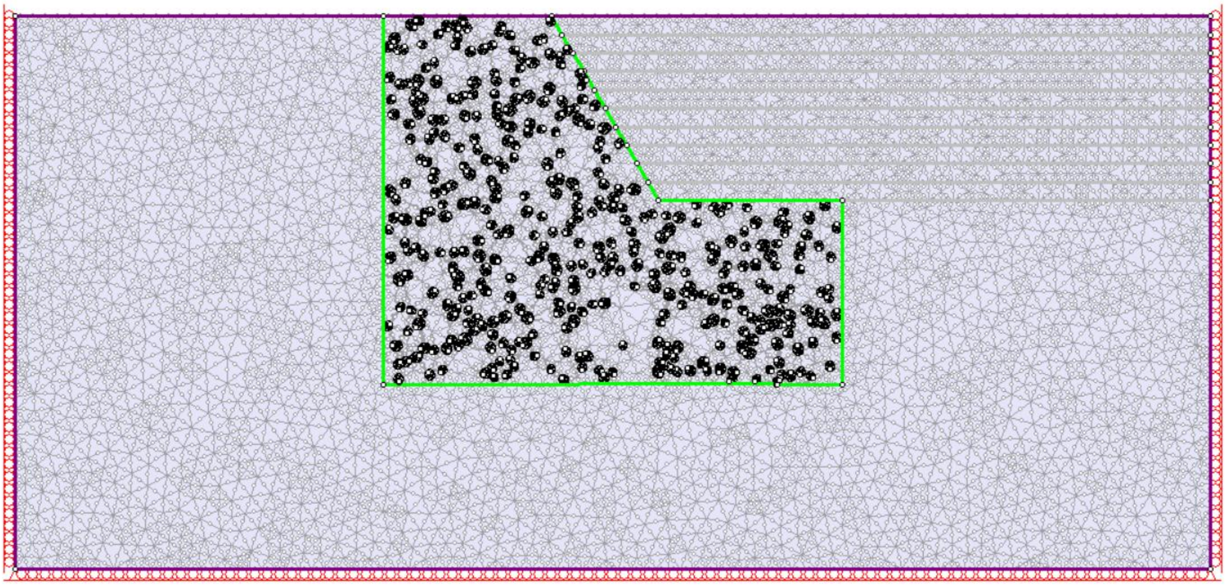


Figure 43: model h20-vbp10-60

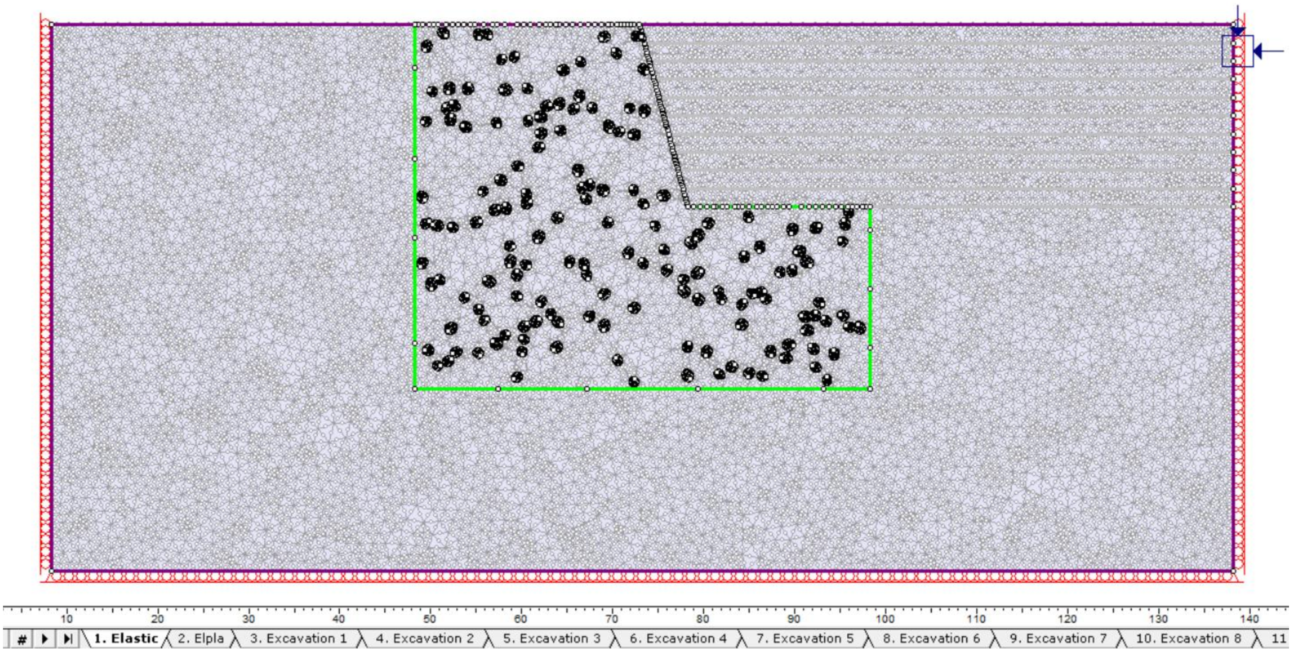


Figure 44: model h20-vbp10-75

Maximum shear strain:

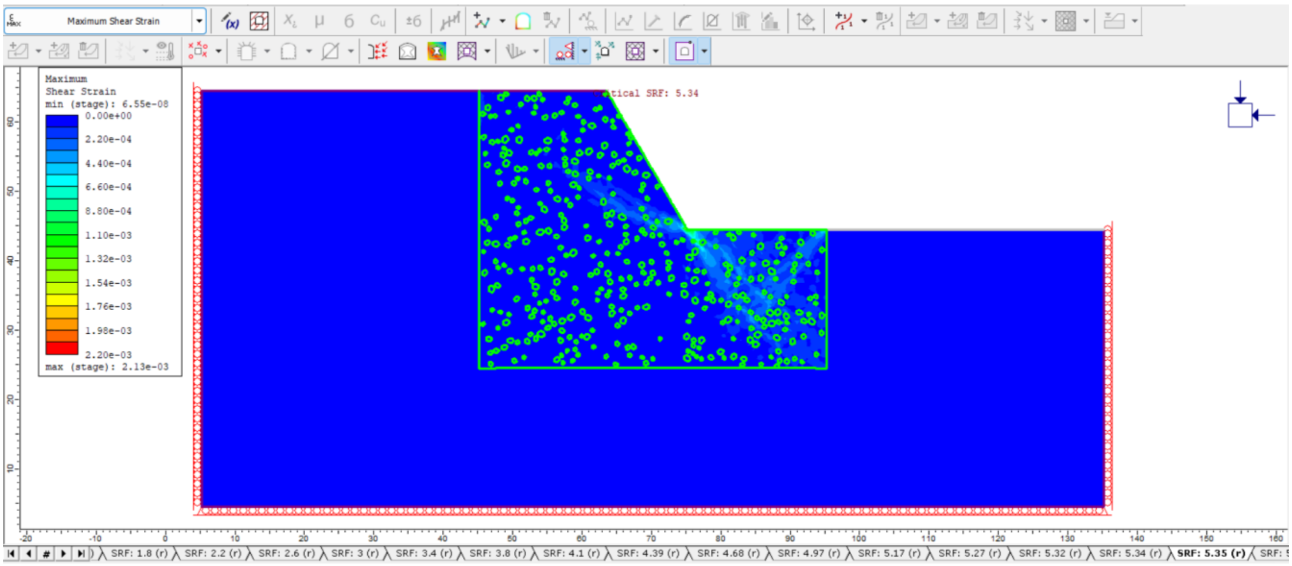


Figure 45: Maximum shear strain h20-vbp10-60

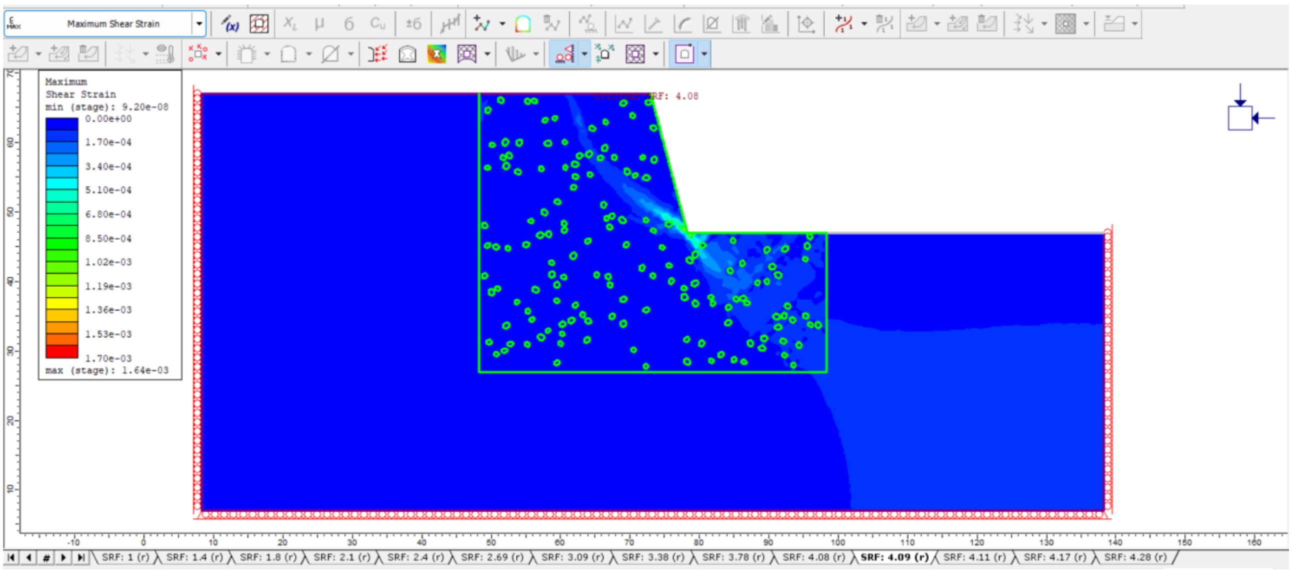


Figure 46: Maximum shear strain h20-vbp10-75

Yielded elements:

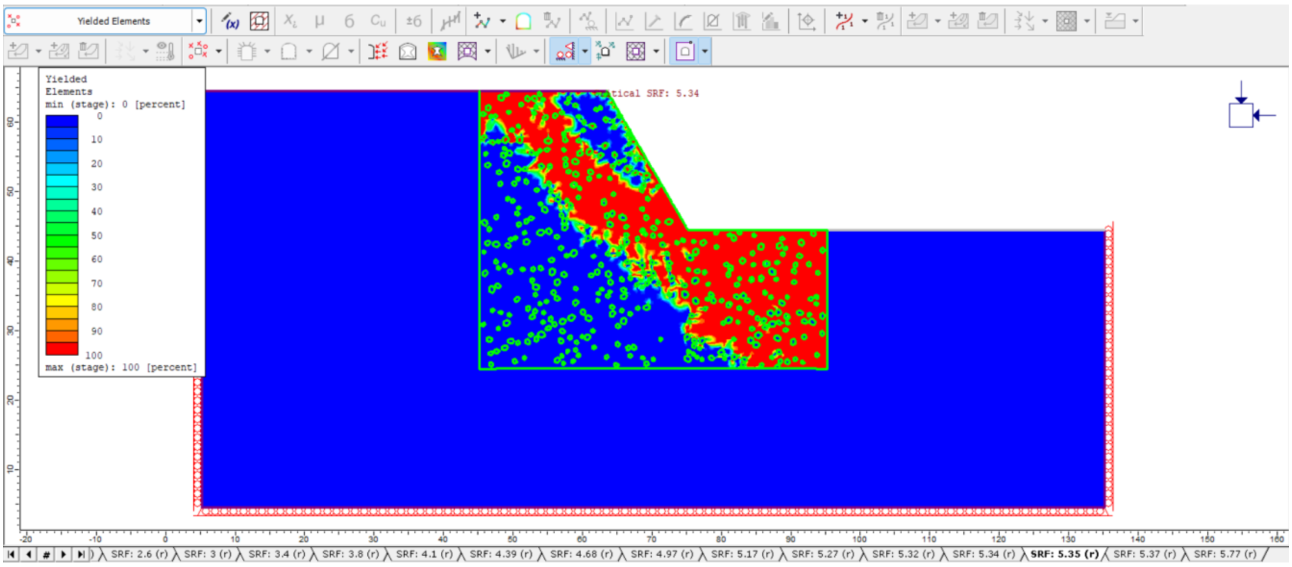


Figure 47: Yielded elements h20-vbp10-60

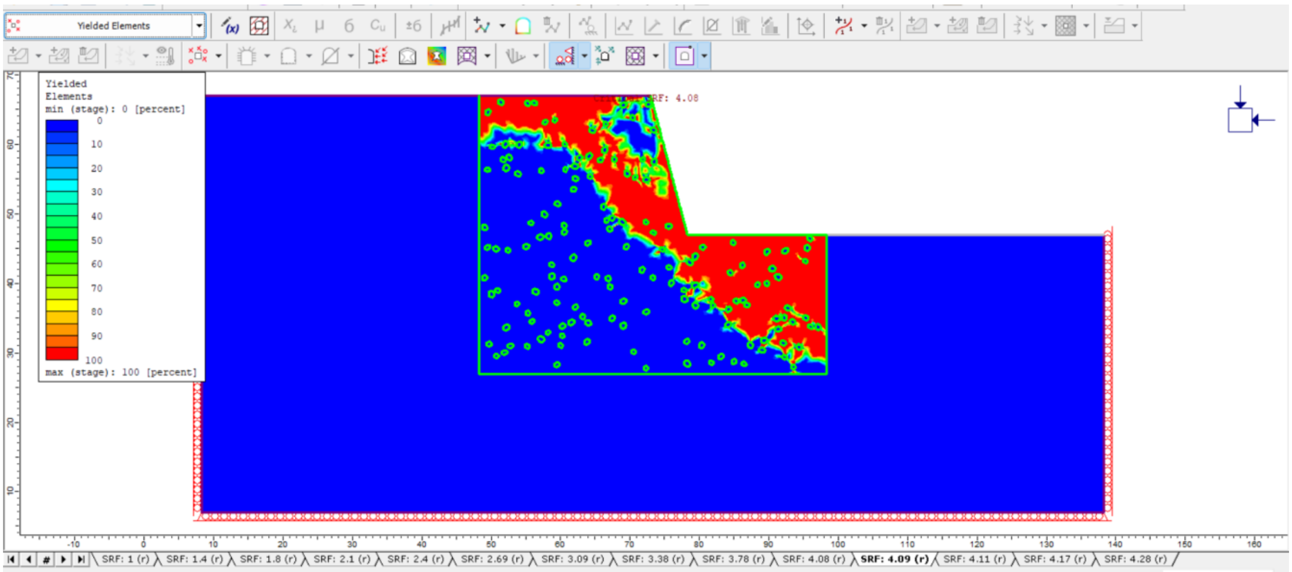


Figure 48: Yielded elements h20-vbp10-75

Total displacement:

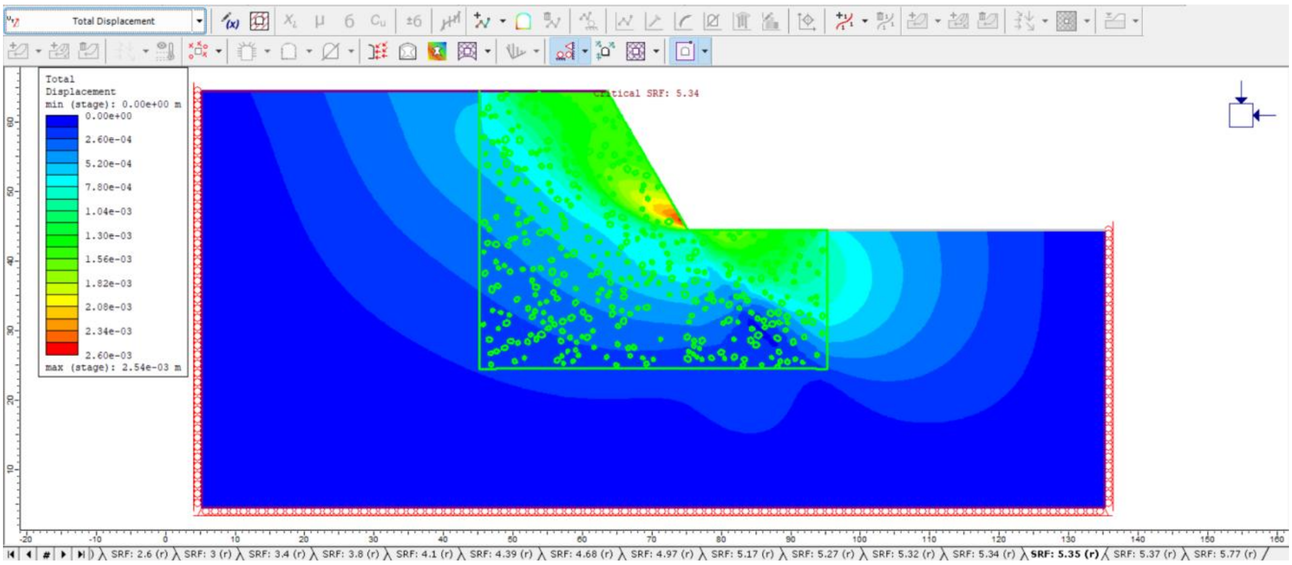


Figure 49: Total displacement h20-vbp10-60

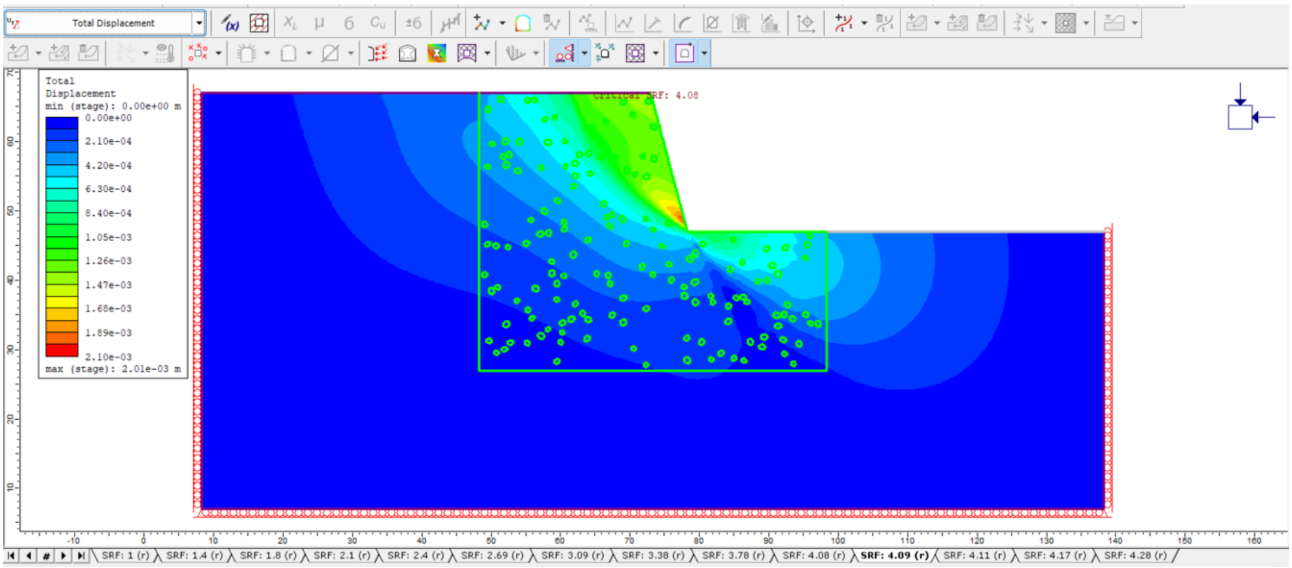


Figure 50: Total displacement h20-vbp10-75

VBP20

Models of 60, 75 degrees of slope angles:

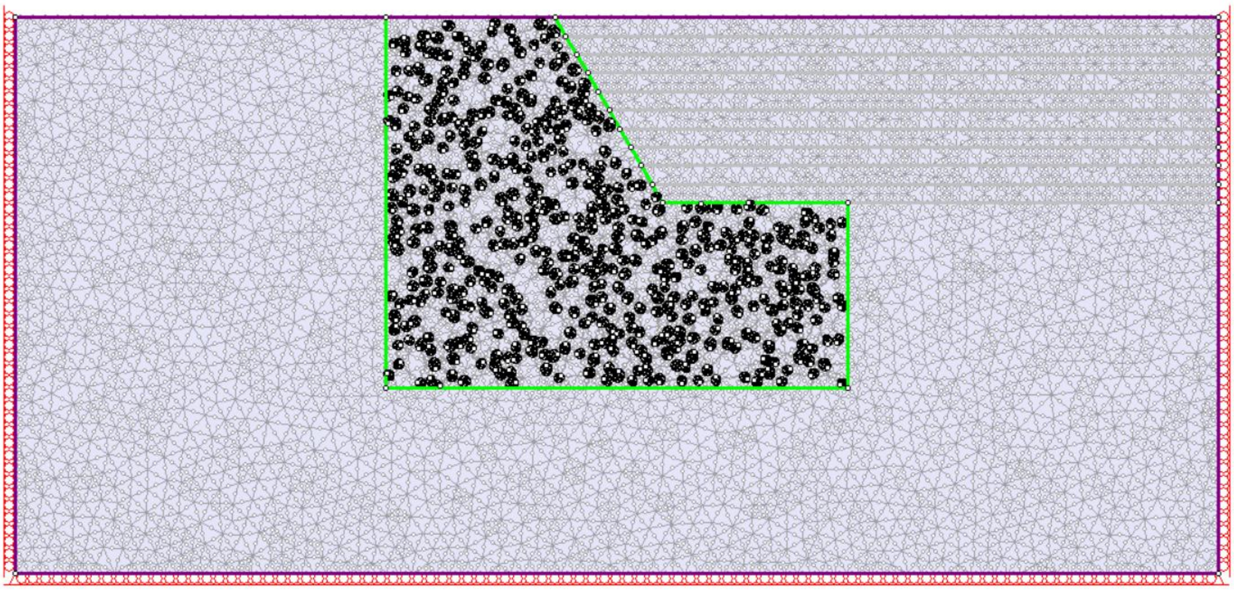


Figure 51: Model h20-vbp20-60

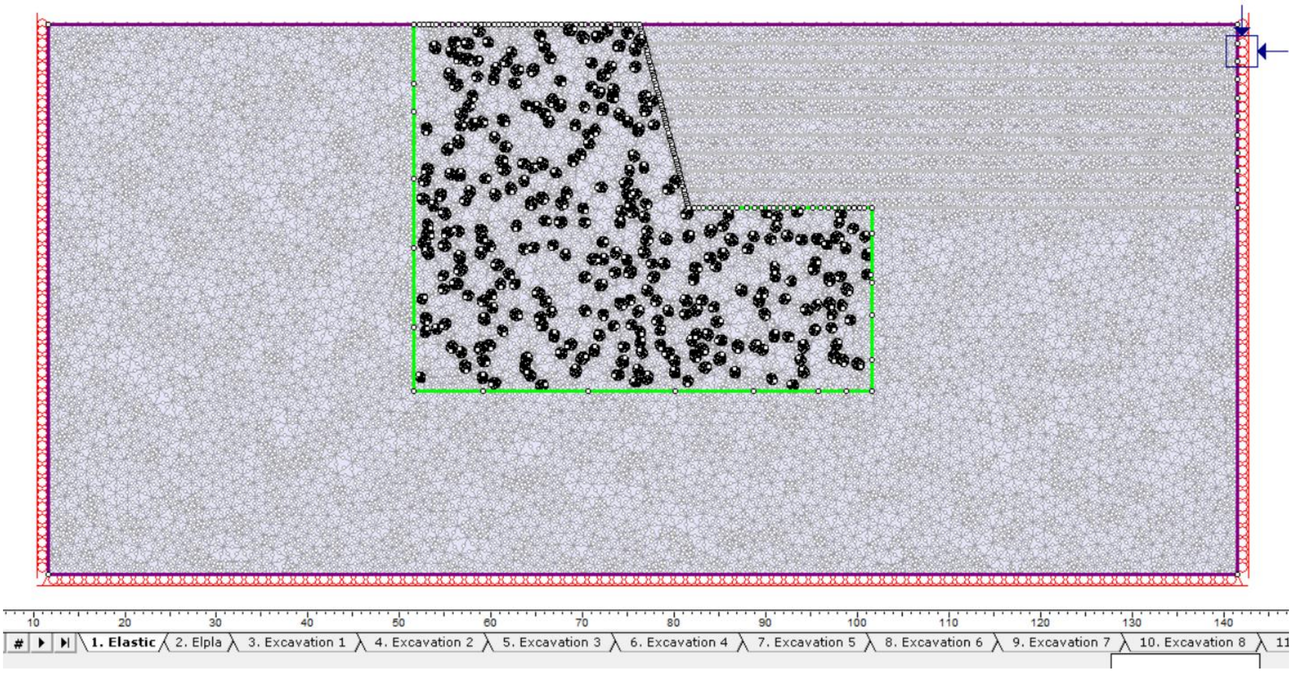


Figure 52: Model h20-vbp20-75

Maximum shear strain:

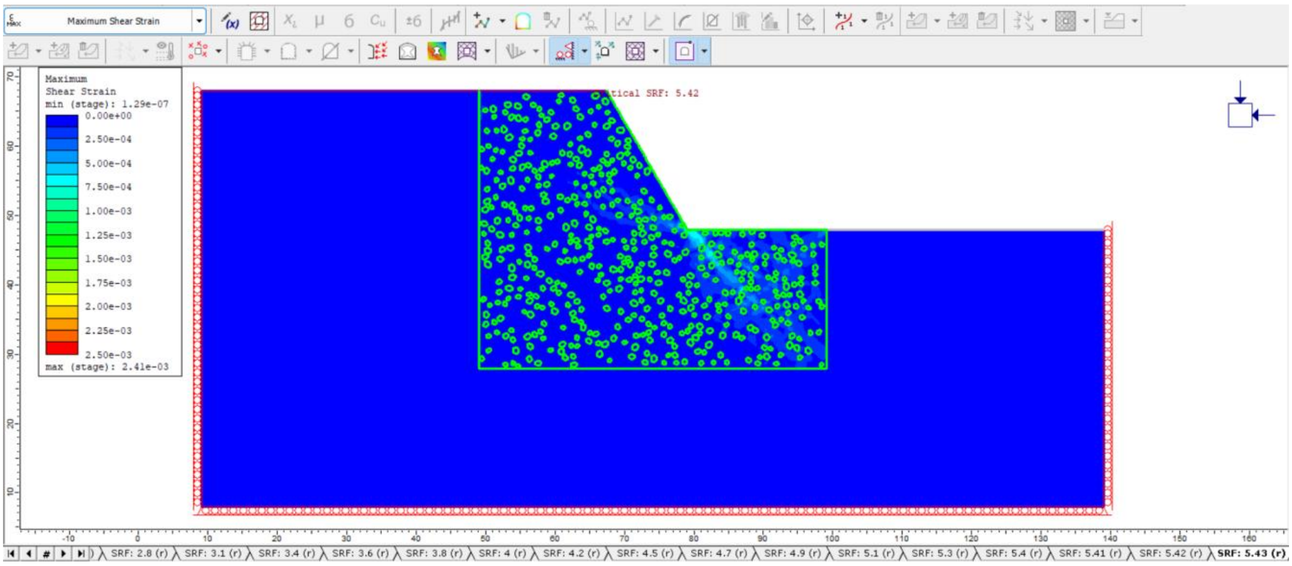


Figure 53: Maximum shear strain h20-vbp20-60

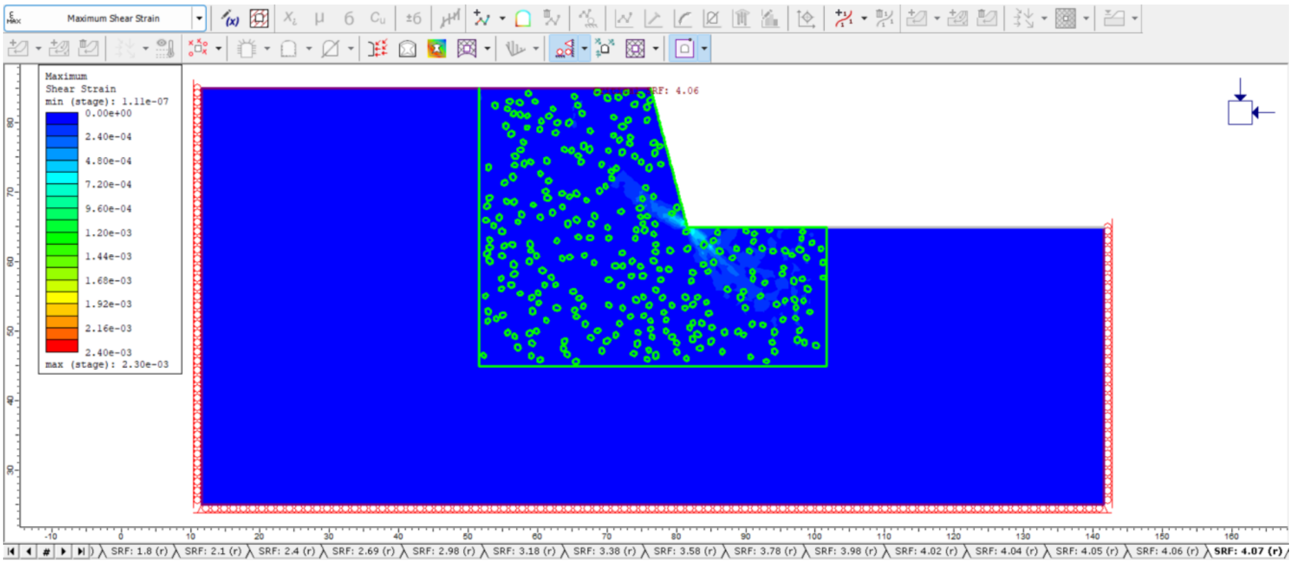


Figure 54: Maximum shear strain h20-vbp20-75

Yielded elements:

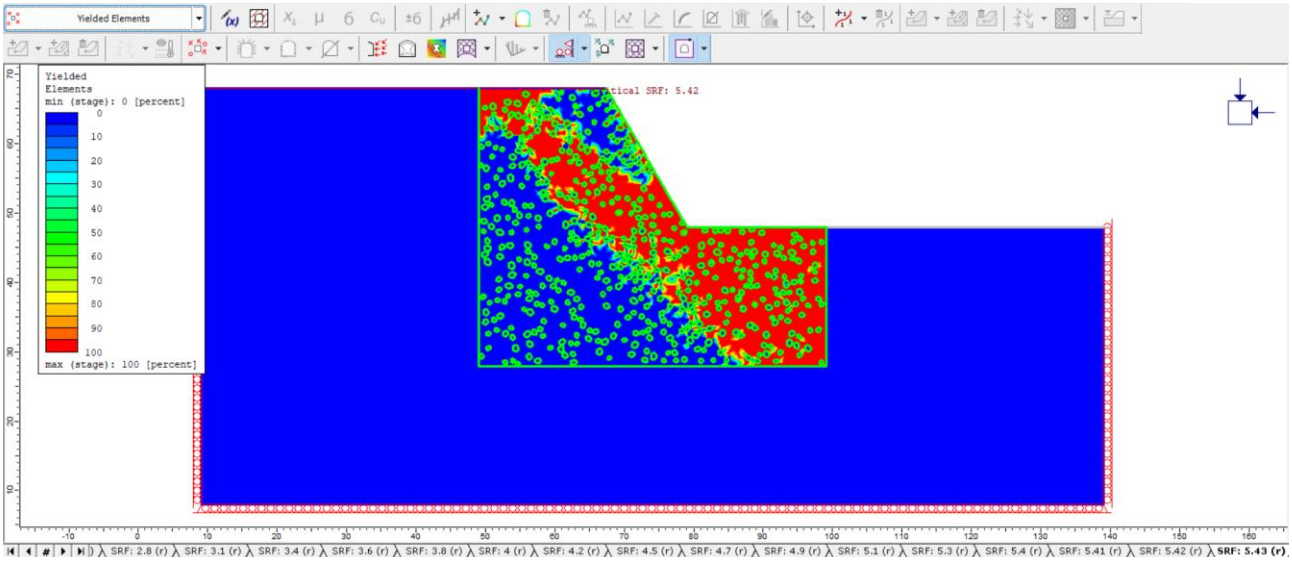


Figure 55: Yielded elements h20-vbp20-60

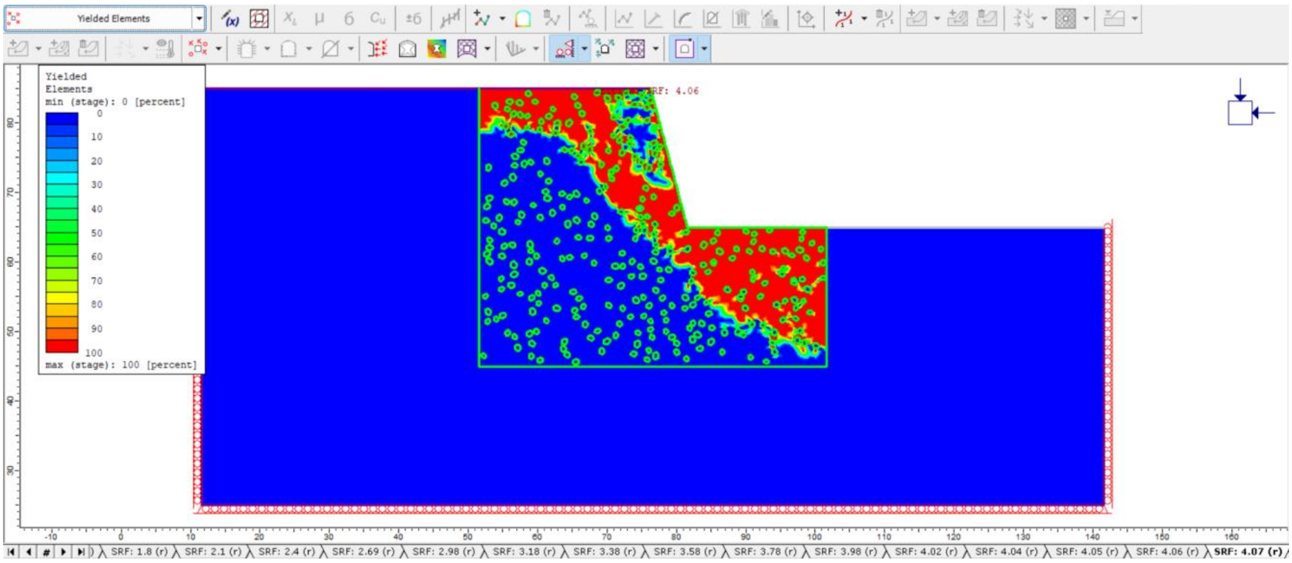


Figure 56: Yielded elements h20-vbp20-75

Total displacement:

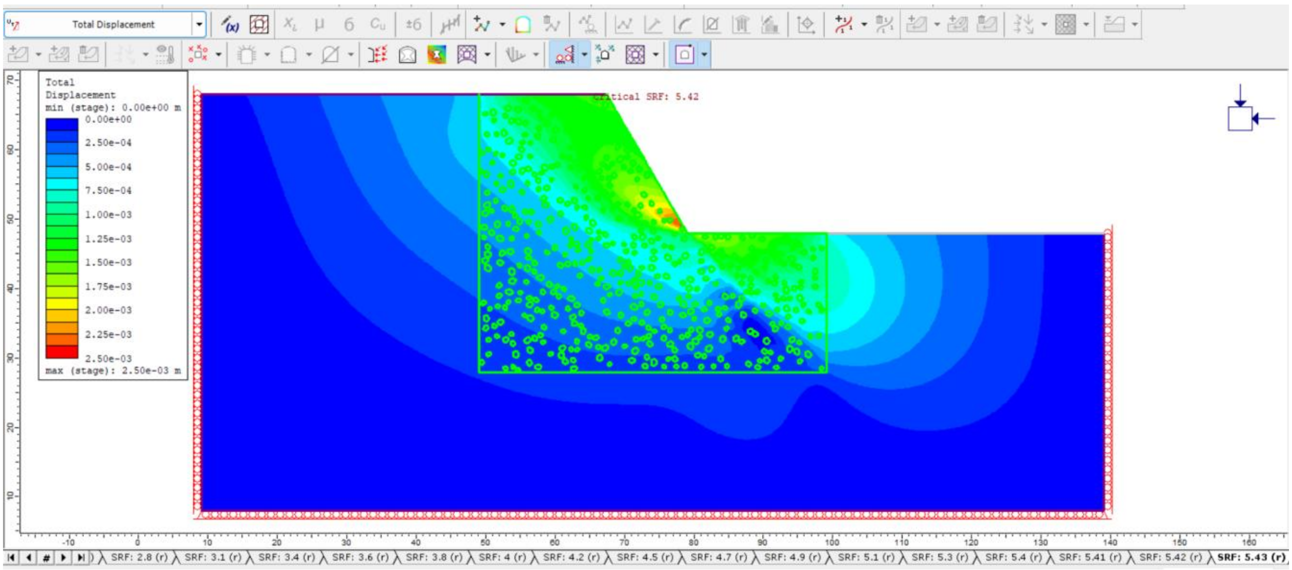


Figure 57: Total displacement h20-vbp20-60

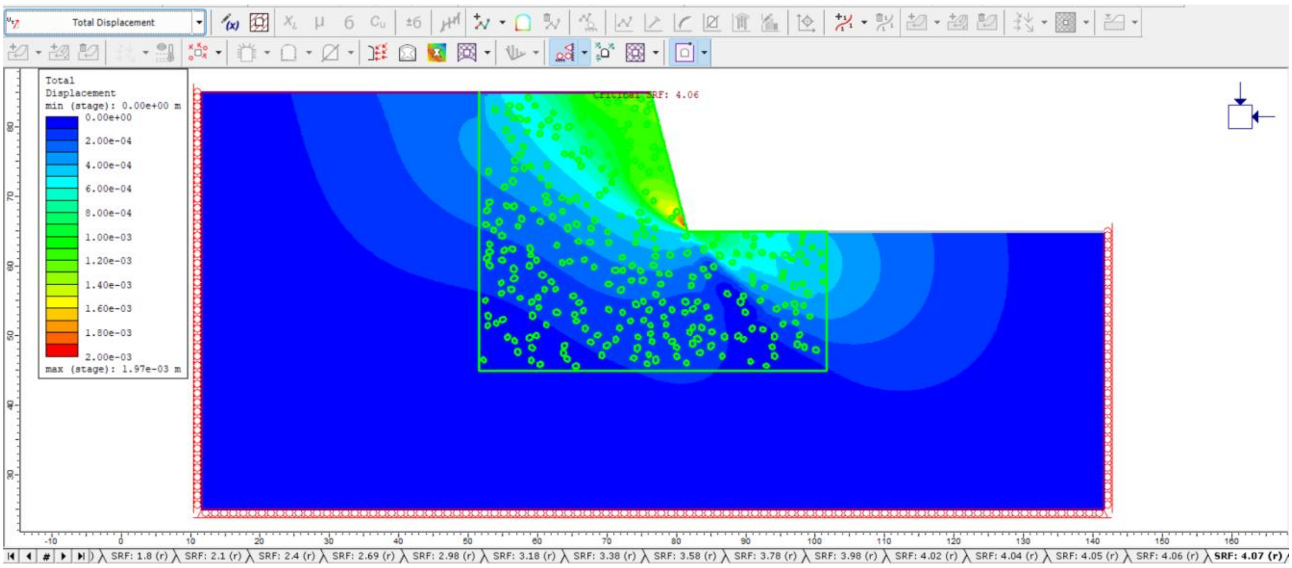


Figure 58: Total displacement h20-vbp20-75

VBP 30

Models of 60, 75 degrees of slope angles:

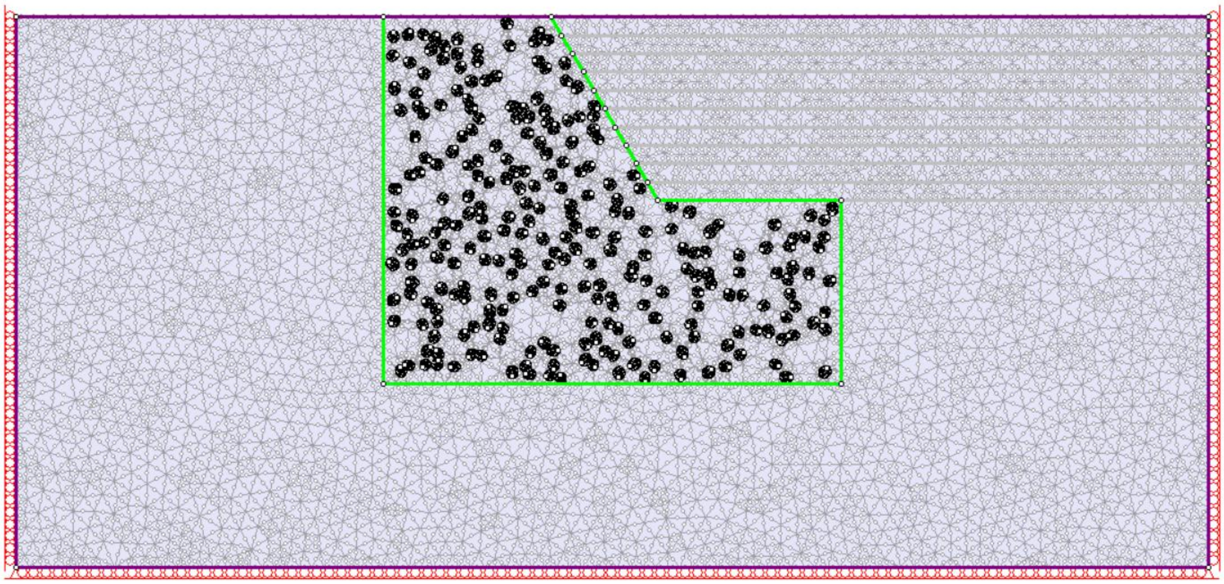


Figure 59: Model h20-vbp30-60

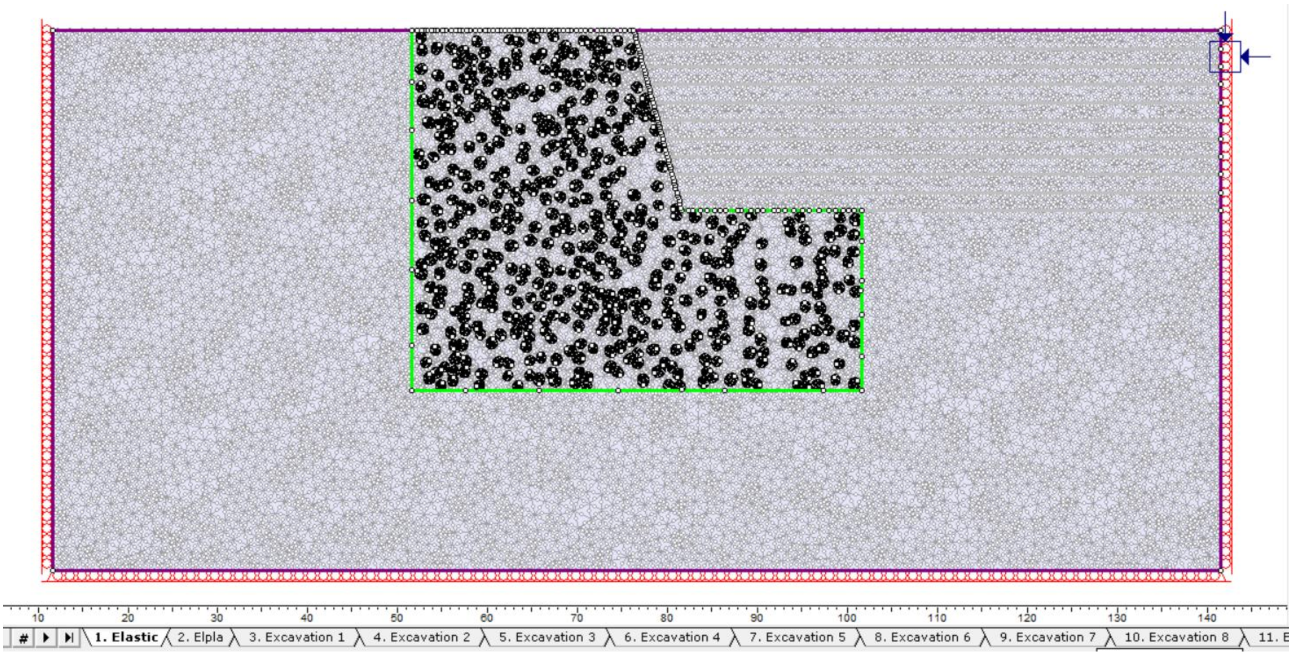


Figure 60: Model h20-vbp30-75

Maximum shear strain:

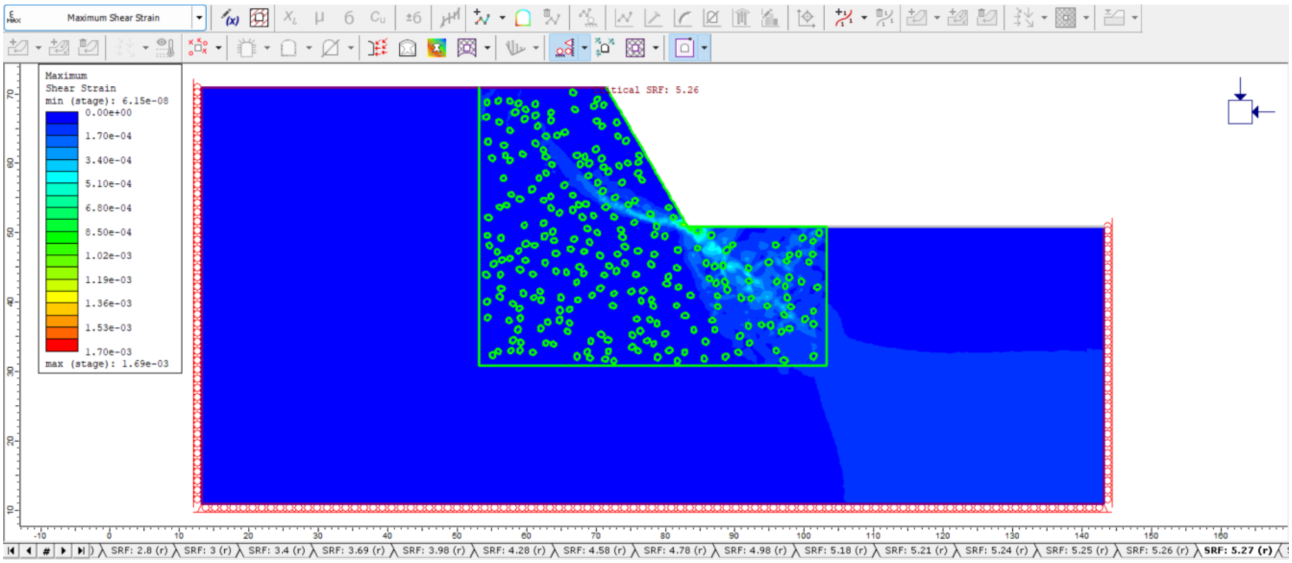


Figure 61: Maximum shear strain h20-vbp30-60

Yielded elements:

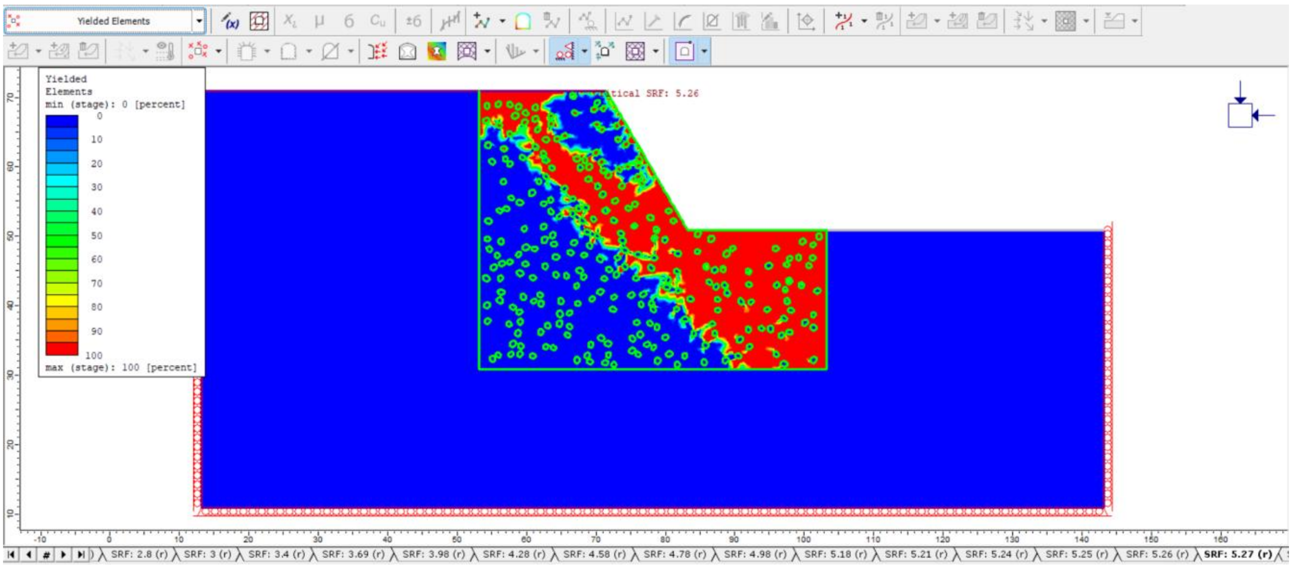


Figure 62: Yielded elements h20-vbp30-60

Total displacement:

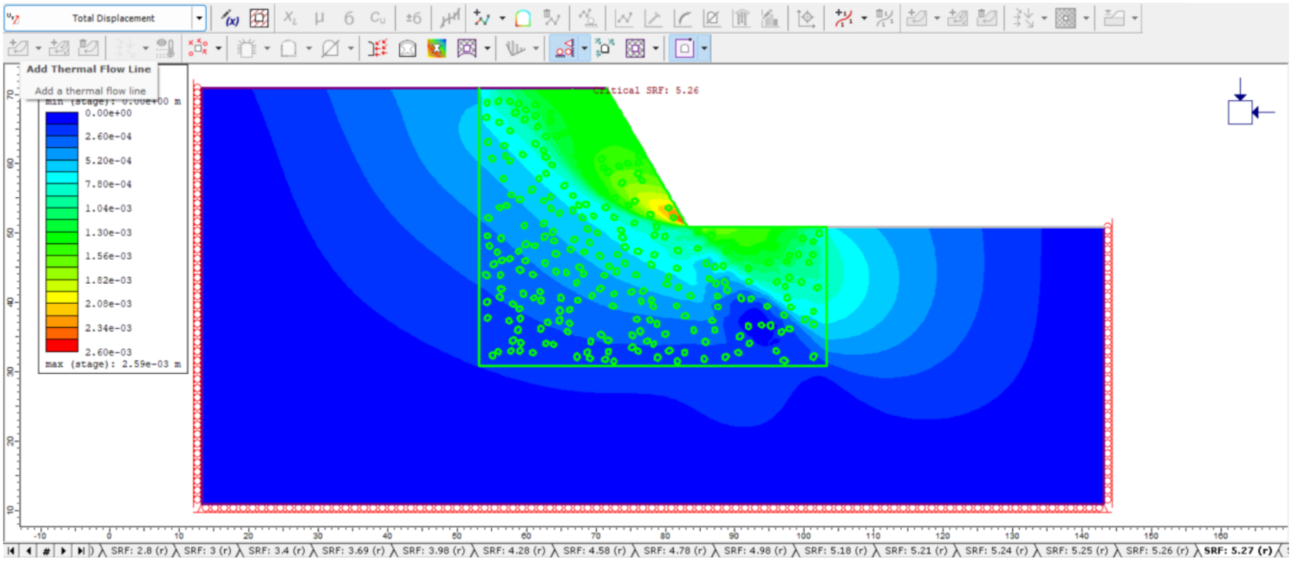


Figure 63: Total displacement h20-vbp30-60

VBP 40

Models of 60, 75 degrees of slope angles:

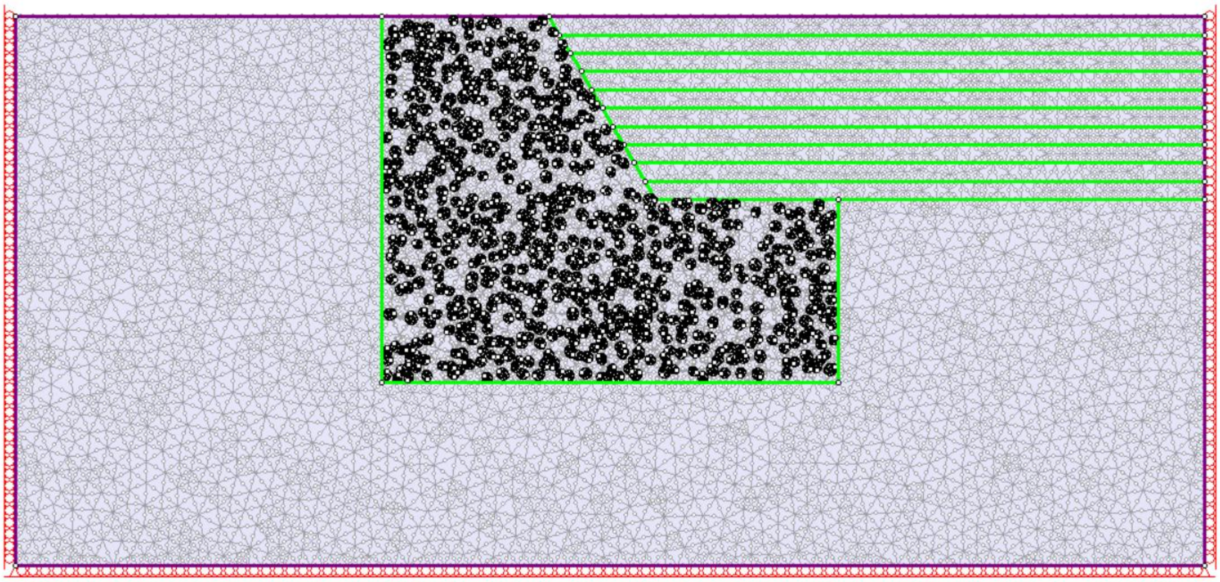


Figure 64: Model h20-vbp40-60

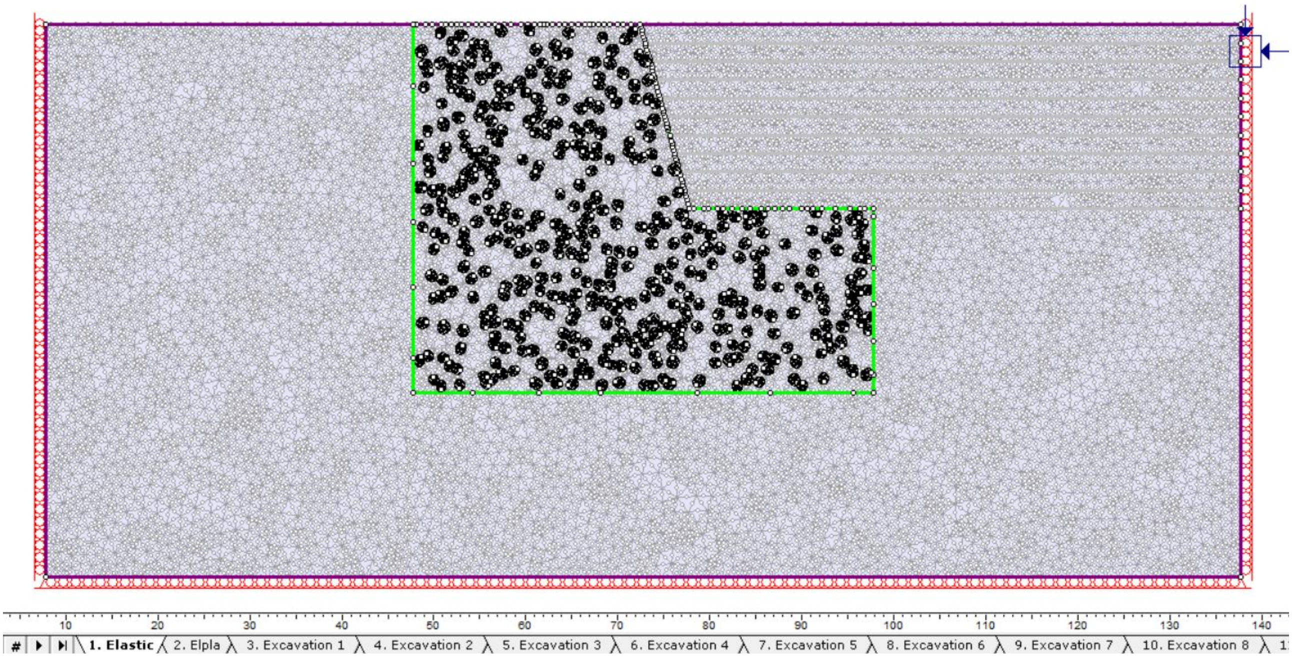


Figure 65: Model h20-vbp40-75

Maximum shear strain:

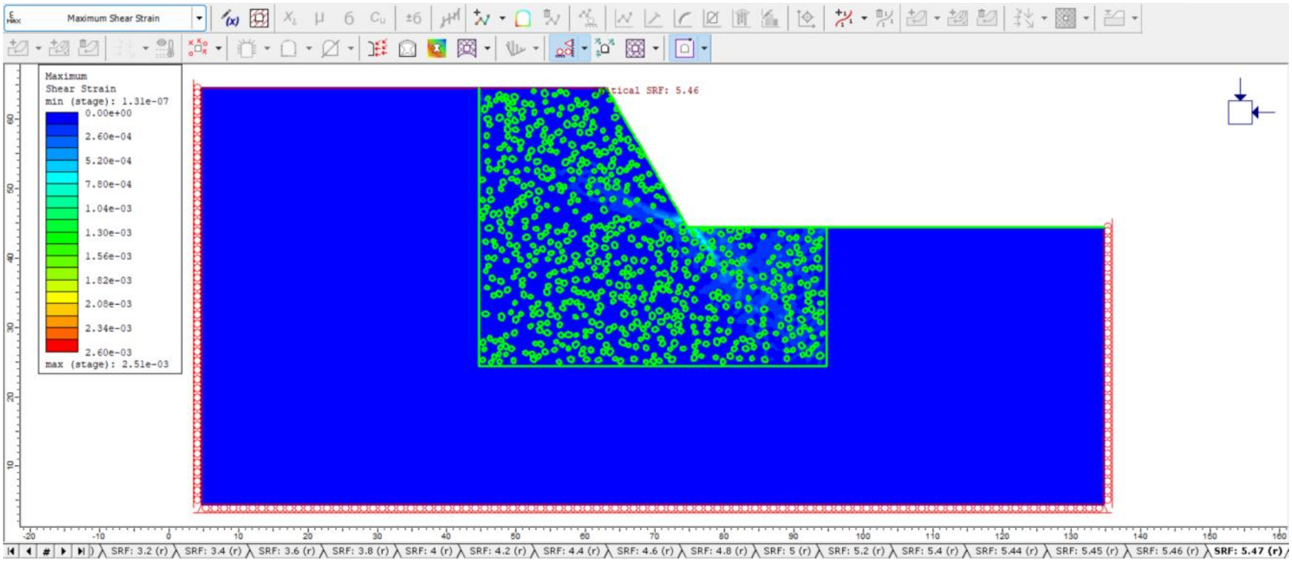


Figure 66: Maximum shear strain h20-vbp40-60

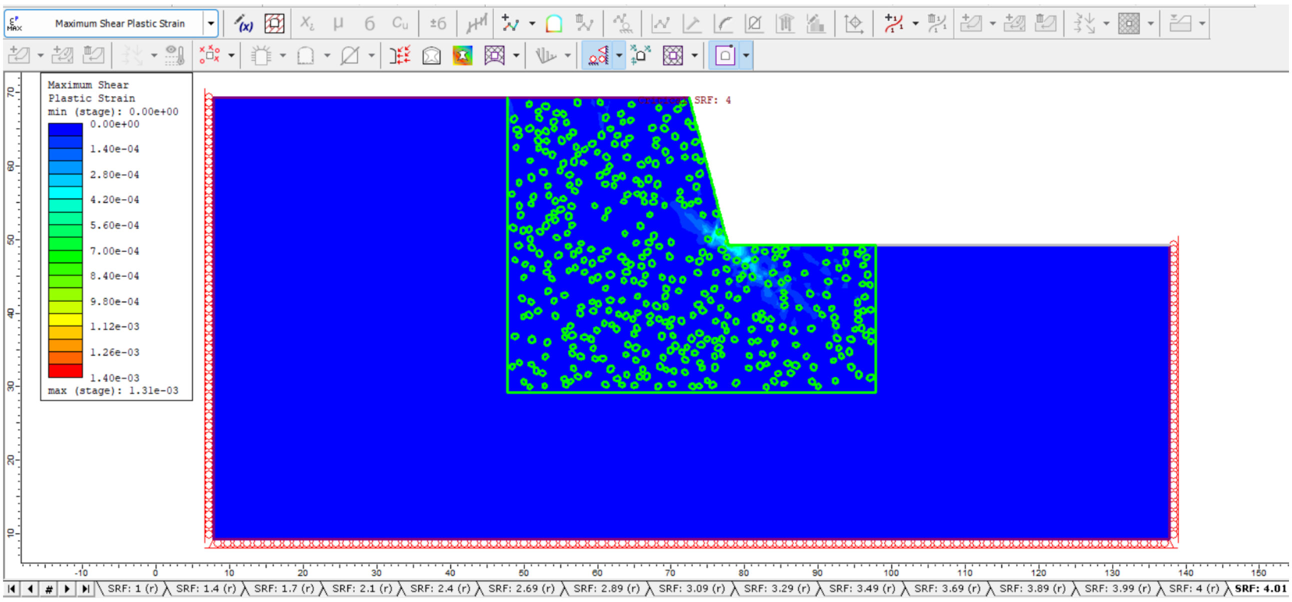


Figure 6767: Maximum shear strain h20-vbp40-75

Yielded elements:

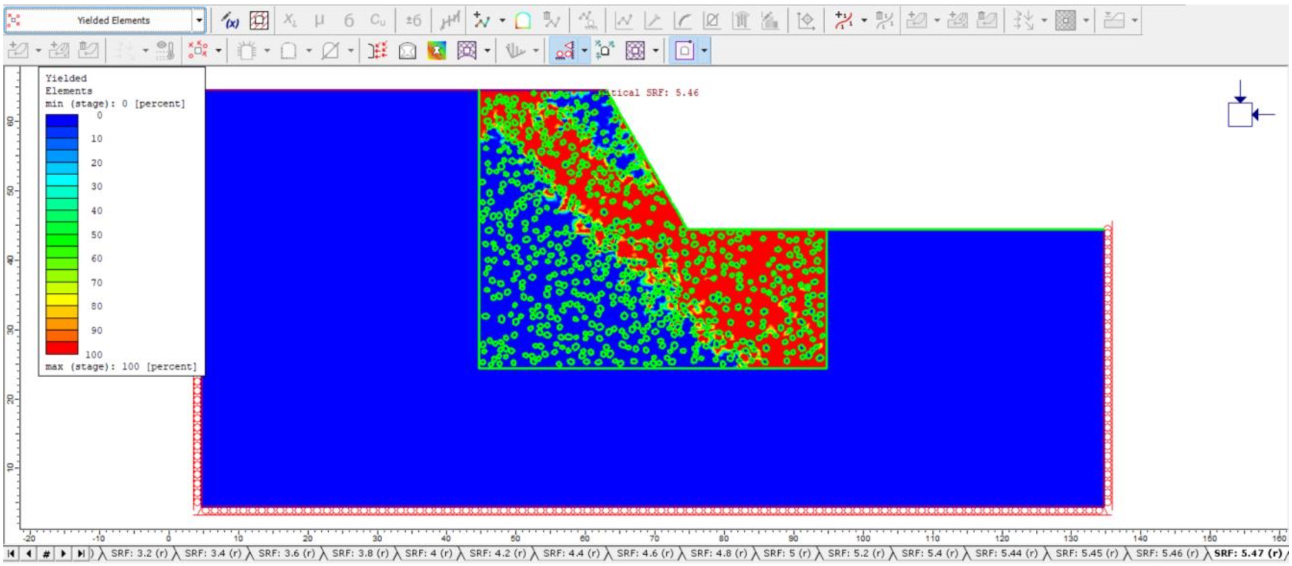


Figure 6868: Yielded elements h20-vbp40-60

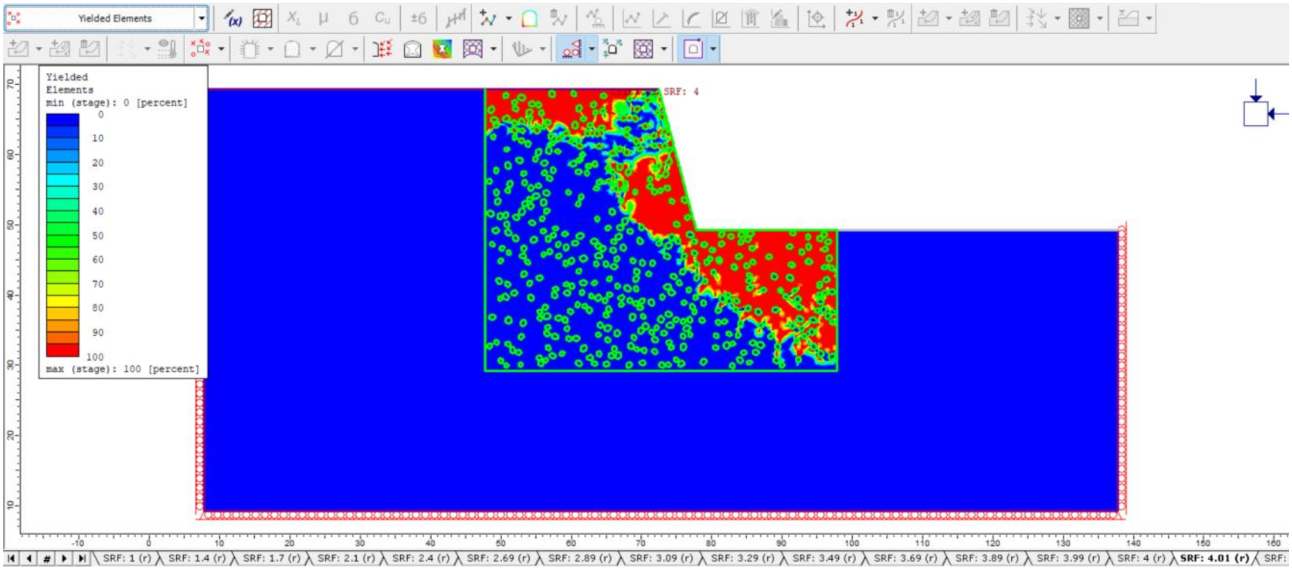


Figure 69: Yielded elements h20-vbp40-75

Total displacement:

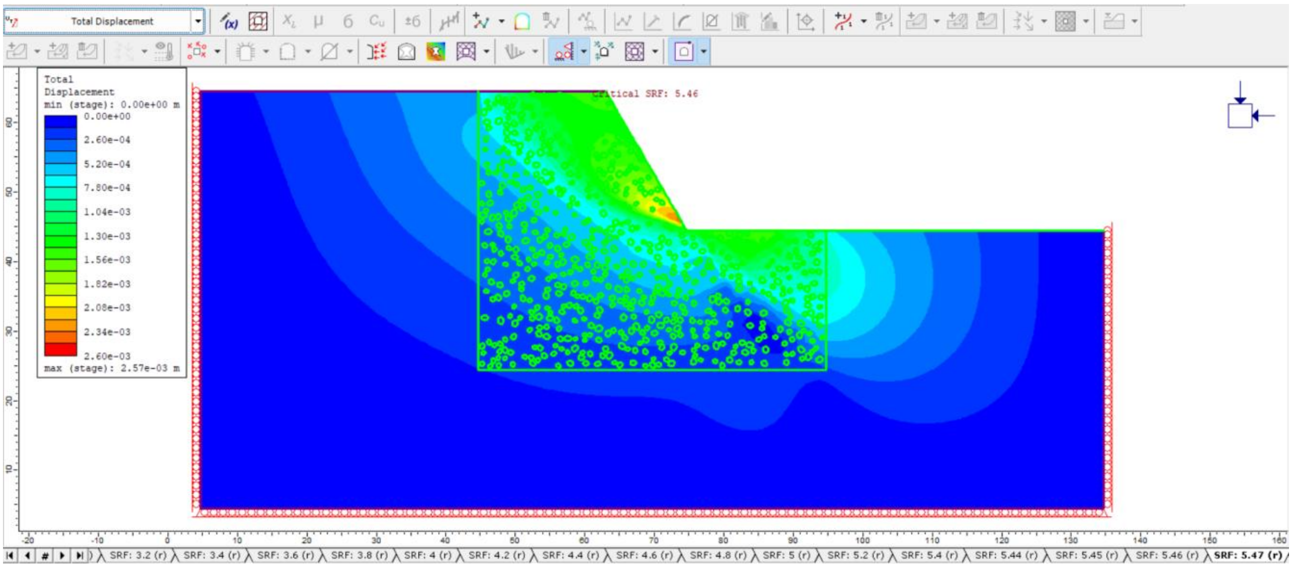


Figure 70: Total displacements h20-vbp40-60

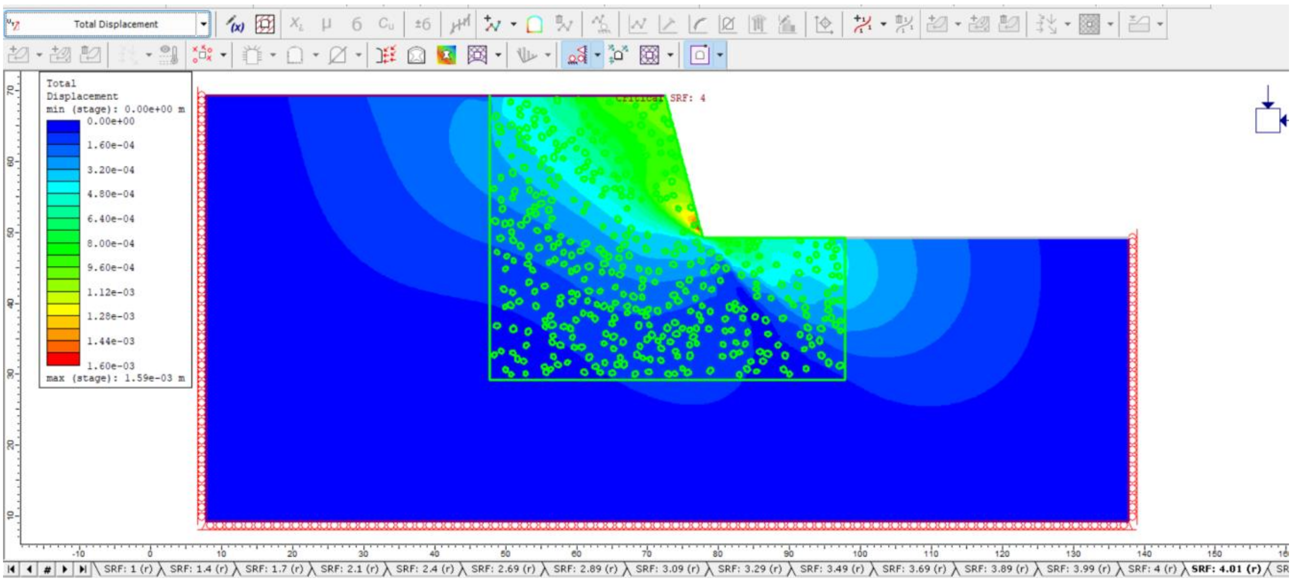


Figure 71: Total displacements h20-vbp40-75

References:

Mention any ongoing geological monitoring projects in Las Médulas.

Suggest specific geotechnical techniques used for stabilization (e.g., slope reinforcement, vegetation cover, or geosynthetics).

Domergue, C. (1990). Les Mines Antiques: La Production des Métaux au Monde Romain.

Orejas, A., & Sánchez-Palencia, F. J. (2002). "Roman Gold Mining in NW Spain: Impact and Landscape Change" – Antiquity 76(293): 272-278.

Faulkner, D. R. (2010). "Rock Fracture and Fluid Flow in Fault Zones" – Geophysical Research Letters.

Fernández-Lozano, J., & Gutiérrez-Alonso, G. (2017). "Remote Sensing Analysis of Slope Stability at Las Médulas" – Engineering Geology 230: 124-138.UNESCO (1997). Las Médulas World Heritage Site Management Plan.

Hustrulid, W., & Johnson, J. (2013). Rock Slope Stability Analysis. CRC Press.

Matsumoto, N., & Onodera, S. (2019). "Water Infiltration and Erosion in Historical Hydraulic Mining Sites" – Hydrogeology Journal 27(3): 543-558.

Hoek, E., & Bray, J. W. (1981). Rock Slope Engineering. London: CRC Press

Lancellotta, R. (1995). Geotechnical Engineering. CRC Press.

Potts, D. M., & Zdravković, L. (2001). Finite Element Analysis in Geotechnical Engineering: Theory and Application. Thomas Telford.

Domergue, C. (1990). Les Mines Antiques: La Production des Métaux au Monde Romain. Paris: CNRS.

Gutiérrez-Alonso, G., et al. (2017). "Geological and Geomorphological Impact of Roman Gold Mining at Las Médulas" – Earth Surface Processes and Landforms 42(4): 645-660.

Rocscience Inc. (2021). RS2 User Manual.

Griffiths, D. V., & Fenton, G. A. (2008). Probabilistic Methods in Geotechnical Engineering. Springer.

Jiménez-Sánchez, M., et al. (2015). "Geoheritage and Geotourism at Las Médulas, Spain" – Geoheritage 7(3): 241-255.

Goudie, A. S. (2018). Human Impact on the Natural Environment: Past, Present, and Future. Wiley.

Domergue, C. (2008). Les Mines de l'Antiquité. Paris: Errance.

Sánchez-Palencia, F. J. (2000). Las Médulas: La Minería de Oro en el Noroeste de Hispania. León: CSIC.

Pliny the Elder. (77-79 CE). Naturalis Historia, Book 33.

Lonely Planet Spain. (2023). Las Médulas Travel Guide.

Rough Guides. (2022). Exploring Northern Spain: A Guide to León and Las Médulas.

Wilson, A. (2012). "Large-Scale Roman Water Management and Its Legacy" – Water History 4(3): 219-244.

Gobierno de España & Junta de Castilla y León. (2020). Las Médulas: Guía del Visitante.

UNESCO World Heritage Centre. (1997). Las Médulas Nomination File.

Alicia Perea (1996). "Las Médulas (León): El Oro de Roma" – Trabajos de Prehistoria 53(2).

Hirt, A. M. (2010). Imperial Mines and Quarries in the Roman World: Organizational Aspects 27 BC-AD 235. Oxford University Press.