Politecnico di Torino

Master of Science in Civil Engineering

Master Degree Thesis

SLOPE STABILITY ANALYSIS IN BIMSOILS

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Summary

In today's scenario a careful and correct characterization of various types of soils can reduce costly design errors and unwelcome surprises during construction or excavation phase. BIMsoils / BIMrocks (Block in Matrix) are very complicated heterogeneous materials that may cause challenging problems during design and construction of structures. They are defined as "a mixture of soil / rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture". (Medley, 1994). These types of formations can be found in many parts of the world and engineering works may be needed to deal with these challenging materials.
In this particular exposition mechanical behaviour of BIMsoils was studied adhering focus on the problem of slope stability of this type of slope. The mechanical behaviour of these materials is difficult to characterize because there are a lot of difficulties that arise in testing and sampling in the laboratory. From an engineering point of view, the variability of mechanical behaviour that characterizes these materials is problematic because it creates difficulties in design and construction of engineering works such as excavations, tunnels and or slope stabilization works. Currently designers who face geotechnical designs in complex formations with block-in-matrix fabric do not have enough data to make their real mechanical behaviour reliable, so the design practice presents several difficulties due to the absence of certain methods to make reliable the design data relating to the values of resistance, deformability and volumetric blocks proportion (VBP).
Different volumetric block proportion (VBP) of rocks, the influence of extracted randomly from a block size distributions typical of Franciscan melange, and the influence of their positioning (which was always random within the slope) were analysed. Four different VBP (25%, 40%, 55% and 70%) were analysed considering different sets of strength parameters for the interfaces.

To simulate the models as BIMsoil, an interface was added around the blocks with required strength parameters like cohesion, internal friction angle and tensile strength with a predefined value and models were analysed numerically. The strength parameters of the interfaces were further reduced to 50% and then 100%, results were compared to studies which were obtained earlier considering the models of BIMrocks (Napoli et al 2021). The results of the numerical analyses were illustrated in terms of safety factors. For further validation of the various models, properties of the joints of rocks (interfaces) were kept same as that of the matrix and change in their factor of safety was observed.

At the final stage of the study the tortuous failure surfaces for all the VBP considered was depicted using AUTOCAD which can be useful to designers in making correct technical and economic assessments.

Sommario

Nello scenario odierno un'attenta e corretta caratterizzazione delle varie tipologie di suoli può ridurre costosi errori di progettazione e sgradite sorprese in fase di costruzione o di scavo. I BIMsoils / BIMrocks (Block in Matrix) sono materiali eterogenei molto complicati che possono causare problemi impegnativi durante la progettazione e la costruzione delle strutture. Sono definiti come "una miscela di suolo/rocce, composta da blocchi geotecnicamente significativi all'interno di una matrice legata di tessitura più fine". (Medley, 1994). Questi tipi di formazioni possono essere trovati in molte parti del mondo e potrebbero essere necessari lavori di ingegneria per affrontare questi materiali difficili.

In questa particolare esposizione è stato studiato il comportamento meccanico dei BIMsoils aderendo al problema della stabilità dei versanti di questo tipo di versante. Il comportamento meccanico di questi materiali è difficile da caratterizzare perché ci sono molte difficoltà che sorgono nelle prove e nei campionamenti in laboratorio. Da un punto di vista ingegneristico, la variabilità del comportamento meccanico che caratterizza questi materiali è problematica perché crea difficoltà nella progettazione e realizzazione di opere di ingegneria come scavi, gallerie e/o opere di stabilizzazione dei pendii. Attualmente i progettisti che affrontano progetti geotecnici in formazioni complesse con tessuto block-in-matrix non dispongono di dati sufficienti per rendere affidabile il loro reale comportamento meccanico, quindi la pratica progettuale presenta diverse difficoltà dovute all'assenza di determinati metodi per rendere affidabili i dati progettuali relativi ai valori di resistenza, deformabilità e proporzione dei blocchi volumetrici (VBP).

Sono state analizzate la diversa proporzione di blocchi volumetrici (VBP) delle rocce, l'influenza delle distribuzioni dimensionali estratte casualmente da un blocco tipiche del melange francescano e l'influenza del loro posizionamento (che era sempre casuale all'interno del pendio). Sono stati analizzati quattro diversi VBP (25%, 40%, 55% e 70%) considerando diversi set di parametri di forza per le interfacce.

Per simulare i modelli come BIMsoil, è stata aggiunta un'interfaccia attorno ai blocchi con parametri di resistenza richiesti come coesione, angolo di attrito interno e resistenza alla trazione con un valore predefinito e i modelli sono stati analizzati numericamente. I parametri di resistenza delle interfacce sono stati ulteriormente ridotti al 50% e poi al 100%, i risultati sono stati confrontati con studi ottenuti in precedenza considerando i modelli di BIMrocks (Napoli et al 2021). I risultati delle analisi numeriche sono stati illustrati in termini di fattori di sicurezza. Per un'ulteriore validazione dei vari modelli, le proprietà dei giunti delle rocce (interfacce) sono state mantenute uguali a quelle della matrice ed è stata osservata la variazione del loro fattore di sicurezza.

Nella fase finale dello studio le tortuose superfici di rottura per tutti i VBP considerati sono state rappresentate mediante AUTOCAD che può essere utile ai progettisti per effettuare corrette valutazioni tecnico-economiche.

Foreword

In the process of understanding the common geomechanical behaviour of the vast variety of soil/rock mixtures, the term “bimrock” (block-in-matrix rock) was introduced to include melanges, sheared serpentinites, breccias, decomposed granites, weathered rocks with tectonically fragmented rocks such as fault rocks. These and other, often chaotic, mechanically and/or spatially heterogeneous rock masses are composed of relatively strong rock blocks surrounded by weaker matrix rocks. These common rock mixtures, referred to as bimrocks (block-in-matrix-rocks) or bimsoils (when the matrix material is soil-like) are very difficult to gauge. It is almost impossible to recover top quality, undisturbed drill core samples or to organize laboratory specimens perform laboratory studies and evaluate geomechanical parameters like cohesion, internal friction angle and uniaxial compressive strength from these complex mixtures.

In this dissertation the mechanical behaviour of bimsoils was studied, the aim was on the problem of slope stability. In this context, the aim of this thesis is to address the issue according to a stochastic approach. For different volumetric block proportion (VBP), the influence of different samples, extracted randomly from a block size distributions typical of Franciscan melange and the influence of their positioning always random within the slope was analysed. Four different VBP were analysed .The results of the numerical analyses are illustrated in terms of safety factor and the position of the failure surfaces. The results were further compared with the previous study of bimrocks with similar volumetric block proportions and a change in trend of the safety factors was observed.

Chapter 1 contains a brief description of the origin of these materials, and shows their geographical distribution. It provides a general framework with the main concepts related to the definition of the complex formations and related to the terminology.

Chapter 2 provides an overview of the studies performed to date. It focuses on the identification, analysis and characterization of structurally complex formations. It describes the results of studies carried out by different authors on the geometrical and geomechanical characterization of bimrocks. Some models are also described in, mainly those of Medley and Lindquist (1994). The main considered aspect was the effect of block proportion on slope stability. The blocks also influence the tortuosity of failure surfaces.

Chapter 3 illustrates the process and the software used to build the models subjected to analysis in the context of this thesis. The implementation of the models and their characteristics are described.

Chapter 4 depicts the results of the numerical analyses in terms of safety factor and concluding remarks on the obtained values are also presented through various pictures, graphs etc.

Chapter 5 an interesting comparison of safety factors related to the bimsoils with respect to the previously performed studies on bimrocks. A final conclusion is also made on the failure surfaces for a better understanding of the project.

Chapter 1

Introduction to BIMsoils/BIMrocks

The term “block-in-matrix rocks” was originally coined by Raymond (1984) for melanges and olistostromes, geological words which have firm and important connotations for geologists but are generally meaningless to engineers. Complex geological mixtures or fragmented rocks such as mélanges, fault rocks, coarse pyroclastic rocks, breccias and sheared serpentines. The term “bimsoil” could also be preferred for complex mixtures which include rock blocks surrounded by soil-like matrix material, such as colluvium and glacial tills. These and other, often chaotic, mechanically and/or spatially heterogeneous rock masses are composed of relatively strong rock blocks surrounded by weaker matrix rocks. These common rock mixtures, referred to as bimrocks (block-in-matrix-rocks) or bimsoils (when the matrix material is soil-like) are very difficult to gauge. It is almost impossible to recover top quality, undisturbed drill core samples or to organize laboratory specimens perform laboratory studies and evaluate geomechanical parameters like cohesion, internal friction angle and uniaxial compressive strength from these complex mixtures.

To focus on the fundamental engineering problems related to the characterization of these and many other “rock/soil” mixtures. Medley (1994) coined the neutral word “bimrocks”, which has no geological connotations. Bimrocks are defined as "a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture.” The expression “geotechnically significant blocks” means there's mechanical contrast between blocks and matrix, and therefore the volume and size of the blocks influence the rock mass properties at the scales of engineering interest.

While the term bimsoil describes a material like bimrock but with an inconsistent matrix with poor mechanical characteristics. Different types of material belong to the category of bimrock including *mélanges* (Medley, 2002). Melanges occur globally in mountainous terrains, and are notorious for their role in slope instability and for providing unexpected and expensive difficulties during excavation and tunnelling; and construction claims are common for unexpected “mixed face” tunnelling conditions and differing site conditions claims.

Medley ranked mélanges like that subgroup of bimrocks that manifests more problems from the engineering point of view (Medley, 2002). The interest for structurally complex rock formations was born with Medley’s study about a particular type of mélange, called *Franciscan Mélange*, located in northern California. This geological formation consists of sedimentary rock formations immersed in a sheared clay matrix. From a textural point of view, the Franciscan Complex consists of the typical structural mélanges conformation which contains heterometric and heterogeneous blocks chaotically arranged inside the matrix (Medley et al., 1994).Blocks in Franciscan melanges are found at all scales of engineering interest and the range of block sizes extends more than seven orders in magnitude, between sand and mountains. The overall mechanical properties of bimrocks are mainly affected by the mechanical properties of the matrix, the volumetric block proportion, the block shapes, the block size distributions and the orientation of the blocks relative to failure surfaces. When the block proportions are between about 25 and 70 %, the increase in the overall mechanical properties of bimrocks is directly related to the volumetric block proportion of blocks in the rock mass.

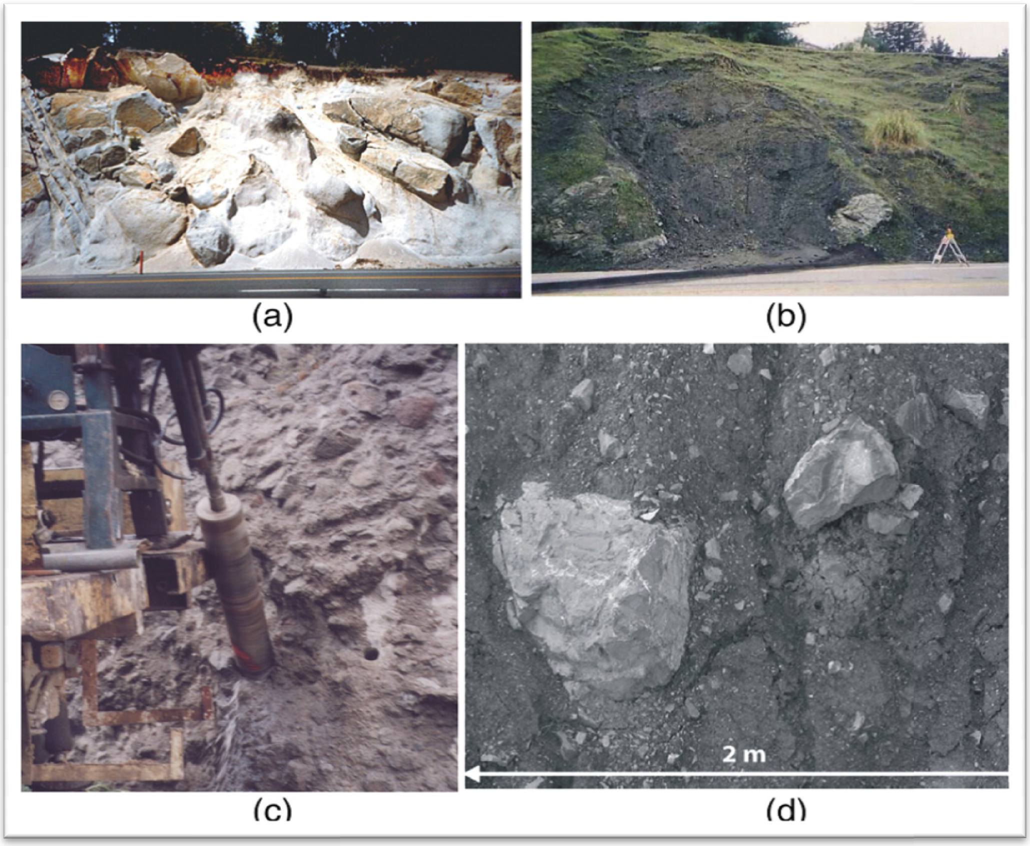

Figure 1 Some pictures of different kinds of bimrocks, (a) a decomposed granite (weathered rock) bimrock in the Sierra Nevada of California (photo: Dr. E. Medley), (b) Franciscan Complex mélange, Northern California (photo: Dr. E. Medley), (c) a welded bimrock Ankara agglomerate (photo: Dr. H. Sonmez), (d) a view of mélange in the Santa Barbara mine of the Northern Appennines (Italy) (from Coli et al., 2011).

Matrix rocks in Franciscan melanges are most often fractured and broken to completely sheared soil siltstone and shale. Shears pass around blocks, and may be numerically denser around large blocks. Melanges are often extensively sheared to soil: about 800 shears per meter were counted in a Franciscan melange (Medley and Sanz, 2004). Geoengineers often neglect the contributions of blocks to overall bimrock strength, choosing instead to design on the basis of the strength of the weak matrix. However, this practice may be too conservative for many bimrocks and often results in ignoring the presence of blocks altogether, to the detriment of accurate characterizations. As block proportions increase, stiffness increases and deformation decreases depending on the relative orientation of blocks.

Figure 2 Picture of a slope of Hong Kong Bouldery Colluvium (T.Y Irfan et al 1993)

Soil-rock slopes are present in most mountainous areas everywhere in the planet, especially within the western China and California region. According to statistics, six of each seven landslide accidents that occurred on the Sichuan-Tibet Highway were related to soil-rock slopes, along which the earthwork susceptible to landslides amounted to 300 million m^3. In addition, consistent with the statistical data of Liao et al, 2006 on the 816 historical landslide accidents reported within the Panxi area in the year 2006, 500 landslide accidents, about 61.3% were associated with soil-rock slopes, indicating that soil-rock slopes account for an outsized proportion of slope accidents.

Bimsoils are common in active or dormant organic belts such as the Alpine or the Franciscan complex. The challenge of these geologic materials is the problematic and chaotic nature prohibiting a simplistic approach for estimating their spatial distribution as well as their complexity and challenging sampling during ground investigations result in lack of good quality laboratory and in situ testing.
Many studies have been carried out in the last few decades to define systematic approaches to properly characterize bimrocks, select the appropriate strength and deformation parameters and perform suitable numerical simulations, so as to properly perform engineering works in these complex formations.

Chapter 2

Slope stability in BIMsoils

To satisfy the term "geotechnical significant" the blocks must satisfy three criteria (Medley, 1994):

1. A mechanical difference in terms of strength exists between the matrix and therefore the blocks.

2. There are significant ratios between the largest and the smallest blocks, and a characteristic engineering dimension of the rock mass. These characteristic dimensions have a wide range, referred as engineering range that depends on the scale of the engineering project in question.

3. The volumetric proportion of the block must vary between the values of 25% to 75%.

The melanges of the Franciscan Complex ("the Franciscan") of northern California are similar to melanges in appearance, properties and the problems they present globally to geoengineers. Melanges are the most difficult of bimrocks to characterize; hence lessons learned from studies of Franciscan melanges can be applied to the characterization of other, more tractable bimrocks. The matrix of Franciscan melanges consists of shale, argillite, siltstone, serpentinite or sandstone.
Medley (1994) estimated that the greatest proportion of blocks in Franciscan melanges were greywacke sandstone, with lesser proportions of volcanic, serpentinite, limestone and exotic metamorphic blocks. The weakest elements in bimrocks are the contacts between blocks and matrix. Only modest mechanical contrast between competent blocks and weaker matrix is required to force failure surfaces to negotiate tortuously around blocks (Medley, 1994; Sönmez et al, 2004, 2006a, 2006b).

The correct identification of a complex formation is important to further investigate with the analysis of the deposit. Some bimrocks/bimsoils can be mistaken with the regular homogeneous boulders or colluvial deposits.

❖ **Identification Surveys**

The identification of bimsoils/bimrocks can often be incorrect in the initial assessment due to the complex nature. Identification surveys are vital criteria as it determines relevant design and execution costs for the structurally complex formation. A first evaluation is performed by the means of geological maps and photographs of the site. It should be done under the supervision of a geologist in order to highlight possible outcrops and their arrangements. The recognition of bimrocks is done in situ through a geological survey (Medley & Wakabayashi, 2004).

One of the main indicators of the presence of bimrocks is found in the geomorphological trend of the deposit. The rocky outcrops are easy to find since the matrix (weaker, easily eroded, and subjected to landslides) leaves the blocks emerging from the deposit. However the topography of the site doesn't always guarantee the presence of bimsoils/bimrocks, sometimes some consistent clays and basalts are arranged in a wavy pattern although they might not belong to the family of structurally complex formations. Presence of limestone, basalt or shale may indicate the presence of melanges. Even the presence of scattered metamorphic rocks with a different metamorphic grade indicates the presence of complex nature of rocks.

Another indicator of the existence of some bimrocks is the occurrence of serpentine, as the structure may have blocks of serpentine immersed in the matrix of shale, sandstone and serpentine or any other formation too.

In the identification stage it is also possible to identify the areas that are characterized by a poverty of blocks in the depressions and areas subjected to landslides. Presence of areas rich in outcrops resistant to erosion and rocky headlands are the identification factors. Once the area is figured it is then essential to study the blocks, with the help of different tools and techniques:

- Lithology of the blocks;
- Study of mechanical contrast of the blocks and the matrix through geologist's hammer.
- Study of contacts between blocks and the matrix.
- Outcrops of different scales can be studied by taking photographs.

- Geognostic survey: The geognostic survey allows reconstructing main features of the subsoil and integrating the information gathered through the geological surveys of surface. For the correct interpretation of heterogeneous material it is not enough to rely on existing geological maps or some superficial investigation. It is necessary to carry on investigations in order not to make any mistake of not recognising the presence of structurally complex formations as well as their hydro geological and geometric characteristics. The hydro geological and the geotechnical characterisation of complex structures are important because the presence of blocks and their distribution can affect the permeability, shear strength and the choice of construction methods. (Haneberg, 2004)

However the stratigraphic reconstruction is complex. The information obtained from boreholes is not sufficient for the designers to get an accurate description of the subsurface. The specimens taken from boreholes remain undisturbed, especially in case of heterogeneous materials. Moreover, even if it were possible to obtain an undisturbed sample, it is unlikely to be representative of the whole formation of interest (Lindquist, 2004).

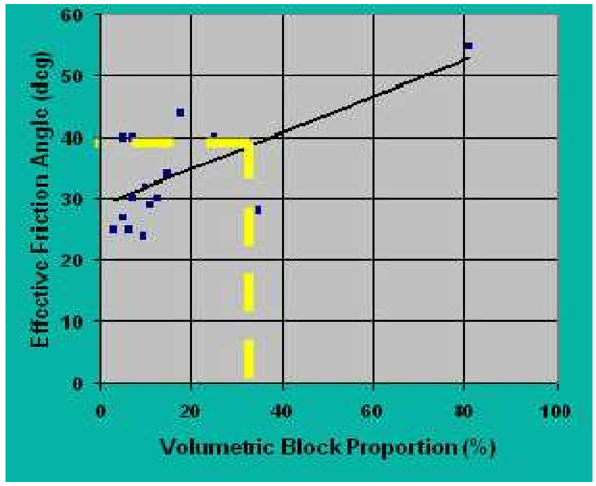

Figure 3 Plot of effective angle of friction as a function of volumetric block proportion, generated from *laboratory testing of Franciscan melange specimens obtained from core drilling at Scott* Dam, northern California (After *Goodman and Ahlgren, 2000)*

The laboratory tests, generally compression tests on undisturbed samples are carried out with the aim to identify the correlation between the percentage of blocks in the sample and its strength. A little amount of dispersion of data is mainly due to the specimens obtained from boreholes, as said specimens are undisturbed especially in case of heterogeneous formations.
To investigate the behaviour of bimsoils, referring to engineering scale of the problem and taking into account the influence of blocks it is therefore necessary to resort to in situ testing and/ or numerical modelling.
The results of the in situ tests are not always easy to interpret, although the utility of the in situ tests is not questionable. These tests can be helpful in determining the characteristics of the deposit. By taking into account the geomechanical properties of the blocks, different techniques can be implemented for the characterization and investigation of the bimrocks, as it is different from the standard procedure used for the normal soil or rocks.

In this aspect the implementation of alternative investigation techniques is targeted and at different scale is proved to be of fundamental importance for the resolution of slope stability problems. (Kim et. al. 2004, Li et al 2004, Medley and Rehermann 2004, Barbero et al 2008,) as well as civil engineering problems related to construction of dams and tunnels (Button et al 2001, Goodman and Ahlgren 2000, Medley and Rehermann 2004).

Even when the bimsoil is recognised it is difficult to identify with certainty the size distribution, volume fractions and the lithology of the blocks. Therefore a complete characterization is needed.

❖ **Main characteristics of bimsoils/bimrocks**

The approach used by Medley (1994) to characterize different size blocks within a weaker matrix was adopted to give a rough estimate of the volumetric block proportion. The geotechnical characterization of highly heterogeneous soils like the boulders colluviums requires a semi quantitative approach. Medley and Lindquist demonstrated the scale independence of the block size distributions of Franciscan melanges (a widely studied bimrock) (Medley 1994; Medley and Lindquist 1995). Scale independence meant that geopractitioners can locate blocks at all scales of engineering works, from the size of laboratory samples to the length of a tunnel or of an even bigger dimension; a wide variety of melanges around the world show such behaviour of their blocks (Grigull et al. 2012). Because blocks vary in sizes, blocks must be distinguished from the matrix through the use of a "characteristic engineering dimension (Lc)," a length that scales the bimrock mass to the problem at hand (Medley 1994; Medley and Lindquist 1995; Medley and Zekkos 2011).

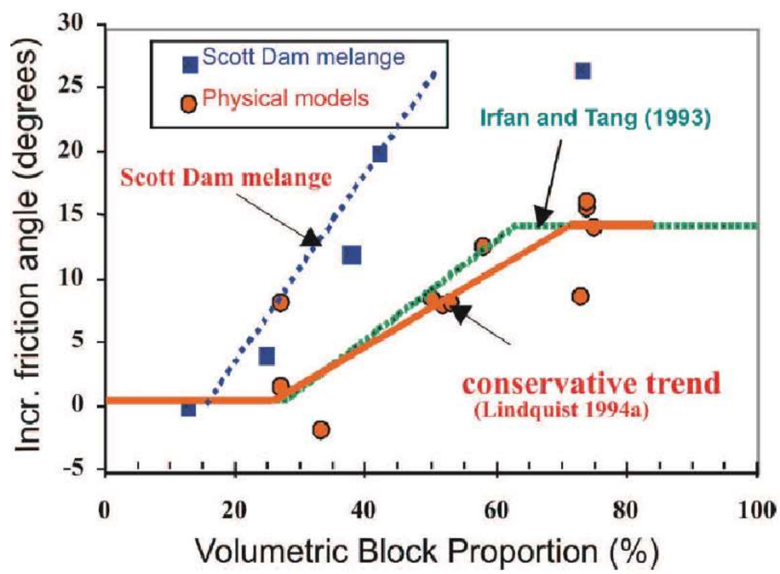

Figure 4 Increment of friction angle with respect to volume proportion of the blocks (after Lindquist, 1994)

Overall increase in the strength in the matrix-only model is directly related to volumetric block proportion (Lindquist, 1994; Lindquist and Goodman, 1994). Strength and deformation of melanges are independent of block strengths. The presence of blocks increases frictional strength of the bimrock, stiffens the mixture, reduces/increases cohesion (depends) and induces tortuous failure surfaces negotiating around blocks. Geotechnical tests must be performed with blocks in specimens because bimrocks at lab scales are models of bimrocks at sites.

Bimrocks have scale independent block size distributions. The relationship (on a log-log plot) between block frequencies and the block sizes is determined by a negative power law. The

exponent of the negative power law is the fractal dimension (D), which means that for n blocks of a specific size class there are nD blocks within the previous one.
Other authors investigated the effects of explicitly taking blocks into account when modelling slope stability in heterogeneous formations like Barbero et al 2008 showcased the presence of blocks within slope models yielded to failure surfaces with irregular positions and shapes, different from homogeneous materials. Medley and Sanz Rehermann found that the factor of safety increased with increasing volumetric block proportions (VBP). Irfan and Tang (1993) determined that changing in both blocks orientation and volumetric block proportion (VBP) yielded to significant differences in the safety factors of theoretical slopes in Hong Kong coarse colluvium. These findings are in good agreement with the evidences provided by numerical and experimental analyses on bimrock specimens, clearly suggesting the importance of explicitly taking the presence of blocks into account in the planning phase of civil engineering projects.

❖ **Factors influencing tortuosity of failure surfaces of BIMsoils/BIMrocks**

Tortuous failure surface are slip surfaces that develop around blocks when bimslopes fail. The geometrical and geomechanical aspects of bimsoils affect the failure surfaces as widely discussed earlier in this chapter. Melanges characterized by the presence of rocks of different lithologies randomly positioned (Medley& Wakabayashi, 2004) within a scaly clay matrix of intensely sheared shale. Medley (2001) defined the characteristic engineering dimension such as height of a landslide, diameter of a tunnel or width of a foundation (depends on the scale of interest). The significant blocks are limited to be between 5% and 70% of the characteristic engineering dimension. The materials below 5% limit are the matrix and those about 70% are considered to be blocky rock masses.

Medley (2004) defined the ratio between L', and L_0 to calculate the tortuosity. This ratio L'/L_0 was referred as tortuous length ratio. The areas A under the irregular tortuous failure lines were measured digitally using image analysis using a software (Medley, 2004). In addition to this, he defined a potential failure zone as the average width of possible tortuous failure surfaces. The average tortuous width or ("superficial roughness") is obtained by dividing the total area A, contained between the irregular tortuous line and the smooth line by the length of the smooth line L_0 (Figure 5). L_0 in this case is the one measured digitally

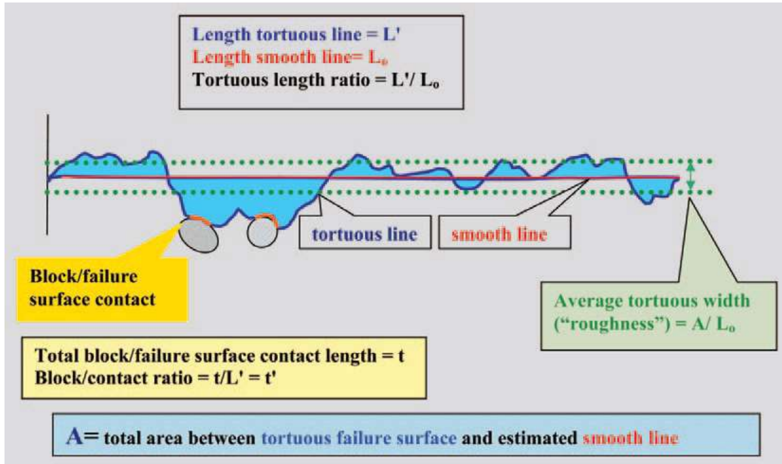

Figure 5 Parameters measured and calculated from traced lines of tortuous failure surfaces. (Medley, 2004)

With the previous studies this can be taken into consideration that overall mechanical properties of the bimrocks are mainly affected by the strength properties of matrix, volumetric block proportions, blocks shape, block size distributions and the orientation of the blocks relative to the failure surface. When the block proportions are between 25 and 70% the increase in overall mechanical properties of the bimsoils or bimrocks are directly related to the volumetric block proportion of the blocks in the rock mass (Lindquist and Goodman, 1994). The estimate of the VBP was done by block chord lengths obtained from the borings and maximum observed dimension of the blocks from the outcrop mapping (Medley, 1994 1997).

The increase in overall frictional strength can be as much as 15 to 20 degrees above the matrix friction strength because of the tortuosity of the failure surfaces. Increase in volumetric block proportion can also lead to an increase of Young's modulus and a decrease in the cohesion of the rock mass in bimsoils.

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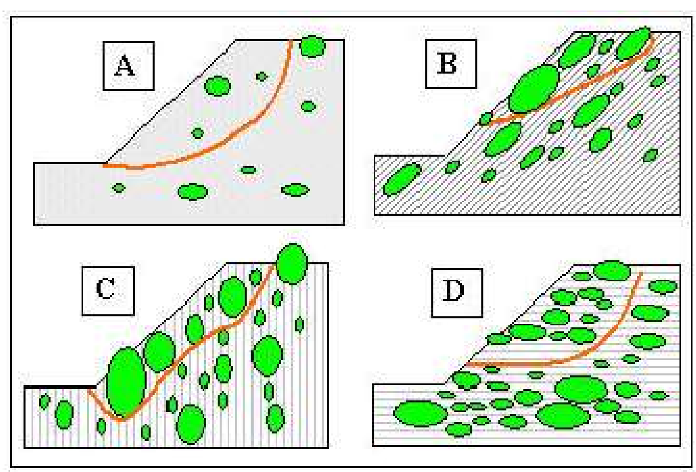


Figure 6 Some possible failure surfaces in bimsoils. A) Low block proportion with critical failure surface unimpeded by blocks. B) Anisotropic bimrock, such as melange, with blocks and shears oriented out of slope, and failure surface guided by the fabric. C) Blocks and shears oriented vertically such that failure surface is

tortuous and slope stability enhanced. D) Regions of block-rich anisotropic bimrock interrupted by block-poor zone with failure surface; slope stability is reduced by heavy upper block-rich zone. (Medley & Sanz, 2004)

Lindquist & Goodman (1994) highlighted also the influence of the orientation of the blocks. They concluded that the bimsoil strength was generally least when the general direction of the major axis of the blocks was oriented to about 30 degrees relative to the direction of maximum principal stress.
Taking into consideration the slope stability, it is important to characterize the fabric of anisotropic bimrocks (Reidmueller et. al, 2001). On the contrary, blocks oriented at higher angles to the slope increase the stability due to increased tortuosity (Medley and Sanz, 2004). Large blocks or block which regions at the toe of the slope tend to buttress slopes and add to slope stability (Medley et al, 2004).
However, in the fault rocks the orientation of blocks and shear fabric vary, as model blocks swirl around the larger block. Consequently, the orientation of failure surfaces depends on the shape of the blocks.
Block shapes influence also the tortuosity of the failure surfaces most when coupled with the orientation of the blocks. Elliptical blocks have greatest effect on the slope stability when the direction of the major axis is coincident with the direction of the shearing stress. (Medley and Sanz, 2004)

Study of Montoya – Araque et al (2020)

Montoya-Araque et al. (2020) created a theoretical model to determine the optimal path of the tortuous failure surface (TFS) in a bimslope, which was a slope comprised of bimrocks or bimsoils. The theoretical model was based on the use of a grid graph in accordance with the study done by Montoya-Araque et al. in 2019. In Figure 7, the bimslope boundary is a polygon with an irregular shape, but its structure is a rectangular arrangement of square cells which are aligned vertically and horizontally.
The bimslope matrix is shown by gray cells which contain information about unit weight and strength parameters while the bimslope blocks are represented by black cells which has information only about unit weight and not about the strength parameters as defined by Lindquist (1994) the tortuous failure surface in bimrock does not pass through blocks but passes around them. The white cells represent the space outside the slope boundary and contain only information to avoid these cells to be selected during the automatic tortuous failure surface definition. Moreover, it is important to know that the bimslope blocks are randomly distributed with a binomial distribution.

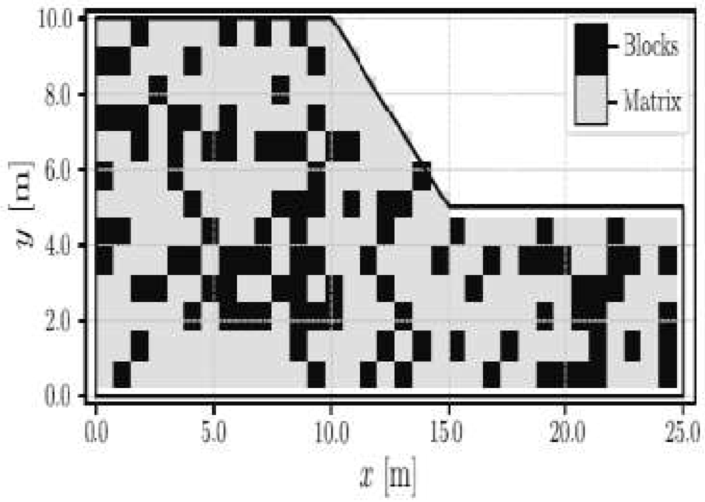


Figure 7 The most basic bimslope model (Montoya-Araque et al., 2020).

The model represented in Figure 7 is used as starting point to create a more sophisticated bimslope model with circular blocks of different sizes. The circular blocks are composed by tiny cells that increase the bimslope resolution making it more accurate. The A* algorithm, described by Montoya-Araque et al. in 2019, generates the circular blocks with different diameters which fill each triangle of the triangular mesh that is contained in the polygon of the bimslope boundary (Figure 8).

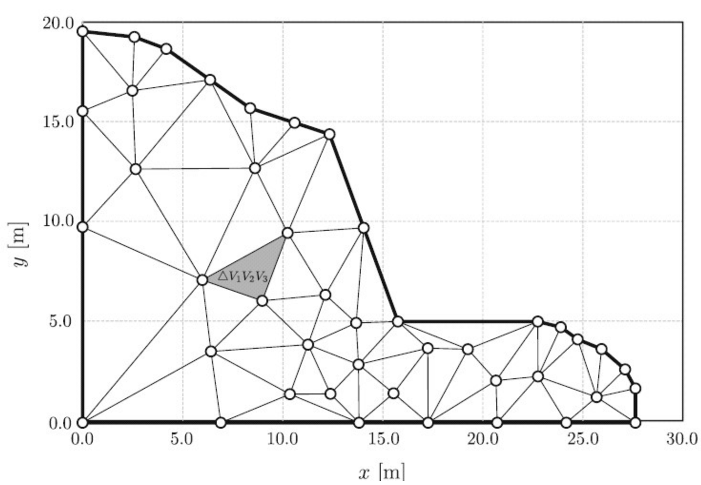


Figure 8 Triangular meshes inside the polygon of the bimslope boundary with each triangle filled with circular blocks of different sizes (Montoya-Araque et al., 2020).

When the circles are all packed in the triangle, a random selection and a shortening of the radii is performed to control the areal block proportion (ABP) assuming equivalence to the volumetric block proportion (VBP) (Montoya-Araque, et al., 2020). In Figure 9 the final bimslope model obtained following the procedure mentioned above is shown.

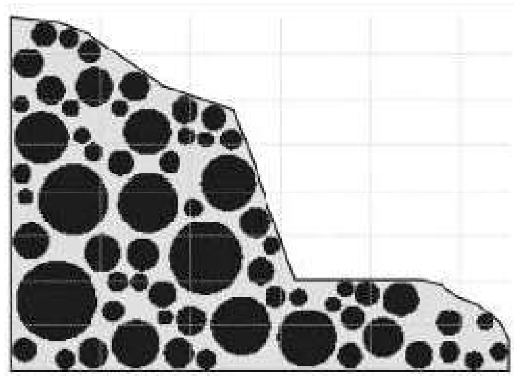


Figure 9 Bimslope model with circular blocks of different sizes (Montoya-Araque et al., 2020).

Montoya and Suarez used pyBIMstab software to perform slope stability analysis evaluating many models. This software which was created by them, uses the GLE (General Limit Equilibrium) procedure to the failure surface of any shape and automatically generates tortuous failure surfaces (TFS) (Montoya-Araque et al., 2018).
It uses the 2D limit equilibrium method (LEM) of Bishop to perform the stability evaluation and to consider the tortuous failure surface of irregular shape that is created inside the bimslope. The pyBIMstab software uses the optimal path finding algorithm A* that was modified by Montoya-Araque et al. in 2019 to track optimal paths conditioned to resemble a preferred path. This modified A* algorithm can model bimsoils/bimrocks in such a way to develop the optimal path of the tortuous failure surface in the matrix passing around the blocks.
The preferred path that they have chosen as input for obtaining a more realistic TFS was the matrix-only circular failure surface. This automatic procedure allows obtaining an optimal TFS avoiding the subjectivity problems that appear when the TFSs are traced manually (Montoya-Araque and Suarez-Burgoa, 2018). In Figure 10, it is assumed that the starting and arrival points of the matrix-only failure surface that is circular coincide with the starting and arrival points of tortuous failure surface of the heterogeneous material.

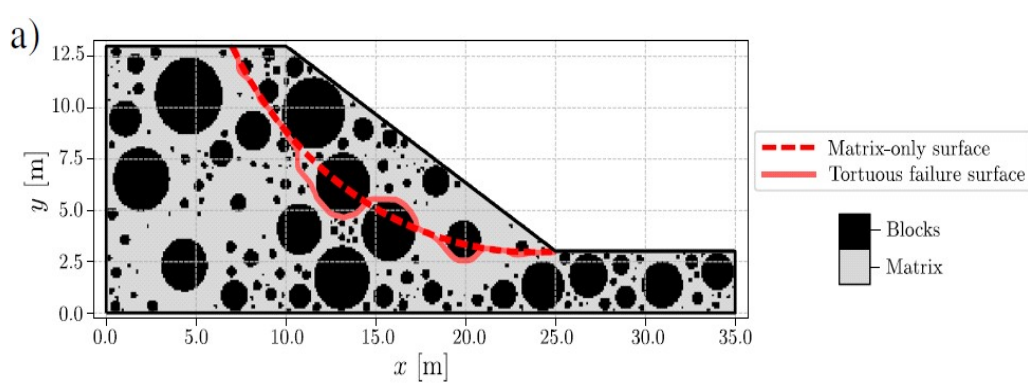


Figure 10 Matrix-only circular failure surface and tortuous failure surface inside a bimslope (Montoya- Araque et al., 2020).

The TFS found allows finding the parameters already used by Medley (2004) to define the tortuosity. These parameters are the *tortuous length ratio* (TLR), which is the ratio of the length of the tortuous failure surface lTFS to the length of the matrix- only failure surface lMOS, and the *average tortuous width* (ATW) which is the light-gray area ATFS in Figure 10 divided by the length lMOS. As ATW increases even the tortuosity increases (Montoya-Araque et al., 2020).

As in Figure 10, the researchers assume also in this representation that the starting and arrival points of the matrix-only circular failure surface coincides with the starting and arrival points of tortuous failure surface of the heterogeneous material. Moreover, Montoya et al. (2020) as Medley (2004) assessed the *failure zone width* which is the range that contains most of the possible tortuous failure surfaces. They, assuming as characteristic engineering length *Lc* the height of the slope sh, have found a failure zone width that is approximately 0.4* S_h because the results of the studies carried out show that most of the possible tortuous failure surfaces are between -2 and 2m deep (Figure 11).

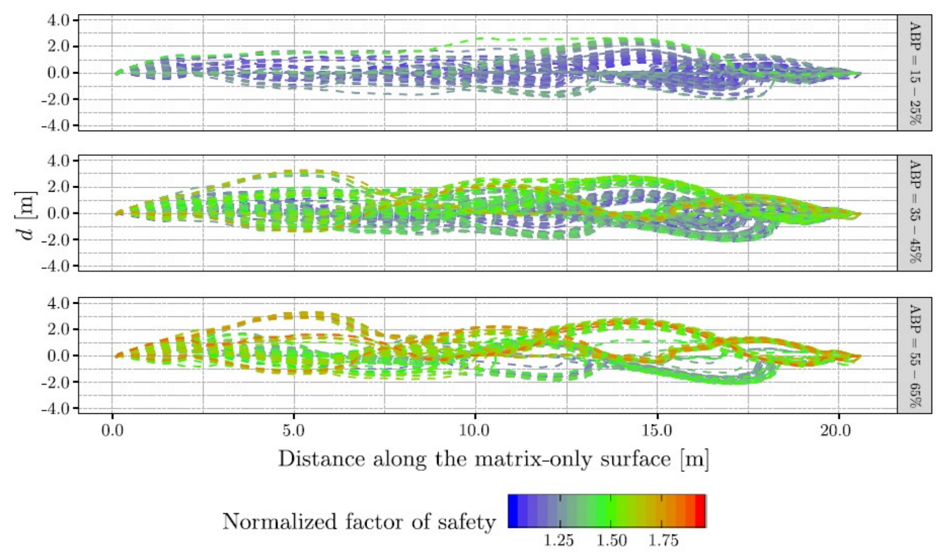


Figure 11 *Possible Tortuous failure surfaces profiles for different Areal Block Proportions (ABPs) with respect the perpendicular depth d starting from the slope surface. It's evident that the roughest profiles are traced for the highest ABP (Montoya-Araque et al., 2020).*

Knowing that the height of the slope S_h used in Montoya et al. (2020) model was equal to 10 m it turns out that the failure zone width 0.4*S_h is wider than the failure zone width found by Medley (2004) which varies between 0.1*S_h and 0.15*S_h. This underestimation can be attributed to the fact that Medley (2004) did not consider the effect of the uncertainties highlighted by the stochastic analysis carried out by Montoya et al. (2020).

Furthermore, Montoya-Araque et al. (2019) have developed the modified A* algorithm that in input has a preferred failure surface path which is the matrix-only circular failure surface and, depending on the location and the size of the blocks inside the bimslope, it finds the optimum path of failure. So instead of inventing the position of the failure tortuous surface, they started from a known location of a circular failure surface and automatically the optimum TFS is provided. Once the optimum TFS is known, it is putted in the pyBIMstab software and the factor of safety can be computed to assess the bimslope stability. It is important to observe that all this procedure assumes that the 2D projection of TFSs is compared to the irregular network of possible paths of a "maze" with a starting point and a variety of possible routes to a unique exit (Montoya-Araque, et al., 2020). At the end of their analysis, they provide an indication of the failure zone width found by the numerical analysis they did.

- **Effects of block proportion on slope stability: Finite Element Analysis**

To predict the mechanical properties of bimsoils, the volumetric block proportion must be estimated. The volumetric block proportion of a bimsoil can be approximated by measuring linear block proportions of drilled cores which, taken in good numbers, are equivalent to volumetric proportions (Weibel, 1980 and Medley, 1994). The linear block proportion is the ratio of the total lengths of blocks intersected to the total length of sample lines. Other methods include measurement of the areal block proportions from outcrops using image analysis (Medley, 1994).

The Factor of Safety for slope stability of bimrocks increases with the tortuosity of actual and potential failure surfaces. The increase is largely related to volumetric block proportions and block orientations. Block orientations (relative to directions of governing stresses) are controlled by anisotropies of block and shear fabrics. The finding that the Factor of Safety is related to volumetric block proportion is encouraging because commonly used analytical tools may then become useful to the practitioner investigating the slope stability of geologically/ geotechnically complex formations such as melanges, fault rocks and other bimrocks. Nevertheless, more work must be performed, perhaps by performing Monte-Carlo type simulations using 3-Dimensional models, to understand the statistical viability of using simple analytical approaches for complex geological conditions.

The block size distribution of a bimrock is an important strength parameter. The more uniformly sized is a bimrock the planar and less undulating the failure plane will be. A bimrock with low block size distribution will have lower shear resistance strength values (Medley and Zekkos, 2010), increasing mainly the angle of internal friction (ϕ). Thus, the more "well graded" the bimrock, the more tortuous the shear planes. For an accurate block size distribution analysis the method used by Medley (1994) is considered essential.

Irfang & Tang (1993), Medley & Sanz (2003, 2004), Barbero et al (2006) dealt with the study of slope stability in bimrocks/bimsoils considering numerical modelling and the medium as continuous. The study mainly focused on investigation of global safety factor of the slope in function of the parameters that categorise the bimrock.

Barbero et al. (2006) used the Finite Difference Method (FDM) for their theoretical slope stability analysis. They used a stochastic approach to randomize the distribution, size and orientation of blocks in the slope. The VBP varied between 20% and 50%. The shapes of blocks were circular and elliptical with different ratios between minor to the major axis (labelled as 'e') as shown in Fig.12 (b). With the use of a prepared code, based on the stochastic approach, indices of the blocks were generated as shown.

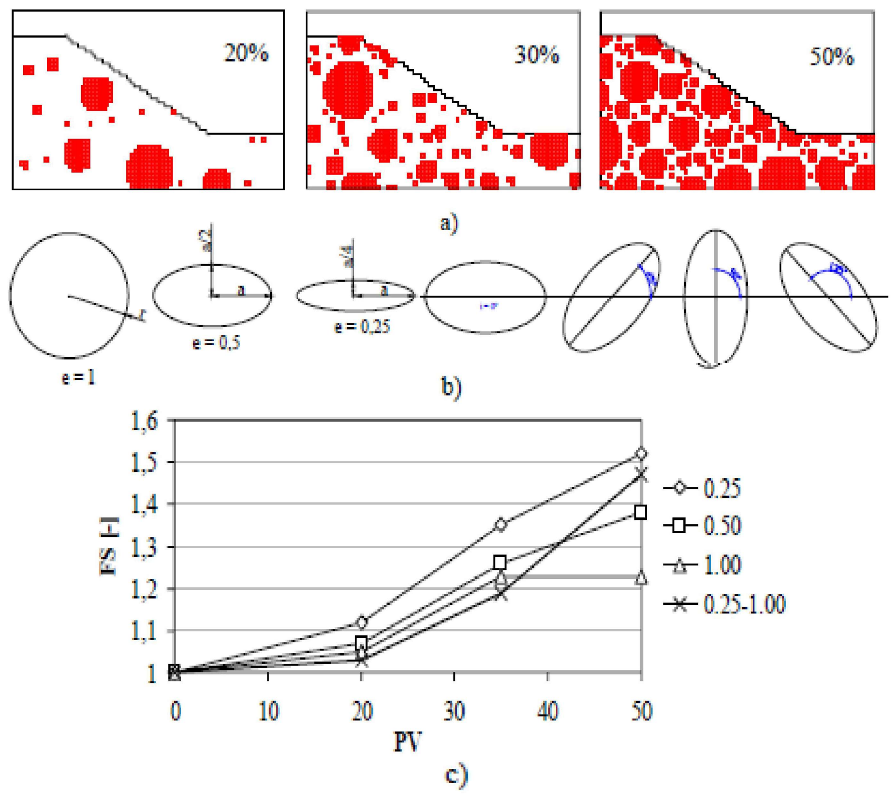


Figure 12 a) Slope models with different VBP b) Shapes and orientations of blocks analysed c) Trend of changing Factor of Safety (Barbero et al., 2006)

Global factor of safety of the slope according to the variation of VBP was evaluated using the SRF reduction factor technique.

The analysed results had some observations which are:

- Safety factor increases as the VBP increases. We can see a direct relationship; the growth is more for values higher than 20%. Therefore for a value below the threshold model behaves as of the matrix only model.
- The safety factor increases significantly when the blocks have an oval-shaped instead it assume the minimum values for the circular blocks. This could be possible as elliptical blocks in some way obstruct the development of the failure surface and it becomes more tortuous.

- In general 20% volume percentage there is not a substantial improvement of stability condition with respect to the case that in which the blocks are not present and the whole slope has the characteristics of the matrix. It was found that 50% the slope stability is greatly improved the sliding surfaces are crucial and much reduced.
- The orientation of block seems not to influence clearly the safety factor for any value of VBP and 'e'.

By taking the example of the above research it can be said that bimsoils are common and problematic for geotechnical engineers in many countries including Greece, Italy, United States and many more. Bimsoils should be purposefully characterized for design and construction even where there is great uncertainty in the characterization or when the volumetric proportion of the block is too little to provide geomechanical benefit.

Understanding the nature of the bimsoil helps in their better characterization. Now with the availability of various procedures for characterization of this type of soils practitioners may reduce expensive surprises by focusing on the difficulties that may be encountered during the design and construction phase.

Chapter 3

Analysis of slope stability in bimsoils: Model implementation

This chapter tells us about the implementation of the numerical models for the slope stability analysis in the structurally complex formation. (bimsoils/bimrocks)
In this portion of the slope stability study, as we have already discussed earlier the trend is to assign the mechanical properties to the block- matrix interfaces. In the previous chapters it is described that the presence of the blocks within the matrix determines an increase in strength properties of the entire mass. This approach leads to an increase in manufacturing cost and possibilities during the construction phase to detect the blocks of the unexpected mechanical and geomechanical characteristics with the consequent loss of time that is not at all favourable.
Another approach can also be used to find the strength of the slope based on the estimate of the block proportion obtained by boreholes and main observations made for rocky outcrops in the maps of photographs that are taken during the investigation survey. If the estimate is too high, it attributes to false geo mechanical properties to the bimrock.
Barbero et al (2006) have introduced the use of numerical methods where the positions, shape, orientation of the blocks are defined within the model using a statistical procedure.

In this thesis use of numerical finite element method is preferred with a computer code of RS2, in order to evaluate the slope stability of bimsoils.
The main aspect was to import different models which were created using the stochastic approach proposed by Napoli et al. 2021 for a random rock block distribution in the slope. This approach takes into account the VBP, size, shape, position, orientation, and eccentricity of the blocks. Specifically, a Matlab code, based on Monte Carlo simulations, was written to generate rock blocks with different geometrical properties and given VBPs from a statistical distribution.
The conditions that are fulfilled by the blocks which were created using the MATLAB by Napoli et al during their study on bimrocks are:

- Blocks cannot intersect each other; a minimum distance between two blocks is 10 cm.
- An intersection of a block (circle) with the domain would lead to a partial loss of block resulting influence on the volume fraction, which would no longer reflect the desired percentage.

The main Matlab code output consists of a text file containing, for each bimrock configuration, a list of both diameters and coordinates of the centers of the circles, representing the blocks. In order to import the bimrock configurations in RS2 software, all Matlab output files were converted in script files, so as to be visualized in AutoCAD software and then saved in DXF format.

For each VBP considered (25%, 40%, 55% and 70%VBP, since 0%VBP represents a matrix-model) fifteen bimrock configurations models used by Napoli et al 2021 during their research were simulated as bimsoils by varying the block- matrix interface properties. Firstly, stability analyses for each considered VBP were carried out with an 50% reduction of value of cohesion of the block-matrix interfaces keeping the value of friction angle same as that of the bimrocks that were analysed by Napoli et al 2021, then, 100% reduction in the cohesion of the block-matrix interfaces were simulated and the factor of safety was noted and compared with the studies carried out on the bimrocks by Napoli et al 2021.

❖ **Stages of model implementation**

▪ AutoCAD
  - Creation of file.scr starting from file.txt containing the same objects.
  - Import of the blocks in Autocad and generating dxf files.
  - Importing the files; observing and comparing the failure surfaces (in the later stages of the research).

▪ RS2
  - Import dxf file.
  - Analysing the models with different strength properties of the interfaces.

▪ Excel
  - Calculations for an average safety factor and standard deviation for the VBPs
  - Comparing the results obtained from previous studies carried out on bimrocks.

❖ **Models in RS2 (version 11.0)**

RS2 is two dimensional finite element software. It is used to solve a variety of civil engineering, geotechnical and mining problems.
There are many advantages of this type of analysis compared to the limit equilibrium models, some facts that are considered are:
• It is not necessary to specify a failure surface.
• It is possible to include both elastic and plastic behaviour of the material in the analysis.
• It is possible to follow the strain process.

The key feature of the finite element method is to divide the geometry of the model under the consideration in discrete portions known as finite element portion.
These have a simple triangular or a square shape and are connected to each other by shared nodes. The set of finite elements and nodes is known as mesh.

The convergence criteria include absolute force and energy, absolute energy, and square root energy while some constitutive laws are Mohr-Coulomb, Hoek Brown and Cam-clay with some other dynamic constitutive laws. In this thesis we have considered the Mohr-Coulomb criteria.

Elastic - perfectly plastic Mohr Coulomb criteria

An elastic-perfectly plastic Mohr- Coulomb criterion belongs to the family of Elastic-perfectly plastic models.

Over past years of study we know that The Mohr- Coulomb failure criterion is the most widely used in the field of soil and rock mechanics. It is also available in almost every finite element software that the practicing civil engineers, geologists etc tend to use.

Mohr Coulomb failure criteria

The material fails when the shear stress acting inside the material exceeds the shear strength τR. The Mohr-Coulomb criterion established a relationship between the shear strength (τ) available on the sliding surface and the normal stress (σ) acting on this plane (characteristics of the material):

$$\tau = c' + \sigma' \cdot tan\ (\varphi')$$

Where:

- τ is the shear strength;
- c' is the effective cohesion;
- ϕ' is the friction angle of the material;
- σ' is the effective stress normal to the sliding plane.

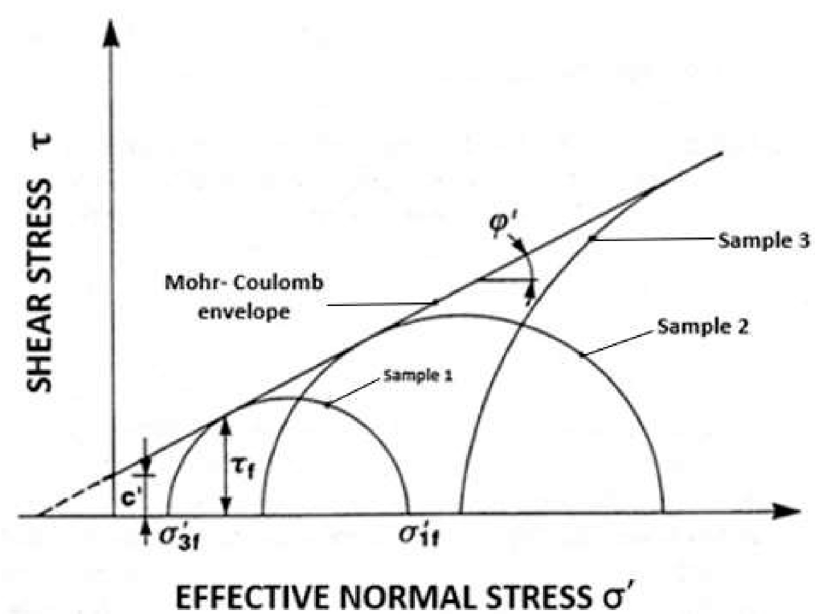


Figure 13 Mohr – Coulomb circles at failure and strength characteristics in effective stresses (AGI, 1994)

In figure 13 a linear envelope of the stress states at failure on the Mohr plane is shown. It depends on the parameters c' and φ', which vary according to the material under consideration. The shear stress parameters c' and φ' are not physical soil characteristics, but are a function of many factors, including stress history, voids index, stress and deformation level, type of structure and particle size composition. Failure occurs in the condition where the effective stress state applied to the specimen corresponds to a Mohr circle tangent to the envelope itself.

Shear Strength Reduction (SSR)

For slope stability analysis, FEM codes such as RS2 use the technique of Shear Strength Reduction (SSR) which allows calculating the critical strength reduction factor for a slope. Critical SSR is equivalent to the safety factor.
The safety factor for a slope can be defined as *"the factor by which soil shear strength must be reduced to bring a slope to the verge of failure"* Duncan (1996). The basic concept of the SSR is that the strength parameters of a slope are reduced by a certain factor, called "Strength Reduction Factor" (SRF), and then the finite element stress analysis is computed. This process is repeated for different values of SRF until the model becomes unstable i.e. the analysis does not converge.
This SRF will be the critical SRF or safety factor of the slope. In the SSR finite element technique, therefore, the material shear strength, assumed elastoplastic, is progressively reduced until collapse occurs.

For Mohr-Coulomb material shear strength reduced by a factor F can be determined from the equation:

$$\frac{\tau}{F} = \frac{c'}{F} + \frac{\tan \emptyset'}{F}$$

The above equation can be written as:

$$\frac{\tau}{F} = c * + \tan \varphi *$$

Where c* $= \frac{c'}{F}$ and tanφ*= arctan $(\frac{tan\varphi'}{F})$........ (3.1)

Equation 3.1 is reduced Mohr-Coulomb shear strength parameters. These values can be put into a Finite Element model and analysed.

The process for systematically searching the critical factor of safety value, F, which brings a previously stable slope to the edge of failure. The steps for a Mohr-Coulomb material are as follows:

• Step 1: For a FE model of a slope the deformation and strength properties, established for the slope materials, are defined. The model is computed and the maximum total deformation in the slope is recorded.
• Step 2: The value of F is increased and the factored Mohr-Coulomb material parameters are computed as described above. The new strength properties are entered into the slope, the model is re-computed. The maximum total deformation is recorded.
• Step 3: Step 2 is repeated, systematically incrementing F, until the FE model does not converge to a solution, i.e. continue to reduce material strength until the slope fails. The critical F value just beyond which failure occurs is the slope factor of safety.

In the case of an unstable slope, safety factor values in steps 2 and 3 must be reduced until the FE model converges to a solution.

The elastoplastic SSR finite element approach eliminates the need for a priori assumptions on failure mechanisms which include the type, shape, and location of failure surfaces.

❖ **Definition of geometric characteristics of the slope in RS2**

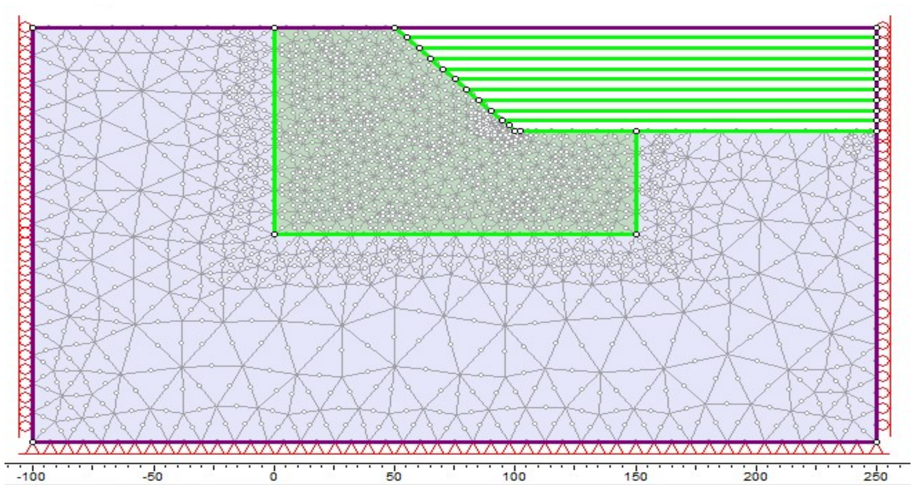


Figure 14 A bimslope model without the blocks (0% VBP) (inRS2)

➢ *Geometry*: A series of FEM analyses with RS2 software were investigated using a 2D slope model both with homogeneous material, with volumetric block proportions (VBP) 0%, and with heterogeneous material with several VBP 25%, 40%, 55% and 70% to consider different position and size of the blocks. In total, 15 models were made for each VBP considered for the heterogeneous material and only one model with VBP 0% for the homogeneous materials. The model represents a generic slope height (S_h) of 50m, inclined at 45 degrees. Random positioning and orientation of blocks was obtained through Monte Carlo simulations by Napoli et al 2021 during their study on bimrocks. FEM analyses results of the homogeneous (matrix-only) material with VBP = 0% produced a classic circular failure surface.

➢ *Boundary Conditions:* Setting of the boundary conditions in the model is also an important task in order to simulate the model correctly. In this study, the boundary conditions were set in terms of the displacements. (refer fig. 14)

➢ *Meshing*: Six-node triangular elements were used to mesh slope models. Sensitivity analyses were performed to evaluate the influence of external boundaries, geometry and mesh density. In particular, with the purpose of avoiding boundary effects, bimrock models were modified to include an outer layer, with a lower boundary of 1.5Lc, a right boundary of Lc and a left boundary of 3Lc (Fig. 14).

An elastic behaviour and the same material properties of the matrix were assigned to this extended part of the geometry of the bimrock models. After discretizing the finite elements, are more practical in creating a high quality mesh as we also had the presence of rock block inclusions. Due to the presence of the (ellipses) rock blocks, the mesh quality varied a lot and it was guaranteed to have no "bad elements" in the model. This condition was checked by using the “show mesh quality” command under the window of “Mesh” in RS2. These ‘bad elements’ are peculiar elements with very high or very low interior angles (in case of triangular elements). An element can also be called “bad” if it has a very high ratio of the maximum side length to the minimum side length of the triangle. These thin/ bad elements determined a worsening of the quality of the mesh with possible negative impact on the reliability of the results. After defining the size and the mesh of the models the actual analyses were performed. (see Fig.14).

➢ *Stages:* Excavation was carried out in 11 stages. Different properties of strength parameters for matrix and the rock blocks (peak internal friction angle, peak cohesion, tensile strength) which were compiled from the earlier researchers (Napoli et al 2021) during their study of bimrocks were defined. Furthermore, these excavation processes was simulated to reproduce the face geometry of the slope, in order to avoid stress modelling disturbance.(Fig 15) .The block- matrix interfaces around all the blocks were added using the ‘joint boundary’ command of RS2 to simulate the model as bimsoil.

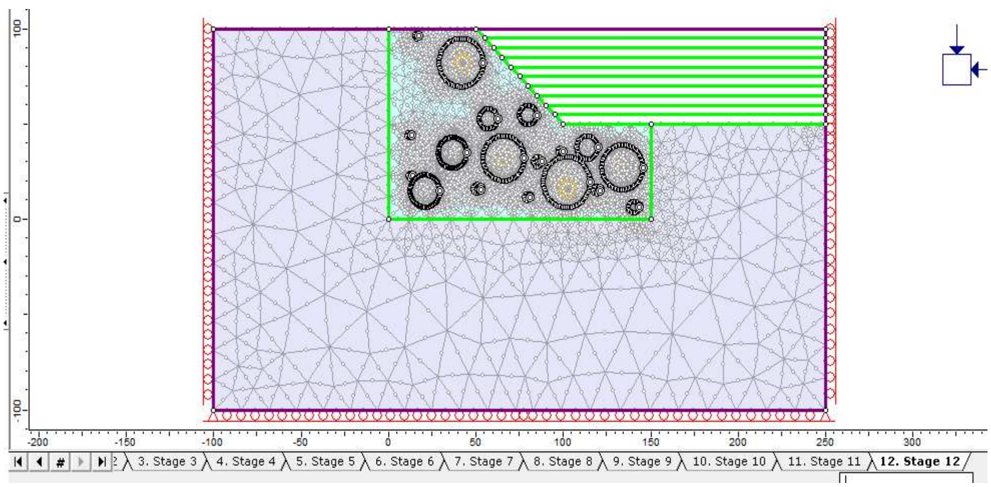


Figure 15 Example of a bimslope model including blocks with interfaces (inRS2)

➢ *Material Properties:* In order to assess the behaviour of the model, a constitutive law must be assigned to each element in the model. Table 1 describes the material properties of the matrix and the blocks and table 2 contains the initial properties of the block-matrix interfaces without considering the reductions. The Mohr- Coulomb failure criteria and elastic-perfectly plastic behaviour was adopted for both blocks and the matrix. The parameters hence assigned to the blocks and the matrix is in accordance with the literature, which suggests that the parameters of stiffness and the strength of the blocks should be at least twice that of the matrix. The external portion of the matrix has also an elastic behaviour and characteristics are same as that of the matrix

	Matrix	Blocks
E (MPa)	37.5	5124
Peak tensile strength (MPa)	0.02	0.5
ν (-)	0.25	0.22
c (MPa)	0.03	0.6
φ (degrees)	24	40
γ (KN/m^3)	22	27

Table 1 Material properties of Matrix and blocks used by Napoli et al 2021 (bimrocks) and in this research

	Block- matrix interfaces
Tensile Strength (MPa)	0.02
φ (degrees)	24
c (MPa)	0.03

Table 2 Initial strength properties of block-matrix interfaces used in this research (equal to those of the matrix)

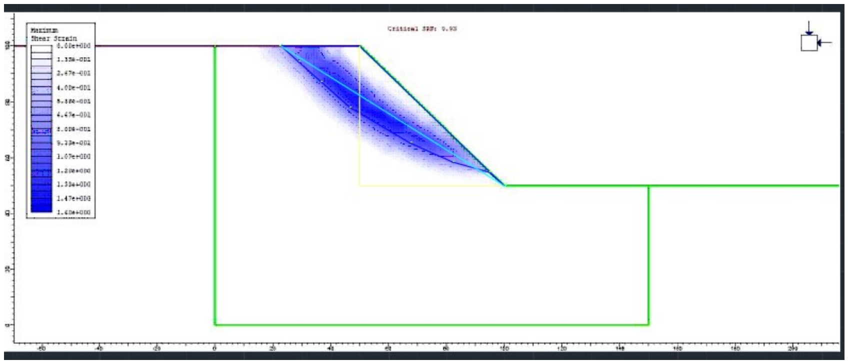
➢ *Field Stress:* Gravitational Field stress is used throughout the slope. The software automatically determines the ground surface above every finite element and a vertical stress is assigned based on the weight of the element above it.

A verification analysis was also performed for the correctness of the model, in which the properties of the matrix were kept same as that of the blocks and Factor of safety was noted and compared. The result thus achieved seemed satisfactory.

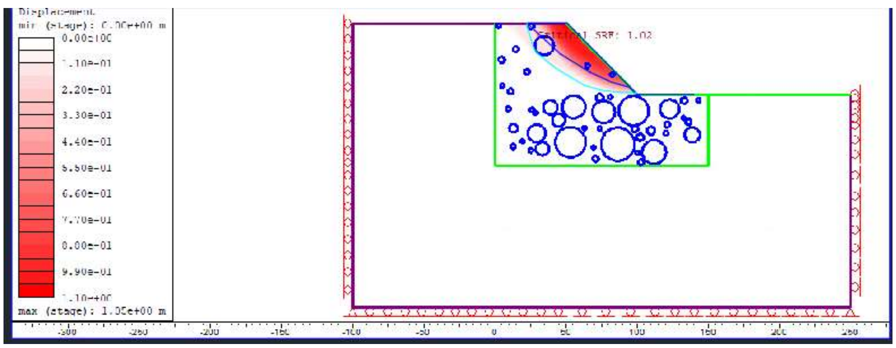
The interpretation of the results and comparison of the average safety factors with the recent studies on bimrocks carried out by Ing. Napoli was made in the later chapter of this thesis.

❖ **Models in AUTOCAD**

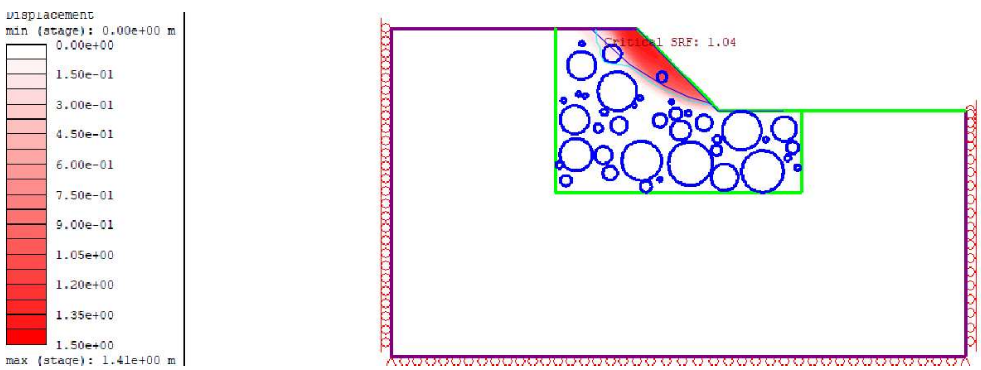
The results obtained from the FEM analyses through RS2 software have been reported on AutoCAD to better highlight the tortuous failure surfaces obtained from the models with VBP 0%, 25%, 40%, 55% and 70% with the help of the function of “Polyline”.
From the FEM analysis on the heterogeneous materials 15 tortuous failure surfaces were obtained for each VBP equal to 25%, 40%, 55% and 70%, instead only one circular failure surface was obtained for the case with VBP equal to 0%. Figures 16.a, 16.b, 16.c, 16.d, 16.e depict the failure surfaces of each VBP when the strength properties of the interface were same as that of the matrix.



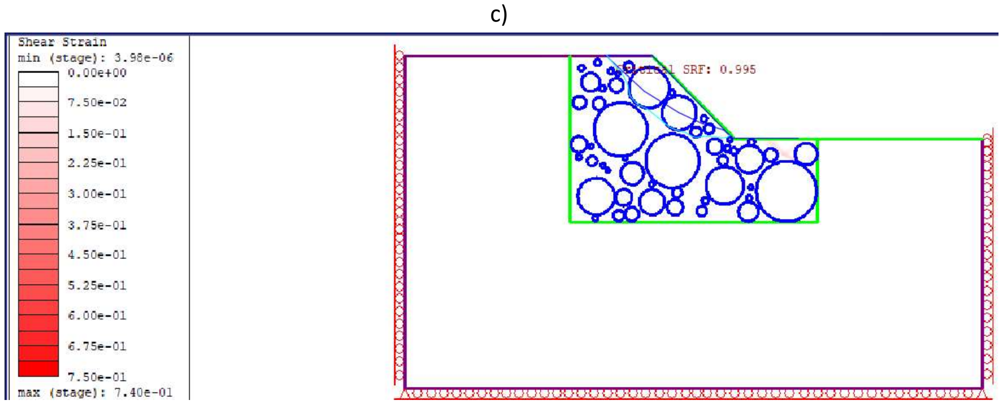
a)


0.00e+00
2.20e-01
3.30e-01
4.40e-01
6.60e-01
9.90e-01
max (stage): 1.00e+00 m
Critical SRF: 1.02

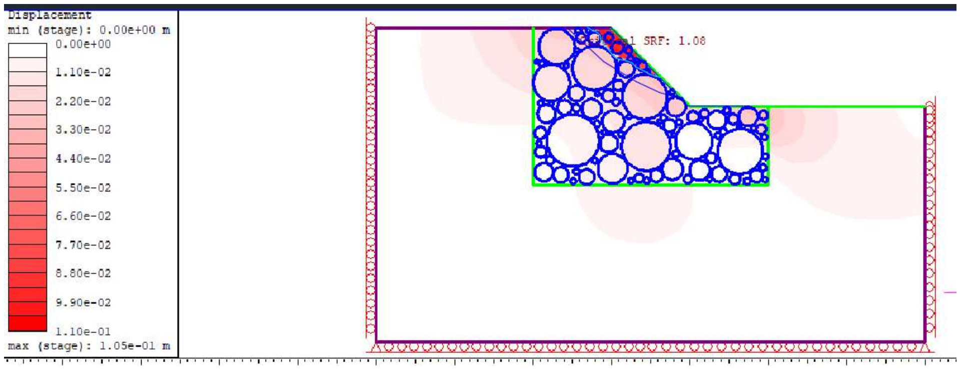
b)


Displacement
min (stage): 0.00e+00 m
0.00e+00
1.50e-01
3.00e-01
4.50e-01
6.00e-01
7.50e-01
9.00e-01
1.05e+00
1.20e+00
1.35e+00
1.50e+00
max (stage): 1.41e+00 m
Critical SRF: 1.04

c)


Shear Strain
min (stage): 3.98e-06
0.00e+00
7.50e-02
1.50e-01
2.25e-01
3.00e-01
3.75e-01
4.50e-01
5.25e-01
6.00e-01
6.75e-01
7.50e-01
max (stage): 7.40e-01
Critical SRF: 0.995

d)



e)

Figure 16 Failure surfaces when the strength parameters of block matrix interface were same as that of the matrix a) 0% VBP b) 25% VBP c) 40% VBP d) 55% VBP e) 70% VBP

Chapter 4

Analysis of slope stability in bimsoils: Results

We further analyse the slope models generated by Napoli et al 2021 during their research on bimrocks by simulating the models as bimsoils by reducing the cohesion of the block- matrix interfaces keeping the friction angle same as that of the bimrock models. In this dissertation we also observe the differences between bimrocks and bimsoils in terms of the stability (safety factors and failure surfaces).
One of the main aims of this thesis was also to find out the influence of block – matrix interfaces on the stability analyses of bimslopes which are often neglected when modelling the bimslopes.
There are many other factors too apart from cohesion that are responsible for the slope stability of the bimsoils such as Volumetric Block Proportions (VBP), block size, block shapes and also the strength properties of the blocks as well as the matrix.
Influence of the blocks at the sliding surfaces has always played a trivial role, while we assess the stability of the slopes.
The results obtained from Finite Element analyses for 5 VBPs (0%, 25%, 40%, 55%, and 70%) are portrayed in terms of safety factors and standard deviations.
This chapter of the research deals with the brief interpretation of the results achieved after the simulations. The abbreviation used for Finite Element Method is FEM and the results are showcased as 25%_1_FEM for the model consisting of 25% VBP and 50% reduction of the cohesion of the block- matrix interface and 25%_1b_FEM represents the model containing 25% of VBP but with a reduction of 100% cohesion for interfaces around the blocks.

❖ Numerical Analysis

Numerical analyses were performed to study the problem of instability in bimsoils. The phases of construction of model have been described in detail in chapter 3 of this thesis.

Based on the indications in literature, the presence of the blocks is relevant for volumetric percentages ranging between 25% and 75%. The volumetric percentages analysed are 25%, 40%, 55% and 70%. For each VBP there are 15 models that differ in the sample extracted from block size distribution and positioning of the blocks within the slope.
In the following analyses the blocks are circular and their possible influence of shape and orientation were not taken into the consideration.
To simulate the bimrock models as bimsoils, an interface around the blocks is added (using the joint boundary command of RS2) reducing the cohesion and tensile strength by 50% and further by 100% to observe the results in terms of stability (factor of safety and failure surface) of the bimsoils.
The results are presented in terms of safety factor, shear strains and maximum displacements involved in the instability. The overall safety factor is an index of the stability of the slope; in this case the method of the reduction of the parameters (SSR Shear Strength Reduction) described in Chapter 3 is applied.

- **Matrix only model**

The primary model was analysed is made up only of matrix which was generated by Napoli et al 2021. In practice, the approach followed is to neglect the presence of the blocks within the matrix; this model is thus a useful comparison for the analyses. Table 3 shows the result obtained in terms of safety factor, (the characteristics of the materials have been described in Chapter 3).

Model	Safety Factor
Matrix_FEM	0.97

Table 3 Safety factor for the matrix only model computed with FEM analysis (Napoli et al 2021)

Figure 17 shows the maximum shear strains. It can be noticed that the involved area affects almost the whole height of the slope, is relatively deep, and shows the tendency to form a circular failure surface. Figure 18 throws light on the total displacements of this particular model.

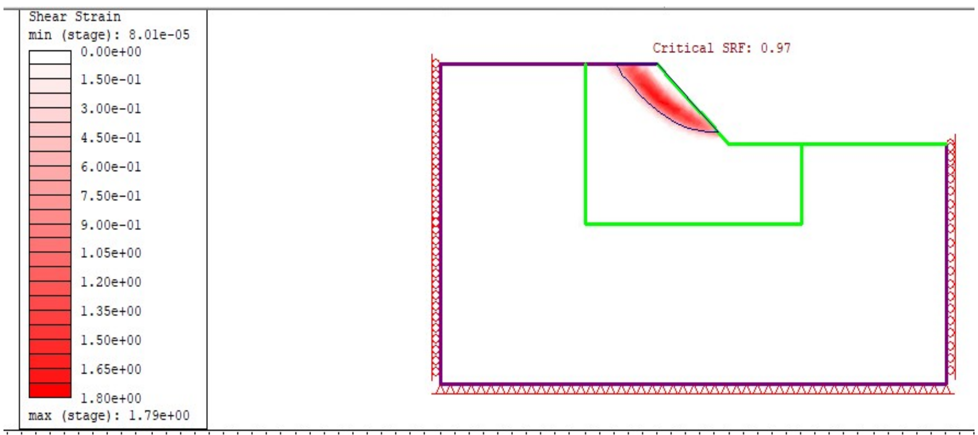


Figure 17 Maximum shear strain of the matrix only model (Napoli et al 2021)

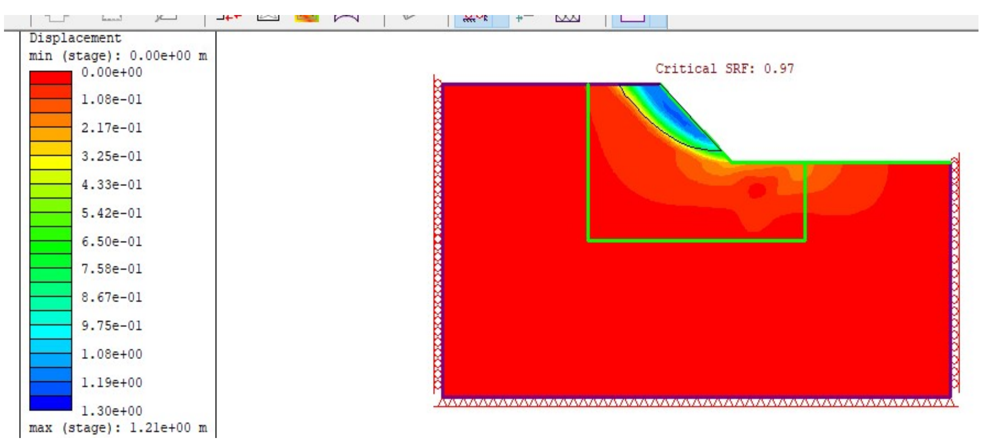


Figure 18 Total displacements of matrix only model. (Napoli et al 2021)

- **Matrix containing blocks with interfaces (joints) of same strength parameters as that of the matrix**

Four models with VBP 25%, 40%, 55% and 70% comprising of blocks whose interfaces have same strength properties (cohesion, friction angle) as that of the matrix were analysed. These models were further used to compare the results with the models in which the interface parameters have been changed and we obtain satisfactory results. Table 4 shows a comparison between the results obtained in terms of safety factors of the models having block- matrix strength properties equal to the matrix and the average safety factors of the bimrock models. Figure 19 shows an example of one of the models. (All results are reported in the Appendix)

Model	Safety Factors of Bimsoils (with the presence of interfaces)	Normalized Average Safety Factors of Bimrocks (Napoli et al 2021)
25%_FEM	1.02	1.02
40%_FEM	1.04	1.00
55%_FEM	0.995	1.10
70%_FEM	1.08	1.35

Table 4 Comparison of safety factors when the block- matrix interfaces strength properties are equal to the matrix with normalized average safety factors of bimrocks (Napoli et al 2021)

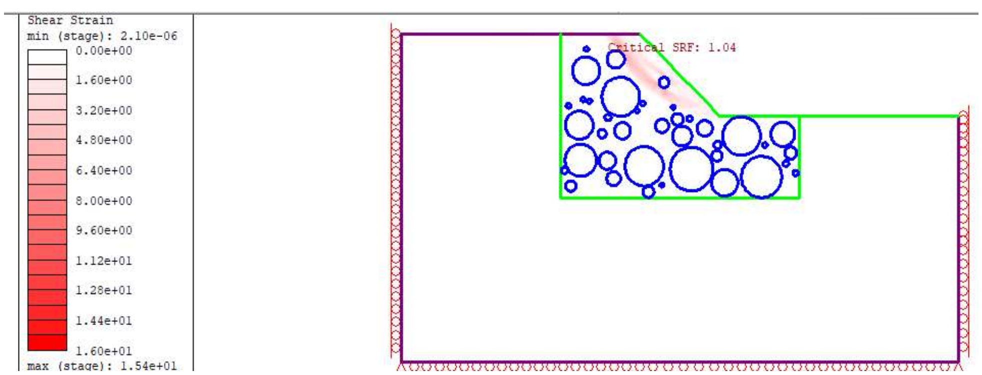


Figure 19 maximum shear strains of the model with 40% VBP when the block- matrix interfaces have same strength properties as that of the matrix

Since the results of the models without and with the block-matrix interfaces with strength characteristics equal to those of the matrix provided comparable results, the analysis is further divided into 2 parts:

1. When cohesion of the interface around the blocks for all the considered VBPs are reduced to 50%.
2. When cohesion of the interface around the blocks for all considered VBPs are reduced to 100%.

- **<u>When the cohesion and the tensile strength of the block- matrix interfaces for all the considered VBPs were reduced by 50%.</u>**

Following properties of block- matrix interfaces for all the VBPs are reduced to 50%, as shown in table 5:

	Properties of block- matrix interfaces
Tensile Strength (MPa)	0.01
φ (degrees)	24
c (MPa)	0.015

Table 5 Strength properties of the block-matrix interfaces when reduced by 50%

- **25% VBP Models**

Fifteen models of 25% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 6 shows the standard deviation and the safety factors of every model analysed.

Model	Safety Factor
25%_1_FEM	1.01
25%_2_FEM	1.01
25%_3_FEM	0.97
25%_4_FEM	1.05
25%_5_FEM	0.94
25%_6_FEM	1.00
25%_7_FEM	1.01
25%_8_FEM	1.03
25%_9_FEM	1.08
25%_10_FEM	1.05
25%_11_FEM	0.995
25%_12_FEM	1.04
25%_13_FEM	0.94
25%_14_FEM	1.02
25%_15_FEM	1.04
Average Safety Factor	1.01
Standard Deviation	0.039

Table 6 Safety Factors and the standard deviation for 15 models with 25% VBP when cohesion of the block-matrix interface is reduced to 50%

From table 6, we can observe that the safety factors range between 0.94 and 1.08. Therefore, it can be said that in some models there is slight decrease in the safety factors with respect to

the safety factors of the model having same strength parameters for block- matrix interfaces and the matrix. Instead for the other cases there is an increase in the safety factor.
Maximum shear strains are shown in figure 20 (all the remaining figures are reported in the Appendix)
The failure surface is not exactly circular but tortuous (figure 21), the tortuosity is influenced by the block size and positions of the blocks which was earlier stated by various researchers in their studies too (Lindquist, Goodman in 1994, Irfan and Tang, 1997, Medley and Sanz, 2003, Napoli et al 2021, Montoya and Araque, 2020 etc).

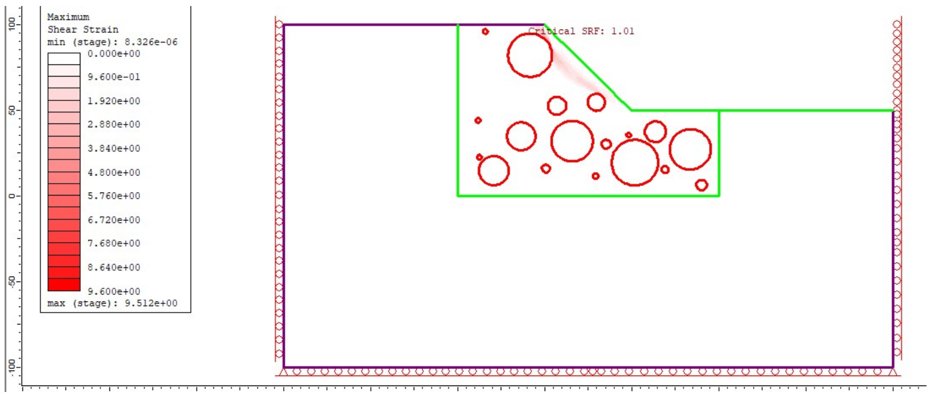


Figure 20 Maximum shear strain of the 25% VBP model when the cohesion of the block- matrix interfaces is reduced by 50%.

Total displacements were also noted for every model. One of the examples is shown in figure 21(others are reported in the Appendix).

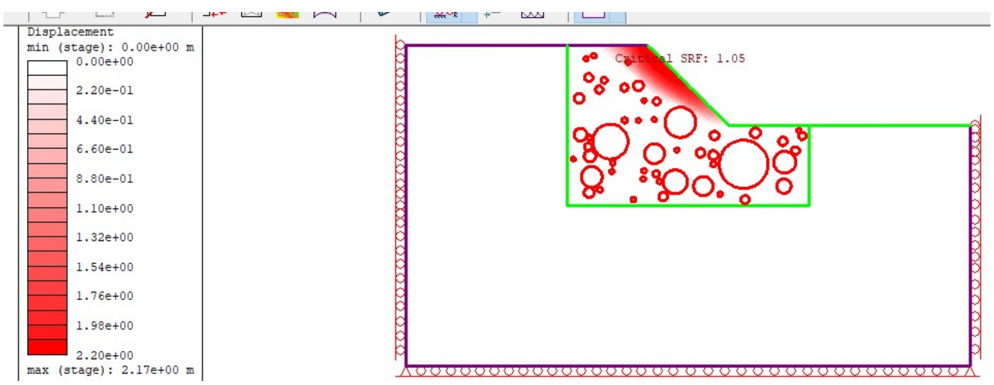


Figure 21 Total displacements in 25% VBP model when cohesion is reduced by 50%

➢ **40% VBP Models**

Fifteen models of 40% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 7 shows us the standard deviation and the safety factors of every model analysed.

The safety factors range between 0.92 and 1.04. Therefore, it can be said that when we consider a VBP of 40%, in some models there is slight decrease in the safety factor with respect to the safety factor of the model having same strength parameters for block- matrix interfaces and the matrix. Instead for the other cases almost no or slight difference in terms of the safety factor.

Model	Safety Factor
40%_1_FEM	1.03
40%_2_FEM	0.97
40%_3_FEM	0.98
40%_4_FEM	0.93
40%_5_FEM	0.94
40%_6_FEM	1.02
40%_7_FEM	0.96
40%_8_FEM	1.04
40%_9_FEM	0.97
40%_10_FEM	1.01
40%_11_FEM	0.93
40%_12_FEM	0.93
40%_13_FEM	0.98
40%_14_FEM	0.92
40%_15_FEM	0.97
Average Safety Factor	0.97
Standard Deviation	0.038

Table 7 Safety Factors and the standard deviation for 15 models with 40% VBP when cohesion of the block-matrix interface is reduced to 50%

With the results obtained, for maximum shear strains, (an example shown in figure 22, all the remaining figures are reported in the Appendix) it is vital to note that deformations occur inside the matrix but never inside the blocks.

We can also comment that the tortuosity also is more evident as the volumetric percentage of the blocks increases in the slope with respect to the earlier analysed model. As noted also by some other authors (Irfan and Tang, 1997; Medley and Sanz, 2003; Barbero et al 2006) an increase in safety factor is influenced by the tortuosity in the failure surfaces.

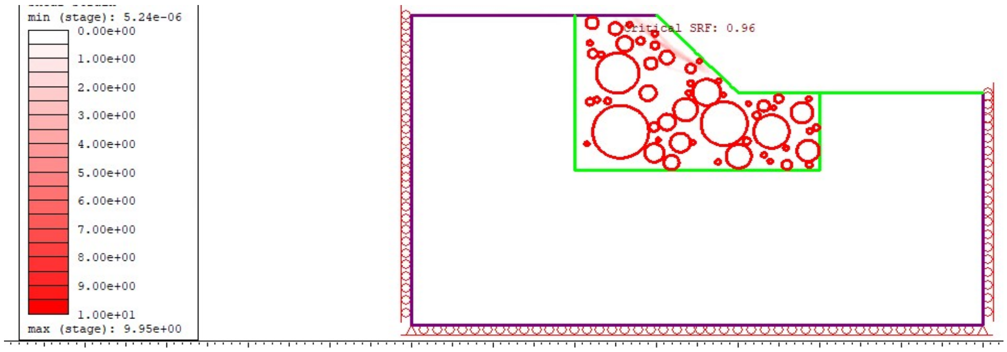


Figure 22 Maximum shear strains of the 40% VBP model when the cohesion of the block interfaces is reduced by 50%.

Total displacements were also noted for every model. One of the examples is shown in figure 23 (others are reported in the Appendix).

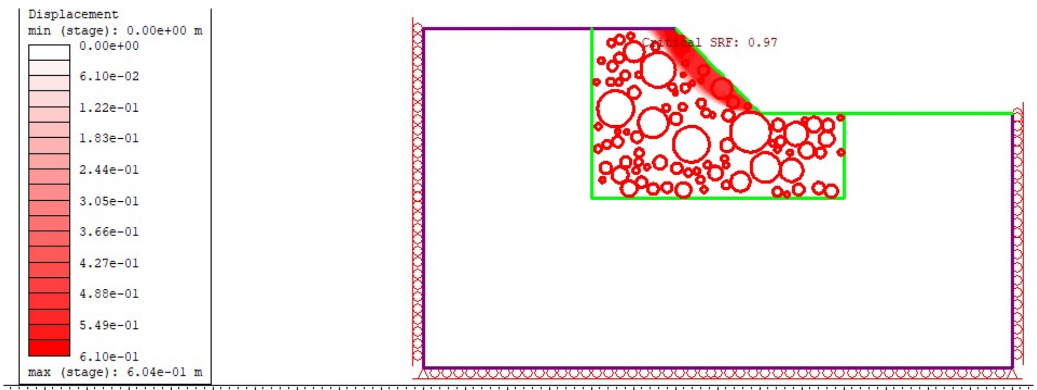


Figure 23 Total displacements of the 40% VBP model when cohesion is reduced by 50%

- **55% VBP Models**

Fifteen models of 55% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 8 shows us the standard deviation and the safety factors of every model analysed.

Model	Safety Factor
55%_1_FEM	1.02
55%_2_FEM	0.99
55%_3_FEM	0.99
55%_4_FEM	1.18
55%_5_FEM	1.08

55%_6_FEM	0.94
55%_7_FEM	0.92
55%_8_FEM	0.995
55%_9_FEM	0.96
55%_10_FEM	0.96
55%_11_FEM	0.99
55%_12_FEM	0.95
55%_13_FEM	0.97
55%_14_FEM	0.98
55%_15_FEM	1.04
Average Safety Factor	0.99
Standard Deviation	0.064

Table 8 Safety Factors and the standard deviation for 15 models with 55% VBP when cohesion of the block-matrix interface is reduced to 50%

The safety factors range between 0.92 and 1.18. Therefore, it can be said that when we consider a higher VBP of 55%, in some models there is almost a negligible variation in the safety factor with respect to the models having same strength parameters for block- matrix interfaces and the matrix. Instead for the other cases there is an increment in terms of the safety factor.

In accordance to the results obtained, for maximum shear strains (an example shown in figure 24, all the remaining figures are reported in the Appendix).

We can also comment that the tortuosity also is more pronounced as the volumetric percentage of the blocks increases in the slope with respect to the earlier analysed model. This was noted also by some other authors (Irfan and Tang, 1997; Medley and Sanz, 2003; Barbero et al 2006) an increase in safety factor is influenced by the tortuosity in the failure surfaces.

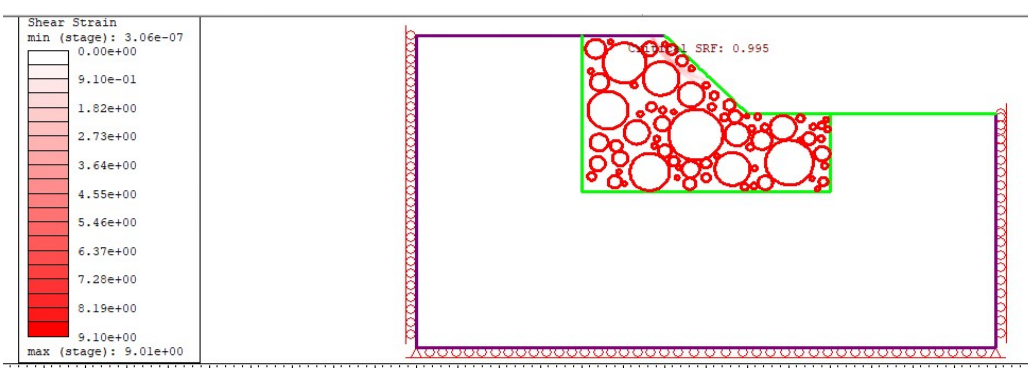


Figure 24 Maximum shear strain of the 55% VBP model when the cohesion of the block interfaces is reduced by 50%.

Total displacements were also noted for every model. One of the examples is shown in figure 25 (others are reported in the Appendix).

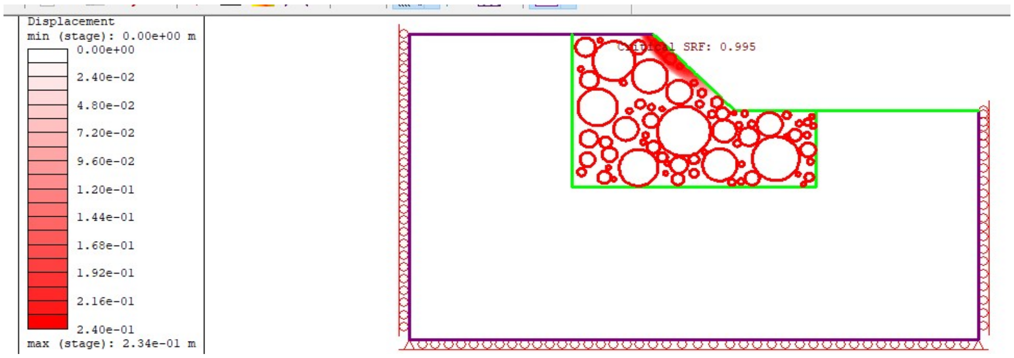


Figure 25 Total displacements of the 55% VBP model when the cohesion is reduced by 50%

- **70% VBP Models**

Fifteen models of 70% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 9 shows us the standard deviation and the safety factors of every model analysed.

Model	Safety Factor
70%_1_FEM	1.28
70%_2_FEM	0.94
70%_3_FEM	1.21
70%_4_FEM	0.98
70%_5_FEM	1.28
70%_6_FEM	1.42
70%_7_FEM	1.07
70%_8_FEM	1.51

70%_9_FEM	1.33
70%_10_FEM	1.29
70%_11_FEM	1.08
70%_12_FEM	1.41
70%_13_FEM	1.02
70%_14_FEM	1.18
70%_15_FEM	1.06
Average Safety Factor	1.20
Standard Deviation	0.174

Table 9 Safety Factors for 15 models with 70% VBP when cohesion of the block-matrix interface is reduced to 50%

The safety factors range between 0.94 and 1.51. Therefore, it can be said that when we consider a higher VBP of 70%, in some models there is very minimal variation in the safety factor with respect to the models having same strength parameters for block- matrix interfaces and the matrix.

Instead for the other cases there is a significant variation in terms of the safety factor. In accordance to the results obtained, for maximum shear strains is shown in figure 26 (all the remaining figures are reported in the Appendix)

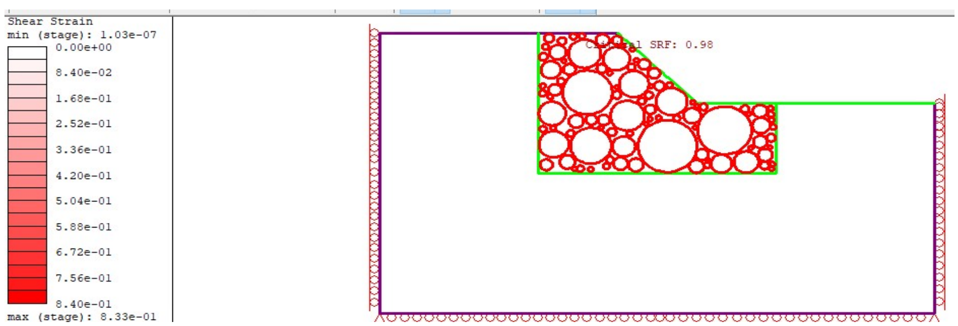


Figure 26 Maximum shear strain of the70% VBP model when the cohesion of the block- matrix interfaces was reduced by 50%.

Total displacements were also noted for every model. One of the examples is shown in figure 27 (others are reported in the Appendix).

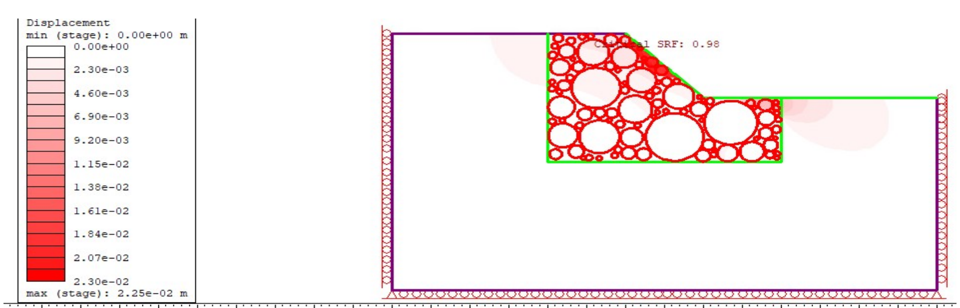


Figure 27 Total displacements in 70% VBP model when cohesion was reduced by 50%

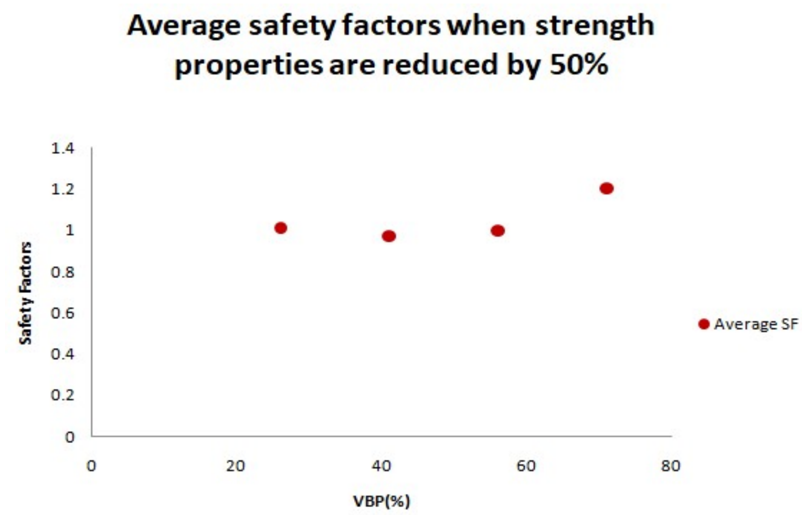


Figure 28 Safety factor with increasing VBPs when cohesion and tensile strength of the block-matrix interfaces were reduced by 50%

Figure 28 shows us the relation of the average factor of safety with the increasing VBPs when the cohesion and the tensile strength of the block-matrix interfaces were reduced by 50%. We note that there is a increase in the average safety factor for higher VBP (70%) only while no specific trend is observed in other considered VBPs (25%, 40%, 55%).

Table 10 depicts average safety factors of models with different VBPs when the cohesion and tensile strength of the block- matrix interfaces were reduced by 50%.

Models	Average Safety factor	Standard Deviation
Matrix- only model	0.97	-
25%_FEM	1.01	0.039
40%_FEM	0.97	0.038
55%_FEM	0.99	0.064
70%_FEM	1.20	0.174

Table 10 Average safety factors and standard deviation of the models with different VBPs when cohesion and tensile strength of the block-matrix interface is reduced to 50%

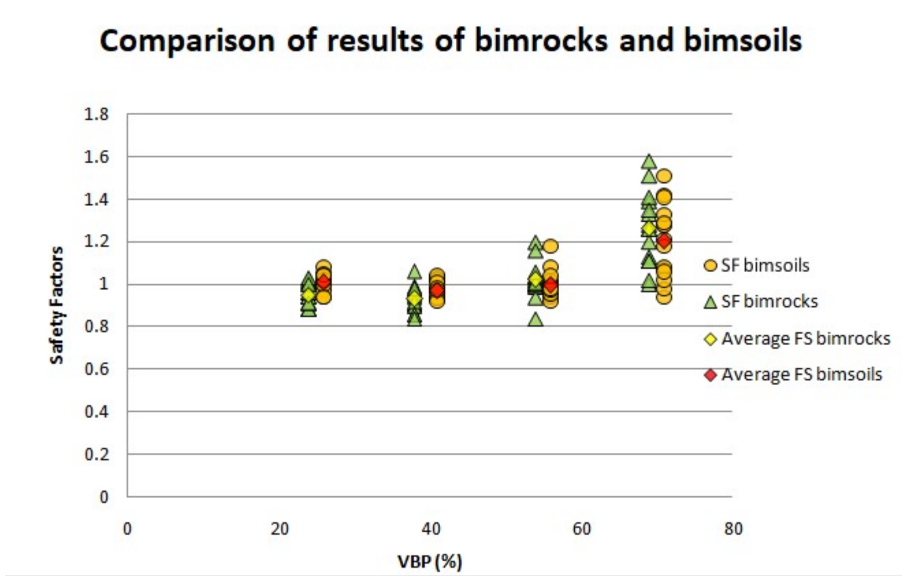


Figure 29 Comparison of safety factors of bimrocks and bimsoils when cohesion and tensile strength of the block- matrix interfaces were reduced by 50%

An interesting comparison is made between average safety factors of bimrocks (Napoli et al 2021) and bimsoils (in figure 29) about which it is discussed later in this chapter.

❖ **When the cohesion and tensile strength of the block- matrix interfaces for all the considered VBPs were reduced by 100%.**

Following properties of the block- matrix interfaces for the VBPs are reduced to 100% as shown in table 11:

	Properties of block- matrix interfaces
Tensile Strength (MPa)	0
φ (degrees)	24
c (MPa)	0

Table 11 Cohesion and the tensile strength of the block-matrix interfaces were reduced to 100%

➢ **25% VBP Models**

Fifteen models of 25% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 12 shows us the safety factors of every model analysed.

Model	Safety Factor
25%_1b_FEM	1.01
25%_2b_FEM	1.02
25%_3b_FEM	0.97
25%_4b_FEM	1.04
25%_5b_FEM	0.97
25%_6b_FEM	1.00
25%_7b_FEM	1.01
25%_8b_FEM	1.02
25%_9b_FEM	1.10
25%_10b_FEM	1.03
25%_11b_FEM	0.995
25%_12b_FEM	0.99
25%_13b_FEM	0.95
25%_14b_FEM	1.02
25%_15b_FEM	1.04
Average Safety Factor	1.00
Standard Deviation	0.06

Table 12 Safety Factors for 15 models with 25% VBP when cohesion of the block- matrix interface is reduced to 100%

From table 12 we can observe that the safety factors range between 0.97 and 1.10. Therefore, it can be said that in some models there is slight decrease in the safety factor with respect to the models having same strength parameters for block-matrix interfaces and the matrix. Instead for the other cases there is an increase in the safety factor.

During a comparison of the normalized average safety factors of the bimrock models with the bimsoil models with a reduction of cohesion of the block- matrix interfaces by 50% we observe that there is a slight increase in the normalized average safety factors of the bimsoil models (Normalized Average SF = 1.04) with respect to the bimrock models (Normalized Average SF = 1.02)

Bimsoil models with a reduction of cohesion to 100% show a similar value of normalized average safety factor as that of the bimrock models (Normalized Average SF = 1.03). (Figure 38)

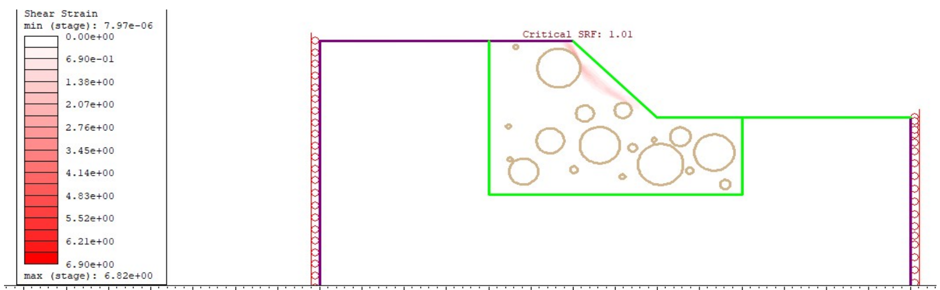


Figure 30 Maximum shear strains of 25% VBP model when the cohesion of the block-matrix interfaces is reduced by 100%.

Total displacements were also noted for every model. One of the examples is shown in figure 31 (others are reported in the Appendix).

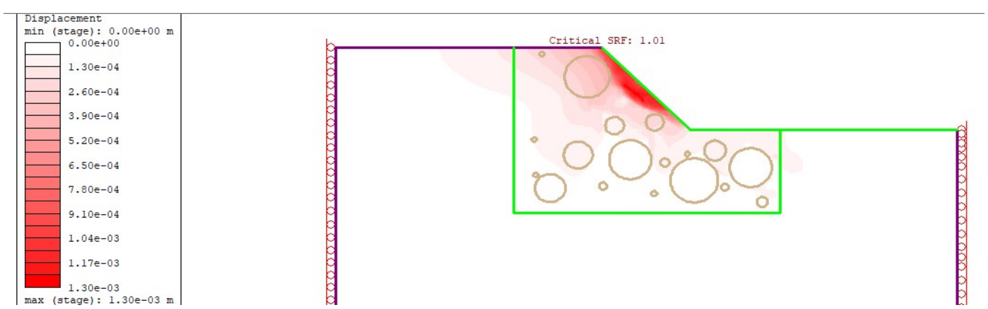


Figure 31 Total displacements in 25% VBP model when cohesion of the block- matrix is reduced by 100%

- **40% VBP Models**

Fifteen models of 40% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 13 shows us the safety factors of every model analysed.

Model	Safety Factor
40%_1b_FEM	1.03
40%_2b_FEM	0.97
40%_3b_FEM	0.63
40%_4b_FEM	0.92
40%_5b_FEM	0.93
40%_6b_FEM	1.03
40%_7b_FEM	0.97
40%_8b_FEM	1.02
40%_9b_FEM	0.96
40%_10b_FEM	0.94
40%_11b_FEM	0.93
40%_12b_FEM	0.91
40%_13b_FEM	0.96
40%_14b_FEM	0.90
40%_15b_FEM	0.95
Average Safety Factor	0.93
Standard Deviation	0.094

Table 13 Safety Factors for 15 models with 40% VBP when cohesion of the block- matrix interface is reduced to 100%

From table 13 we can observe that the safety factors range between 0.63 and 1.03. Therefore, it can be said that in some models there is significant decrease in the safety factor with respect to the models having same strength parameters for block-matrix interfaces and the matrix. Instead for the other cases there is almost a very little difference in the safety factor.

In accordance to the results obtained, for maximum shear strains are shown in figure 32 (all the remaining figures are reported in the Appendix). Failure seems to be circular but very deep.

As we proceed towards a comparison of the normalized average safety factors of the bimrock models and the models with a reduction of cohesion of the block- matrix interfaces to 50% we observe almost no difference in the normalized average safety factors of the bimsoil models (Normalized Average SF = 1.00) with respect to the bimrock models (Normalized Average SF = 1.00)
Bimsoil models with a reduction of cohesion of the block- matrix interfaces to 100% show a lower value of normalized average safety factor (Normalized Average SF = 0.96) as that of

the bimrock models because of the reduced cohesion between the block- matrix interfaces. (Figure 38)

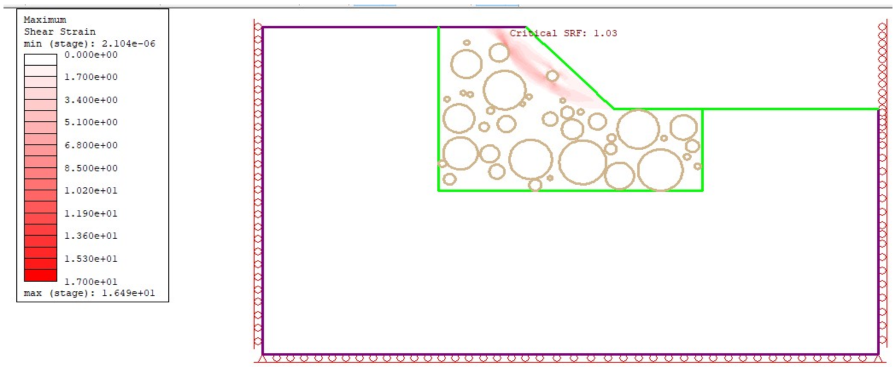


Figure 32 Maximum shear strains of 40% VBP model when the cohesion of the block- matrix interfaces is reduced by 100%.

Total displacements were also noted for every model. One of the examples is shown in figure 33 (others are reported in the Appendix).

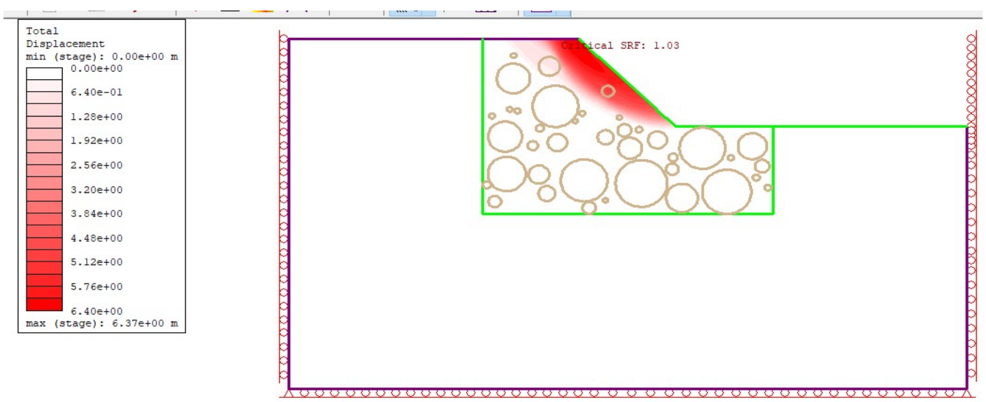


Figure 33 Total displacements in 40% VBP model when cohesion is reduced by 100%

- **55% VBP Models**

Fifteen models of 55% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 14 shows us the safety factors of every model analysed.

Model	Safety Factor
55%_1b_FEM	1.01
55%_2b_FEM	0.78
55%_3b_FEM	0.63
55%_4b_FEM	0.76
55%_5b_FEM	1.06
55%_6b_FEM	0.92
55%_7b_FEM	0.89
55%_8b_FEM	0.97
55%_9b_FEM	0.94
55%_10b_FEM	0.93
55%_11b_FEM	0.93
55%_12b_FEM	0.92
55%_13b_FEM	0.78
55%_14b_FEM	0.56
55%_15b_FEM	1.02
Average Safety Factor	0.87
Standard Deviation	0.144

Table 14 Safety Factors for 15 models with 55% VBP when cohesion of the block-matrix interface is reduced to 100%

From table 14, the safety factors range between 0.56 and 1.06. A very low value of factor of safety is reported in a few models probably due to the geometry and the position of larger blocks with almost no cohesion present in the block- matrix interface.

Therefore, it can be said that in some models there is drastic decrease in the safety factor with respect to the models having block- matrix interface strength properties equal to those of the matrix.

In accordance to the results obtained, maximum shear strains are shown in figure 34 (all the remaining figures are reported in the Appendix)

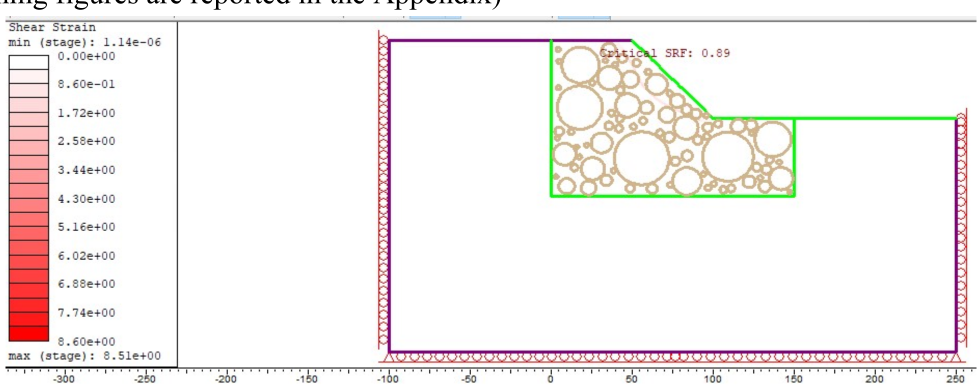


Figure 34 Maximum shear strain of the55% VBP model when the cohesion of the block interfaces is reduced by 100%.

Total displacements were also noted for every model. One of the examples is shown in figure 35 (others are reported in the Appendix).

We interpret by a comparison of the normalized average safety factors of the bimrock models and the bimsoil models with a reduction of cohesion and tensile strength of the block- matrix interfaces to 50%, there is a decrease in the normalized average safety factors of the bimsoil models (Normalized Average SF = 1.02) with respect to the bimrock models (Normalized Average SF = 1.10)

Bimsoil models with a reduction of cohesion of the block- matrix interfaces to 100% show even a lower value of normalized average safety factor (Normalized Average SF = 0.90) as that of the bimrock models. (Figure 38)

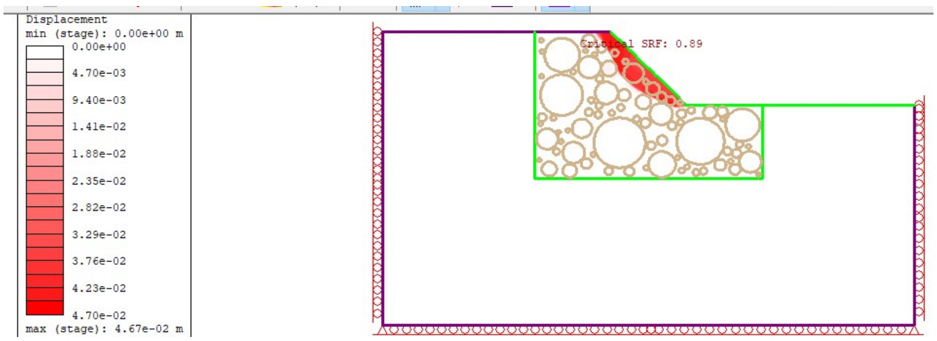


Figure 35 Total displacements in 55% VBP model when cohesion is reduced by 100%

- **70% VBP Models**

Fifteen models of 70% VBP with random block size distribution and positions of the circular blocks in the slope were analysed. Table 15 shows us the safety factors of every model analysed.

Model	Safety Factor
70%_1b_FEM	0.62
70%_2b_FEM	0.92
70%_3b_FEM	0.64
70%_4b_FEM	0.89
70%_5b_FEM	0.74
70%_6b_FEM	0.56
70%_7b_FEM	0.94
70%_8b_FEM	0.80
70%_9b_FEM	1.03
70%_10b_FEM	0.94
70%_11b_FEM	0.51
70%_12b_FEM	0.64
70%_13b_FEM	0.76
70%_14b_FEM	0.61
70%_15b_FEM	0.67

Average Safety Factor	0.75
Standard Deviation	0.156

Table 15 Safety Factors for 15 models with 70% VBP when cohesion of the block- matrix interface is reduced to 100%

From table 15, we can observe that the safety factors range between 0.51 and 1.03. For a model with higher safety factor than the others it can be noticed that the result is strongly influenced by the positions of the blocks in the matrix. Presence of larger blocks in the middle and at the bottom of the slope plays an important role in stability of this particular bimslope model.
Therefore, it can be said that in some models there is significant decrease in the safety factor with respect to the models having equal strength parameters for block-matrix interfaces and the matrix when the strength properties were completely reduced.
In accordance to the results obtained, for maximum shear strains are shown in figure 36 (all the remaining figures are reported in the Appendix)

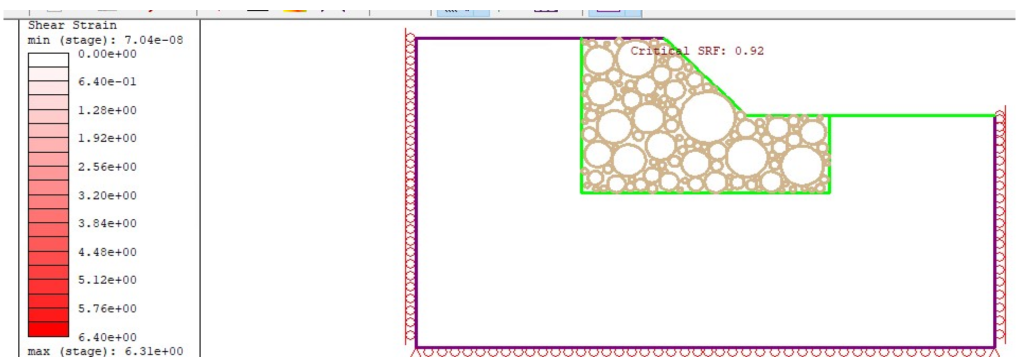


Figure 36 Maximum *shear strain of the70% VBP model when the cohesion of the block interfaces is reduced by 100%.*

Total displacements were also noted for every model. One of the examples is shown in figure 37 (others are reported in the Appendix).

By comparing the normalized average safety factors of the bimrock models with the models with a reduction of cohesion and tensile strength of the block- matrix interfaces to 50% , there is a decrement in the normalized average safety factors of the bimsoil models (Normalized Average SF = 1.24) with respect to the bimrock models (Normalized Average SF = 1.35).
Bimsoil models with a reduction of cohesion and tensile strength of the block- matrix interfaces by 100% show a low value of normalized average safety factor (Normalized Average SF = 0.77) as that of the bimrock models. (Figure 38)

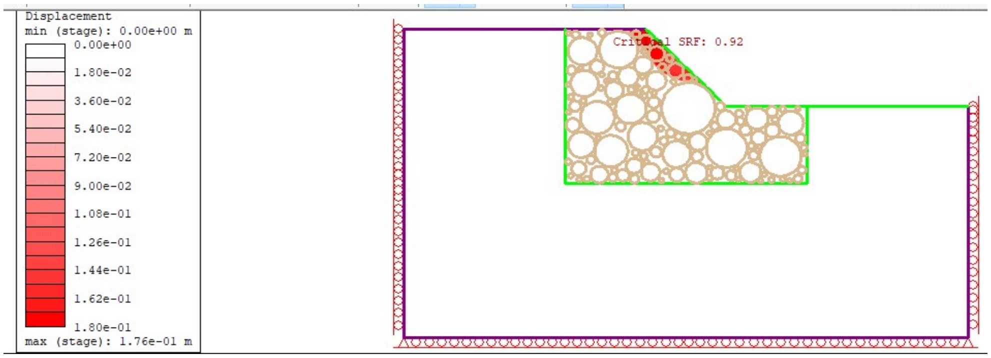


Figure 37 Total displacements of the 70% VBP model when cohesion is reduced by 100%

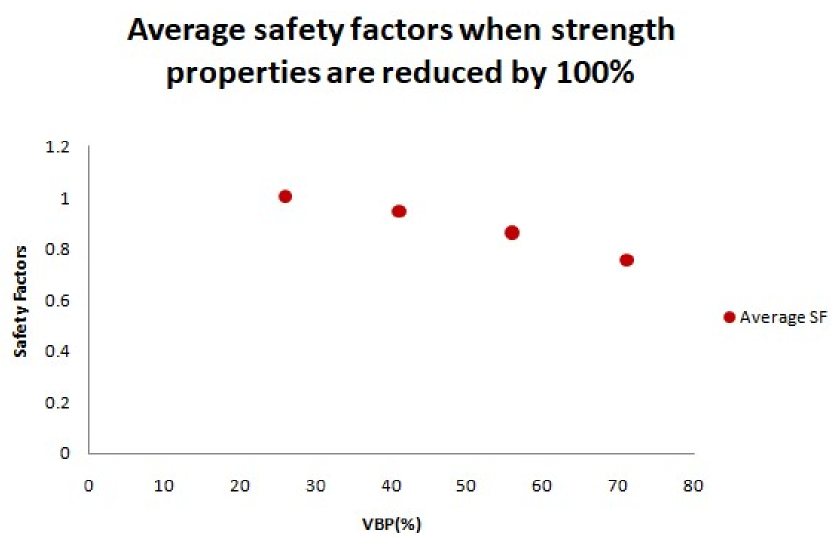


Figure 38 Safety factors with increasing VBP when cohesion and tensile strength of the block-matrix interfaces were reduced by 100%

Figure 38 shows us a trend that is depicted in the average safety factors when the model behaves as bimsoil. The safety factors decrease with increasing VBPs when the cohesion and the tensile strength of the block-matrix interfaces are completely reduced.

❖ **Comparison of results: Bimrocks Vs Bimsoils**

After various simulations we were able to find out the variations in terms of stability (factor of safety and failure surfaces) of the bimsoils, reducing the cohesion around the block-matrix interfaces.

The intent of the comparison was to study the change in safety factors for bimrocks, when simulated with the lower values of cohesion leading the model to behave like a bimsoil model.

A further comparison of results is done with the models containing same properties of strength for block-matrix interface and the matrix to check the correctness of the study.

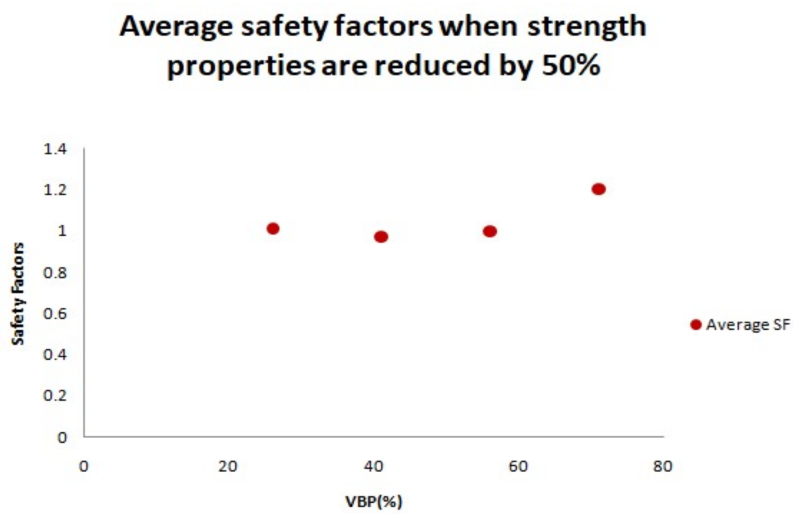
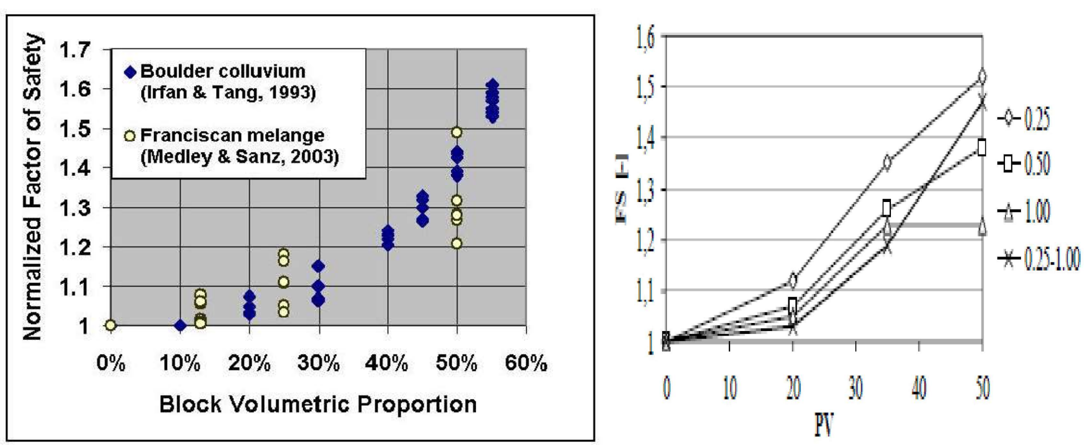


Figure 39 Safety *factors with respect to VBP when cohesion of the block- matrix interfaces is reduced by 50%*

The results provided by Irfan and Tang (1993); Medley and Sanz (2003) using Limit Equilibrium (figure 40.a) and those investigated by Barbero et al (2006) using the Finite element method (figure 40.b) stated that the factor of safety of slopes containing Hong Kong boulder colluviums and Franciscan melange (bimrocks) increases with increasing VBP, this doesn't hold true in the case when the cohesion of the block-matrix interfaces was reduced by 50% (Figure 39). The average safety factor of 70% VBP is increased with respect to other VBP while no significant trend is observed in the safety factors of rest of the VBPs.



a) *b)*

Figure 40 a) Comparison of results for models of geologically disparate rock/soil mixtures: Hong Kong boulder colluvium (Irfan & Tang (1993) and Franciscan melange (Medley & Sanz, 2003).

b) Trend of safety factor with respect to changing VBP (Barbero et al, 2006)

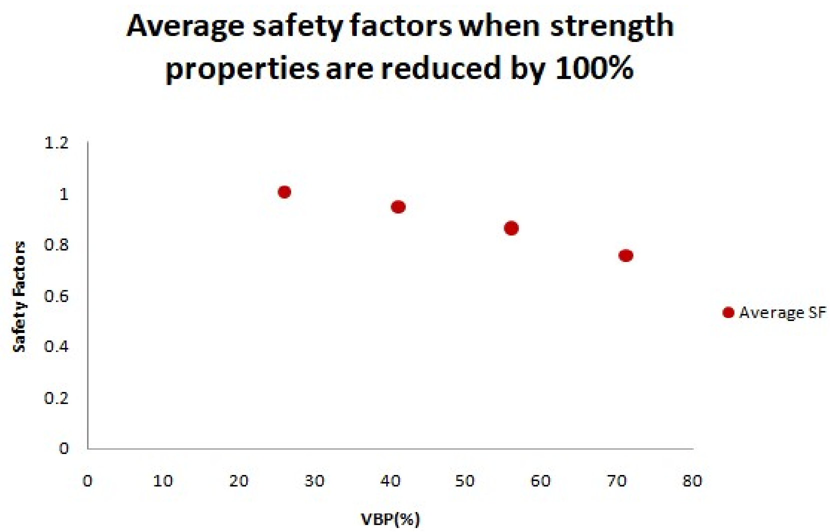


Figure 41 Safety factors with respect to VBP when cohesion is reduced by 100%

On the contrary, we analysed a trend of lower values of factor of safety with increasing VBPs when the cohesion of the block- matrix interfaces was reduced to 100% (fig.41). At this point, the model behaved as a bimsoil. One of the main aims of this thesis was also to analyse the contact strength between blocks and the matrix. A further study on the failure surfaces was also performed using AUTOCAD.

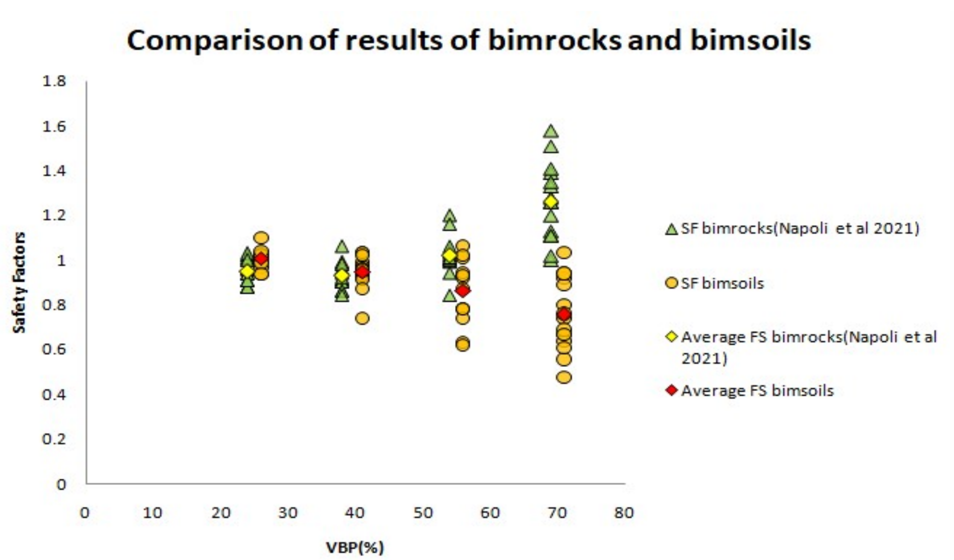


Figure 42 Comparison of Safety factors of bimrocks and bimsoil models with strength properties of block-matrix interfaces reduced to 100%

From the figure 42 we can note that there is a very minimal variation of the average factor of safety for 25% and 40% VBPs of the bimsoil models in comparison with the bimrock models.

Further, a significant decrease in the average safety factors can be noted for the higher values of VBP (55%, 70%) of bimsoils with respect to the bimrock models studied earlier. A henceforth research is suggested for further knowing the behaviour of bimsoils.

Models	Normalized Average Safety Factors of Bimrocks (Napoli et al 2021)	Normalized Average Safety Factors of Bimsoils (50% reduction of strength properties)	Normalized Average Safety Factors of Bimsoils (100% reduction of strength properties)
Matrix only	0.97	0.97	0.97
25% VBP	1.02	1.04	1.03
40% VBP	1.00	1.00	0.96
55% VBP	1.10	1.02	0.90
70% VBP	1.35	1.24	0.77

Table 16 Comparison between the normalized average safety factors of bimrocks and bimsoil models with reduction of strength properties of the block-matrix interfaces by 50% and 100% with respect to the matrix

Table 16 points out a differences and similarities among the normalized average safety factors of bimrocks, bimsoil models with reduction of strength properties of the block-matrix interfaces by 50% and 100% with respect to the matrix.

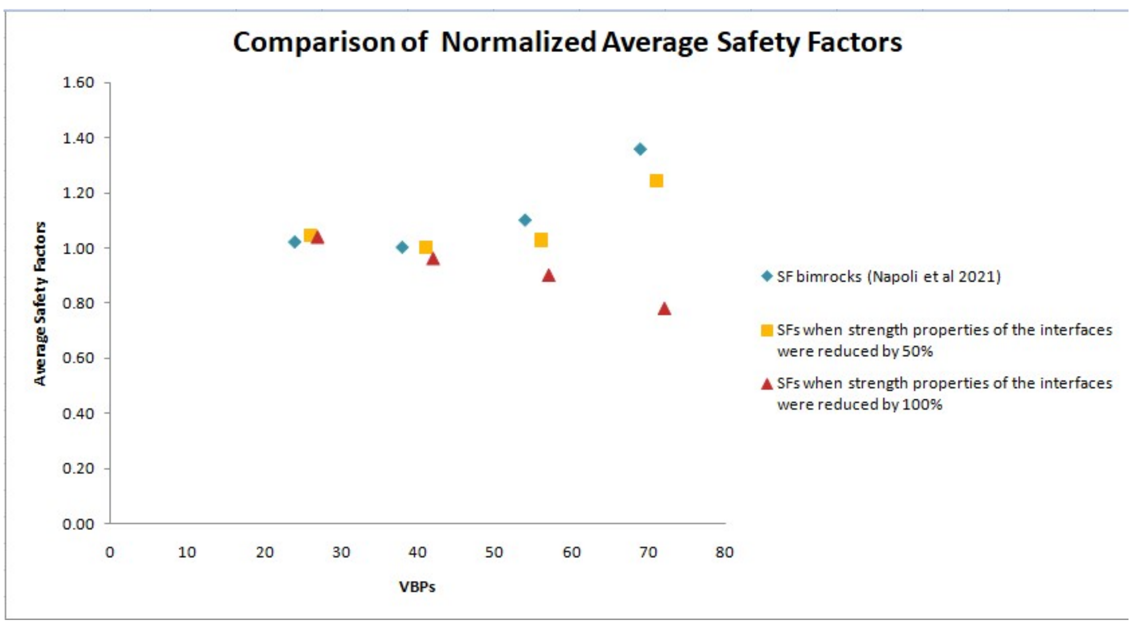


Figure 43 Comparison between the normalized average safety factors of bimrocks and bimsoil models with strength properties of the block- matrix interfaces reduced by 50% and 100% with respect to the properties of the matrix

Figure 43 depicts a comparison between the normalized average safety factors of bimrocks (Napoli et al 2021) and bimsoil models with strength properties of the block- matrix interfaces reduced by 50% and 100% with respect to the properties of the matrix.

❖ Observations of failure surfaces in AUTOCAD

With the FEM analysis carried out on bimsoils with different VBP, another representation on their failure surfaces was carried out using AUTOCAD. The models analysed in RS2 were exported to AUTOCAD.

Considering the maximum shear strains of the model the image was scaled as per the geometrical characteristics of the slope. A failure surface of the homogeneous material (0% VBP) considering the maximum shear strains was drawn using 'Polyline' function of AUTOCAD with a blue line.

The failure surfaces of heterogeneous materials (VBP of 25%, 40%, 55% and 70%) was plotted using a red line and further failure surfaces of each of the 15 models from each VBP were overlapped and studied.

The failure surfaces of the bimrocks were studied which were analysed earlier by Napoli et al 2021. It was observed that the tortuous failure surfaces in bimsoils/bimrocks are absolutely not related to the failure surfaces of the homogeneous material (matrix-only) because performing FEM analysis on heterogeneous material like bimsoils/bimrocks generally results on a very high stresses concentration on the surface of the bimslope and therefore the possible position and the shape of the failure surfaces are completely different each other.

Figure 44 depicts one of the models when the strength characteristics of the block- matrix interfaces and the matrix are same. (Others reported in Appendix)

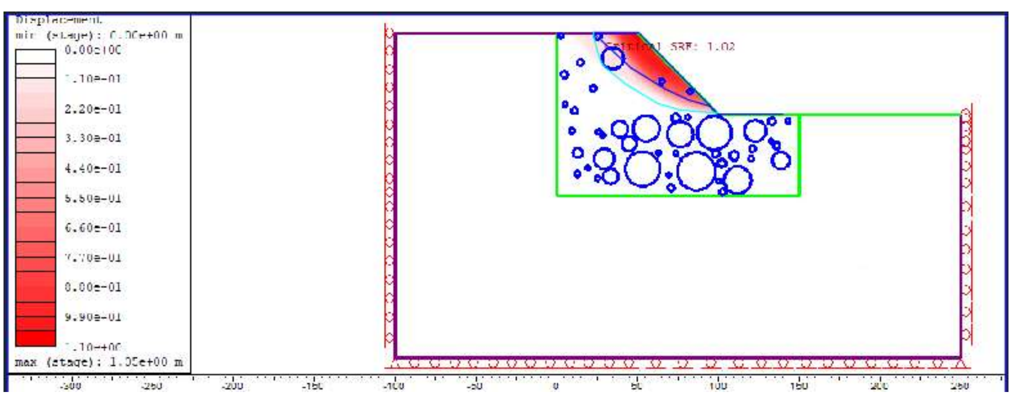


Figure 44 Failure surface of 25% VBP when strength properties of block- matrix interfaces and matrix are equal

Instead, the results of the heterogeneous material produced tortuous failure surfaces with different paths and extensions depending on the VBP considered. Even the red line, which indicates the TFS of the heterogeneous material, has been traced on AutoCAD considering the maximum shear deformations. Figure 45 shows a comparison of the failure surfaces of bimrocks (red lines) and that of bimsoils (green lines) considering 25% VBP, when the cohesion and the tensile strength of the block- matrix interfaces were reduced by 50%.

Figure 45 Comparison of failure surface of bimsoils (green lines) and bimrocks(red lines) (25% VBP when properties of interfaces were reduced by 50%)

We observe different positions of the tortuous failure surfaces and in some cases; they are very superficial (Figure 46).
All these analyses were made with circular blocks of several dimensions and can be compared with the results obtained by Montoya-Araque et al. in 2020. The difference with respect to the study of Montoya – Araque et al is that when we overlap the 15 Tortuous Failure Surfaces (TFS) of each analysed VBP, each failure surface starts from a different position with respect to each other (figure 45). They never start or even coincide with the position of the failure surface of the homogeneous material (blue line). This kind of result is achieved with all the considered VBPs (25%, 40%, 55%, and 70%) but with different paths and lengths of the TFS.

Figure 46 Comparison of failure surface of bimsoils (green lines) and bimrocks (red lines) (70% VBP when the cohesion and tensile strength of the block-matrix interfaces were reduced by 100%)

Chapter 5

Conclusion

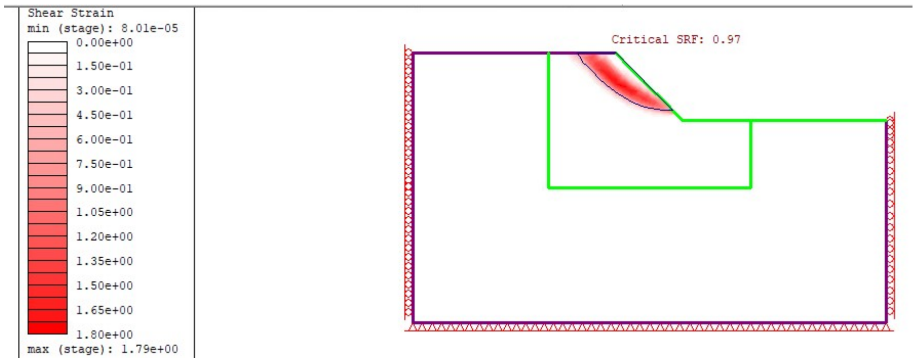
The present thesis reports a study carried out to investigate the role of block – matrix interfaces on the stability analyses of bimslopes which are often neglected when modelling the heterogeneous uncemented geomaterials.
The same bimrock slope models analysed by Napoli et al 2021 during their research were chosen and further the contact strength of the blocks and the matrix was studied by reducing the cohesion and the tensile strength of the block- matrix interfaces with respect to the matrix so that the model behaves like a bimsoil.
In this dissertation we also observe the differences between a simplified homogeneous material, bimrocks and bimsoils in terms of safety factors and failure surfaces.

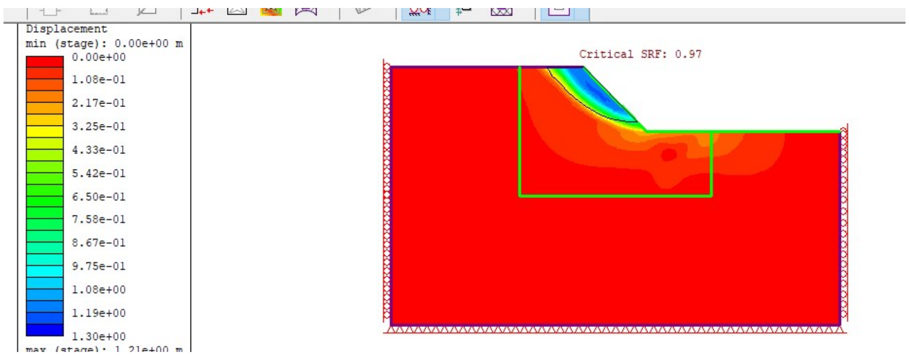
Key aspects that were observed are the following:

- A careful evaluation of the degree of cementation / lithification of the geomaterial must be made, in order to better calibrate the block-matrix interface strength parameters. If the material is welded: no interfaces are required, otherwise the interfaces must be considered because the safety factors vary.
  We observed that when the cohesion and the tensile strength of the block-matrix interfaces were 50% reduced with respect to the strength properties of the matrix the average safety factors of the bimsoils were slightly higher for 25% and 40% VBP but there was a slight decrement in the average safety factor for the higher VBPs (55%, 70%) with respect to the average safety factors of bimrocks.
- When the cohesion and the tensile strength of the block-matrix interfaces were 100% reduced we can say that there was a very minimal variation of the average factor of safety for 25% and 40% VBPs of the bimsoil models in comparison with the bimrock models, but a significant decrease in the average safety factors can be noted for the higher VBPs (55%, 70%) of bimsoils with respect to the bimrock models studied earlier (Napoli et al 2021).
- A comment can also be made on the failure surfaces of the bimsoil, they do not coincide with the position of the failure surface of the homogeneous material. This kind of result was achieved with all the considered VBPs (25%, 40%, 55%, and 70%) but with different paths and lengths of the TFS.
  We can confirm the findings of previous research (Napoli et al 2021): that it is not realistic to model a homogeneous material and to consider that failure surface, because it is not tortuous.
  During the study of the failure surfaces of the bimsoil models, we observe an increase of tortuosity of the failure surfaces as VBP increases and as the cohesion of the block-matrix interfaces decreases.

Appendix

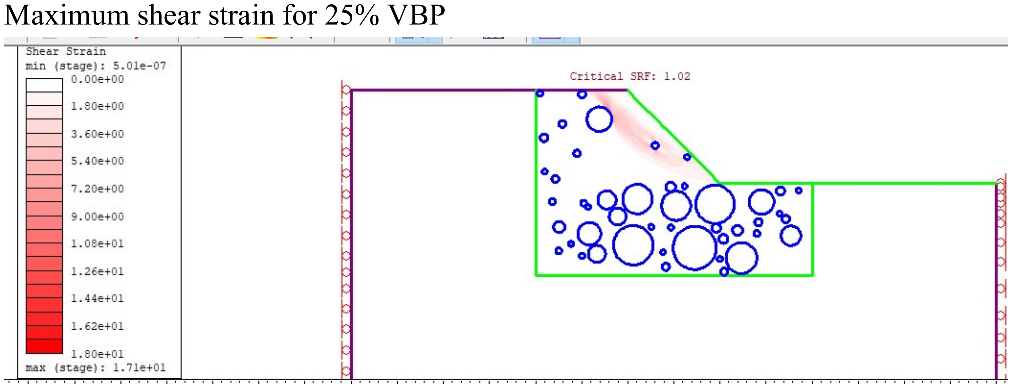
- Results of matrix only models



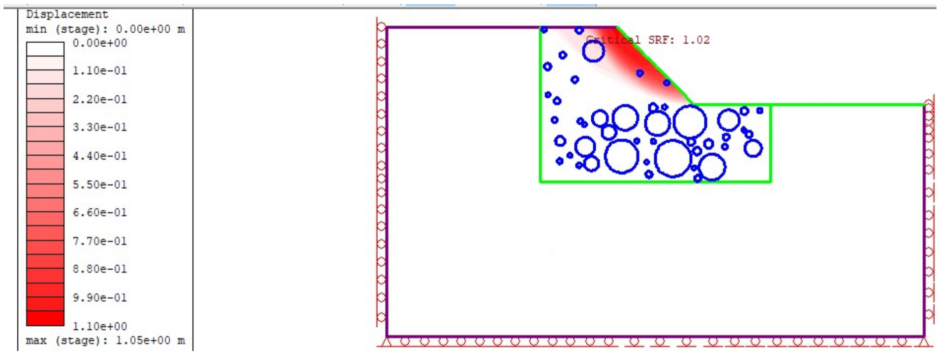


- Results when matrix and block- matrix interfaces have same strength properties

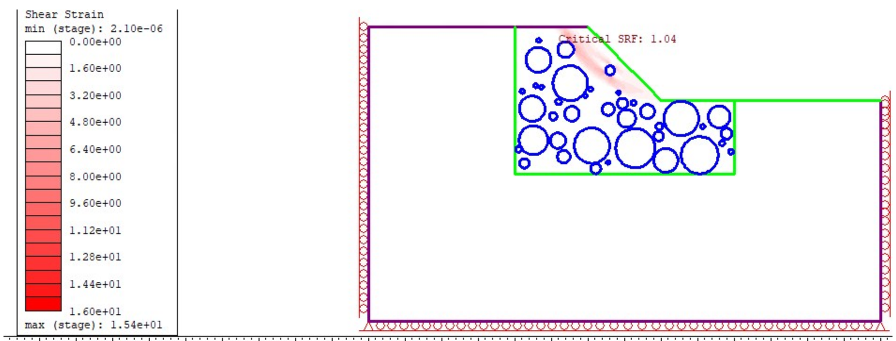
Maximum shear strain for 25% VBP



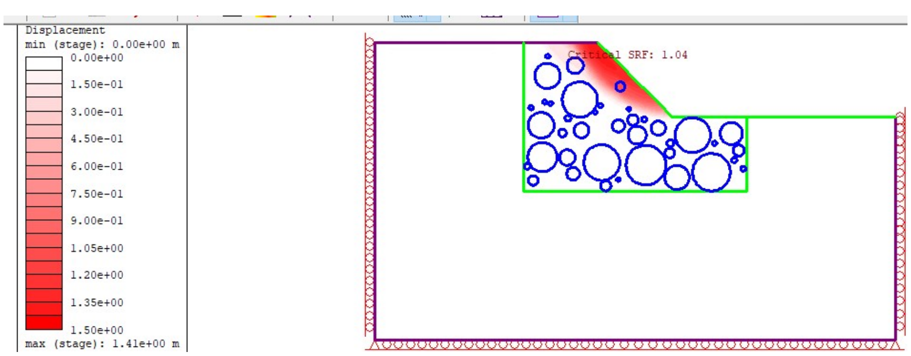
Total displacements for 25% VBP



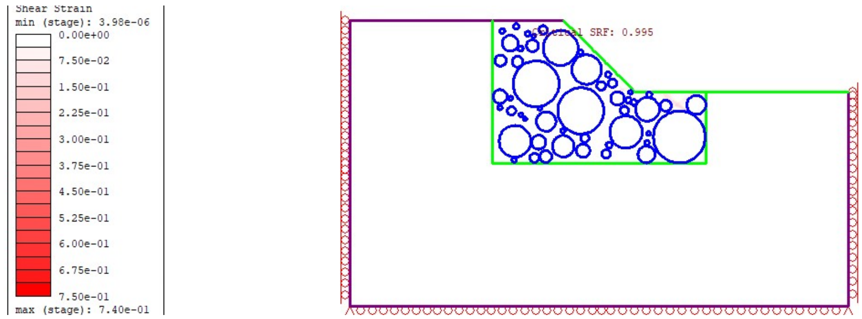
Maximum shear strain for 40% VBP



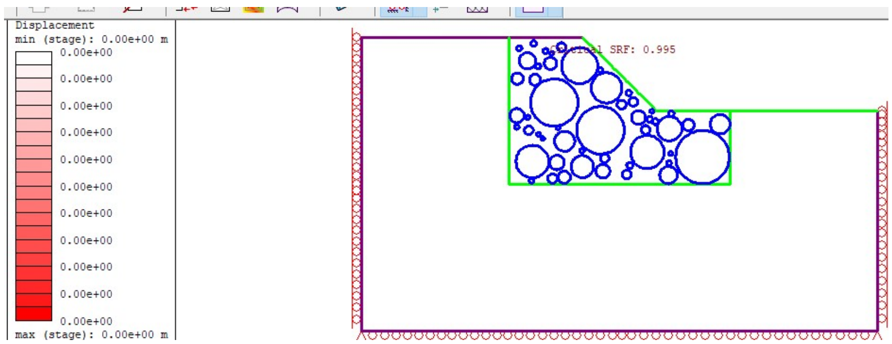
Total displacements for 40% VBP



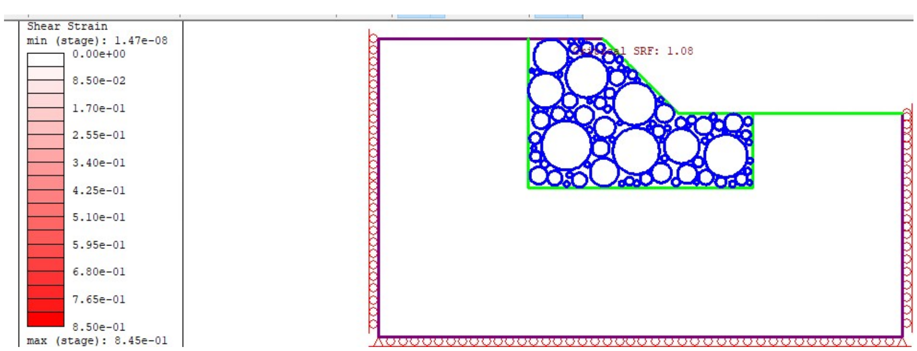
Maximum shear strain for 55% VBP



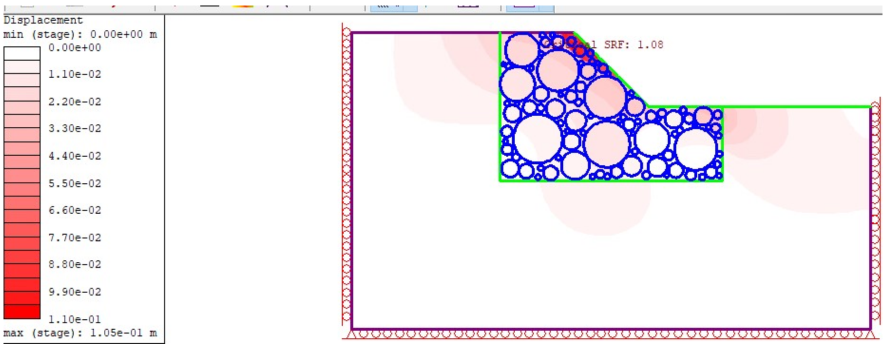
Total displacements for 55% VBP



Maximum shear strain for 70% VBP

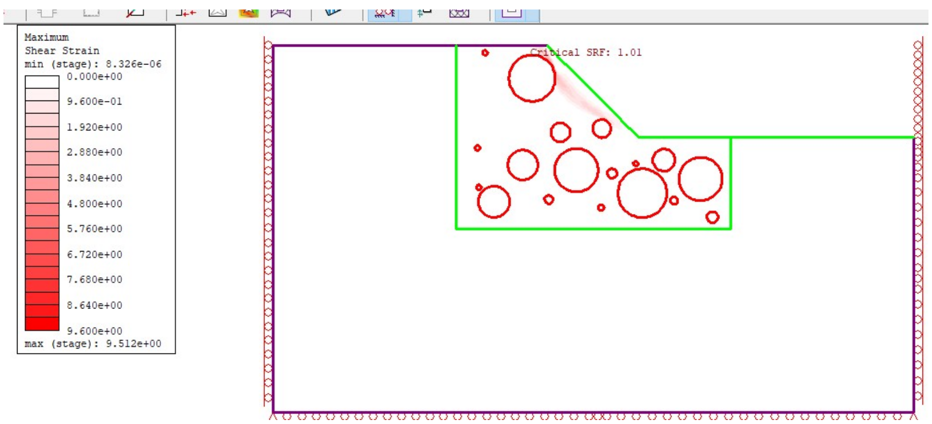


Total displacements for 70% VBP

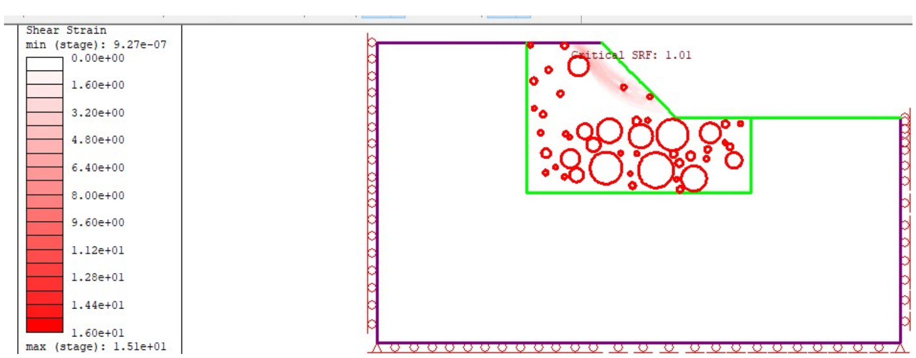


- <u>Results when the cohesion and tensile strength of block- matrix interfaces are reduced by 50% (c= 0.015 MPa, φ = 24° , Tensile Strength= 0.01MPa)</u>

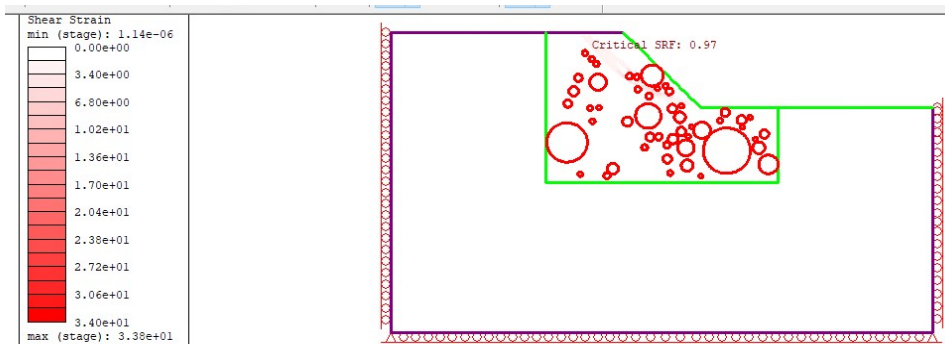
25%_1_FEM



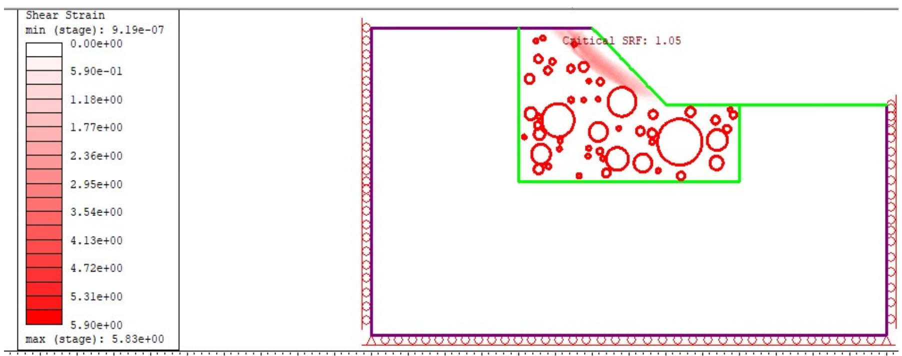
25%_2_FEM



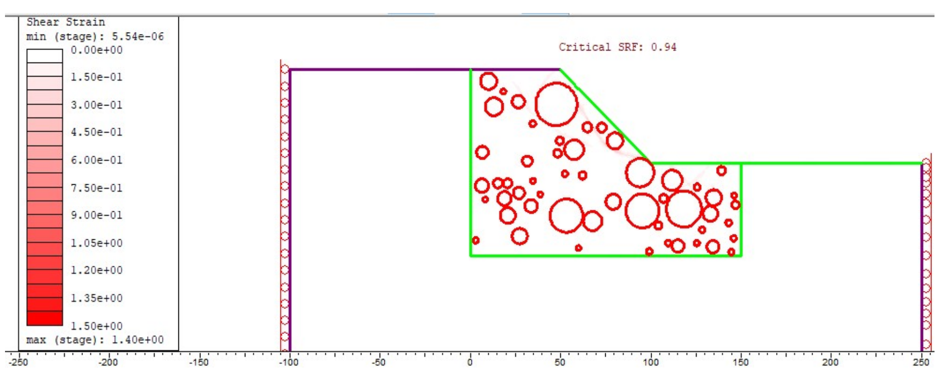
25%_3_FEM



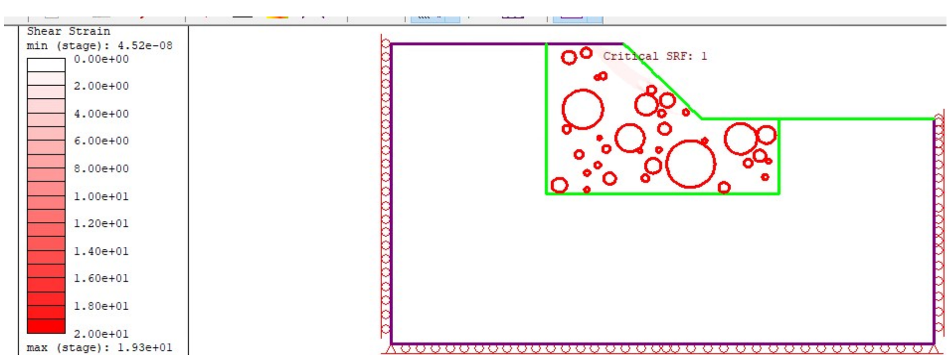
25%_4_FEM



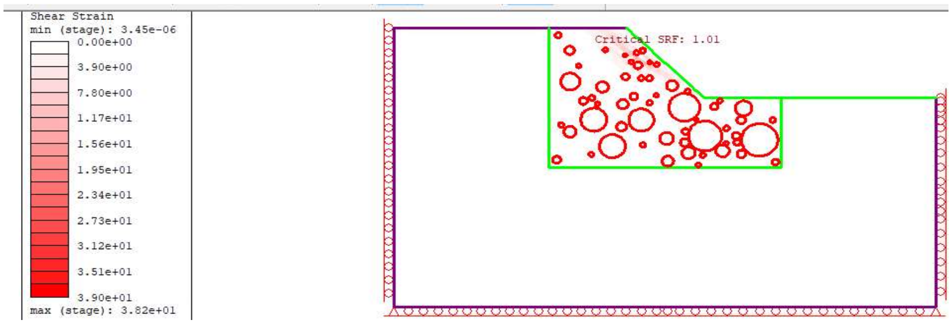
25%_5_FEM



25%_6_FEM



25%_7_FEM



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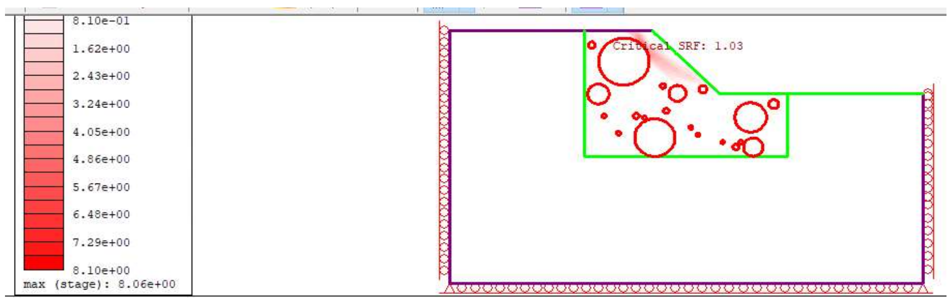

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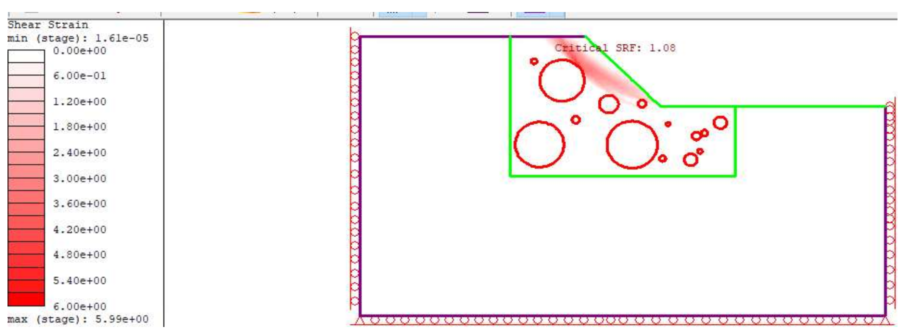
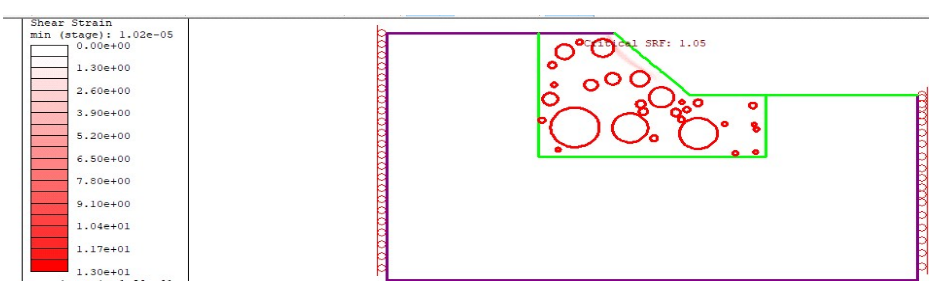
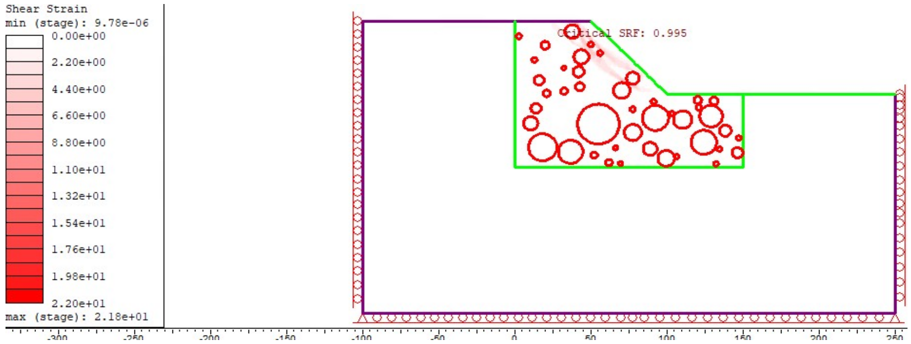


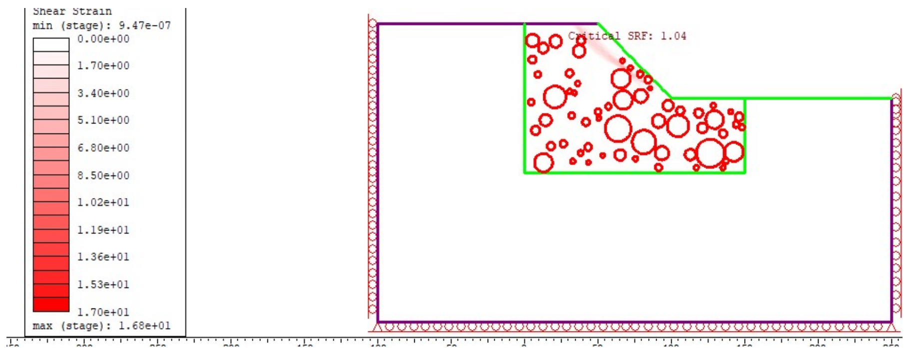
25%_10_FEM



25%_11_FEM



25%_12_FEM



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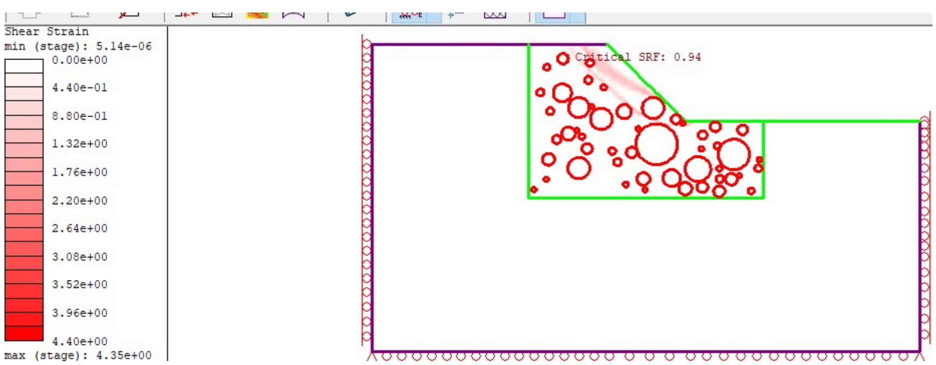

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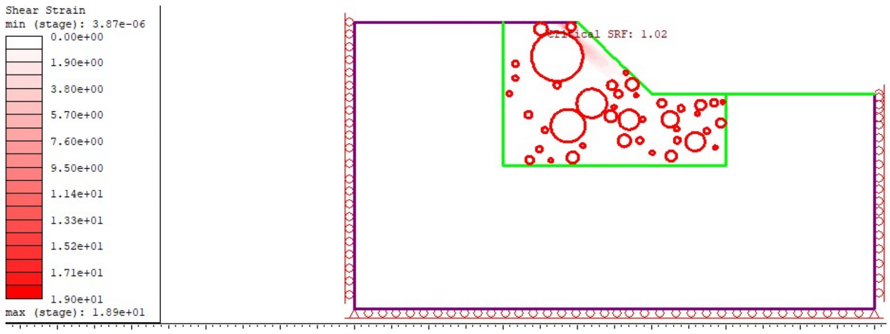

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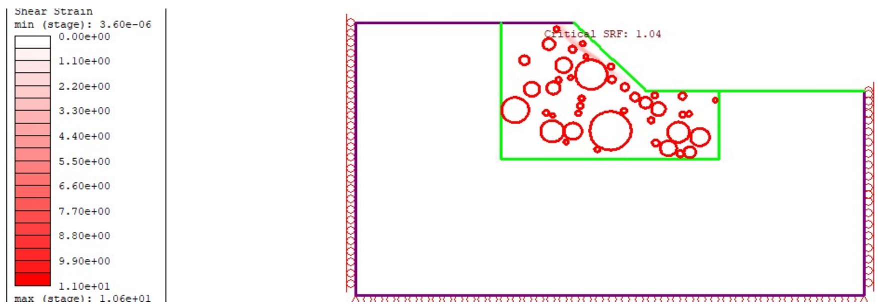
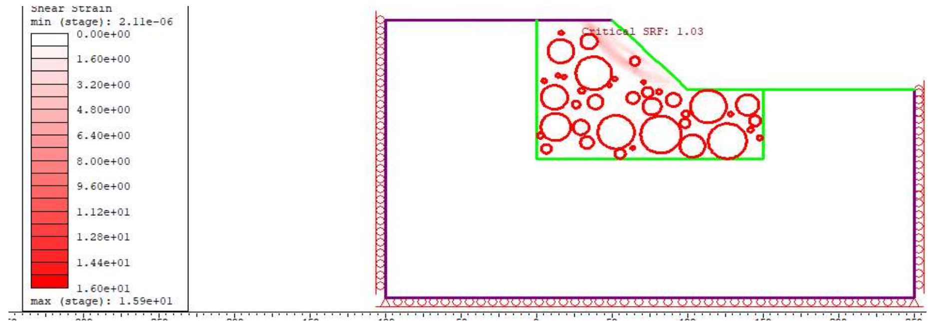


40%_1_FEM



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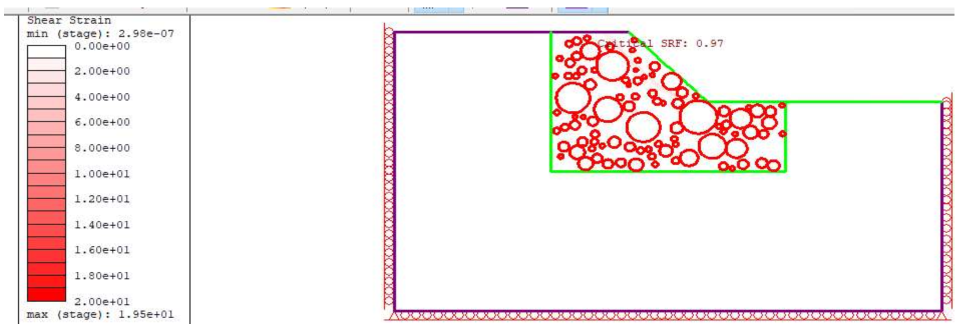

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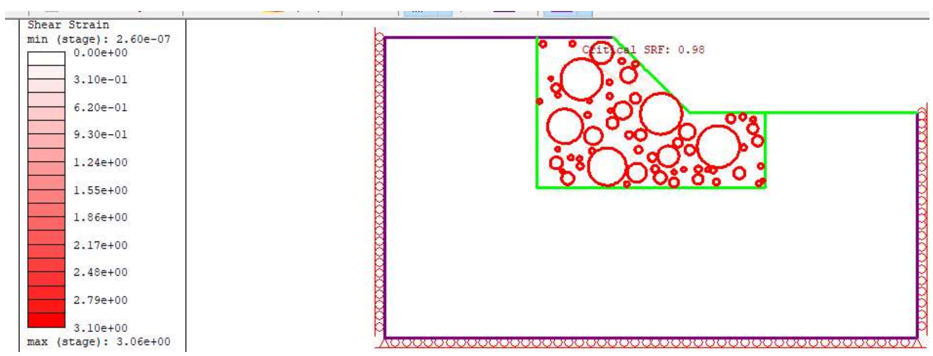

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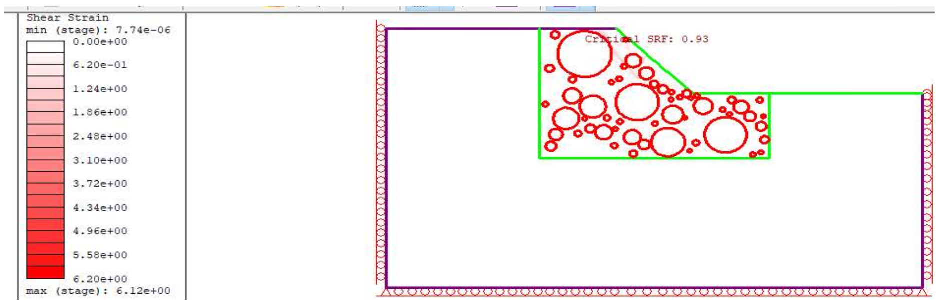

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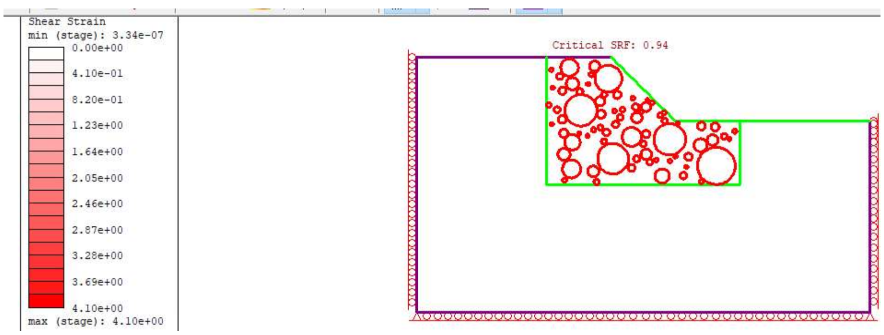
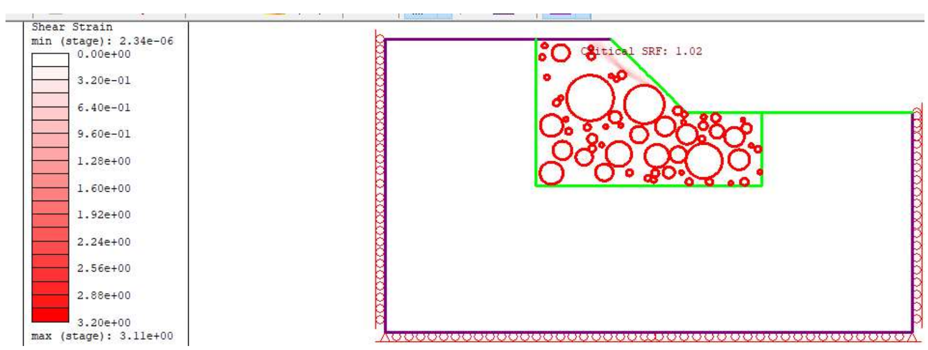


40%_6_FEM



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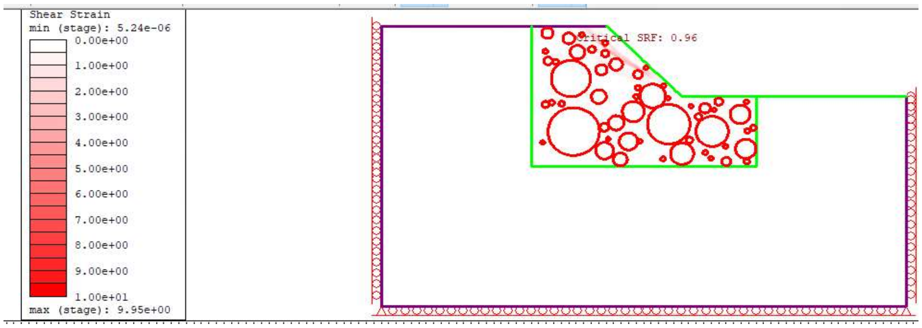

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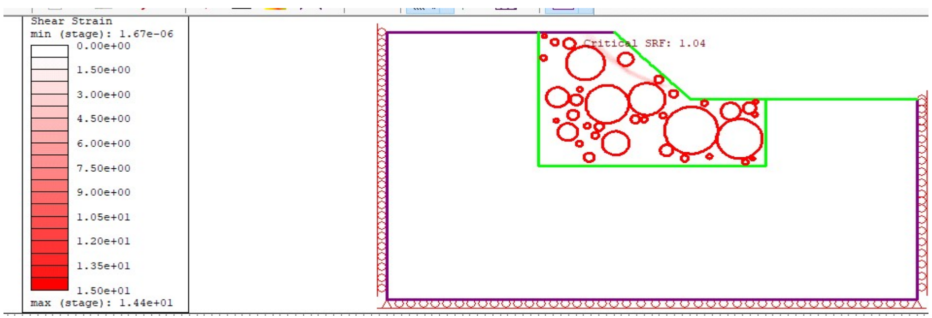
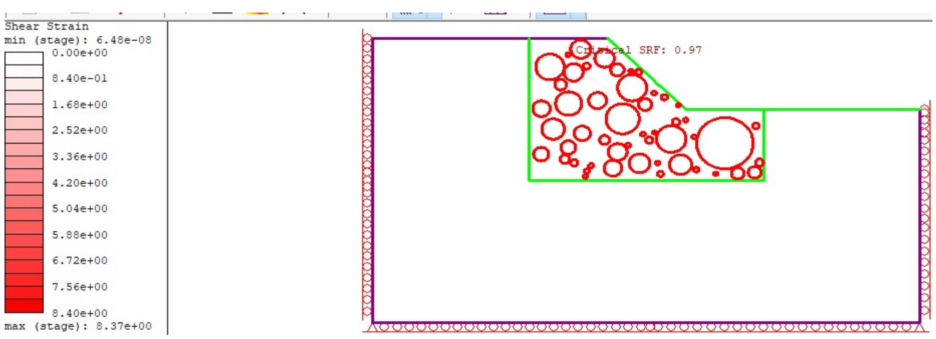
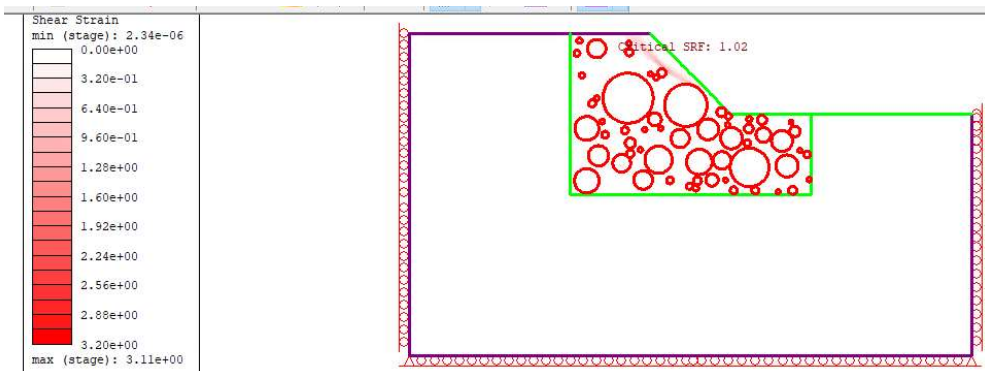


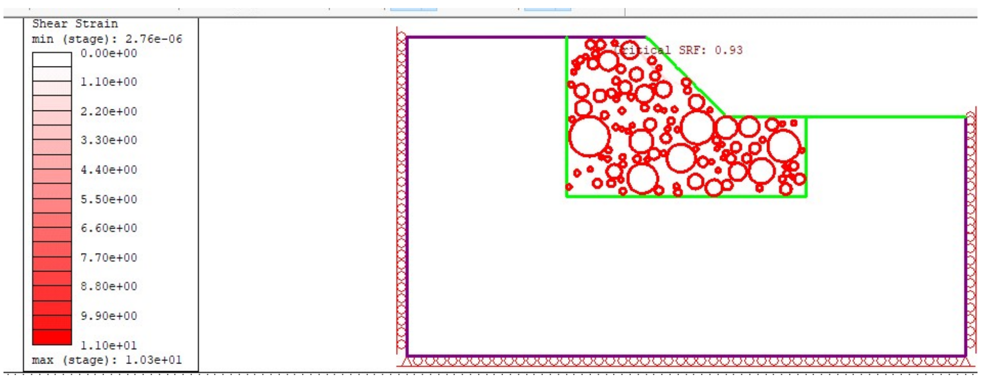
40%_9_FEM



40%_10_FEM



40%_11_FEM



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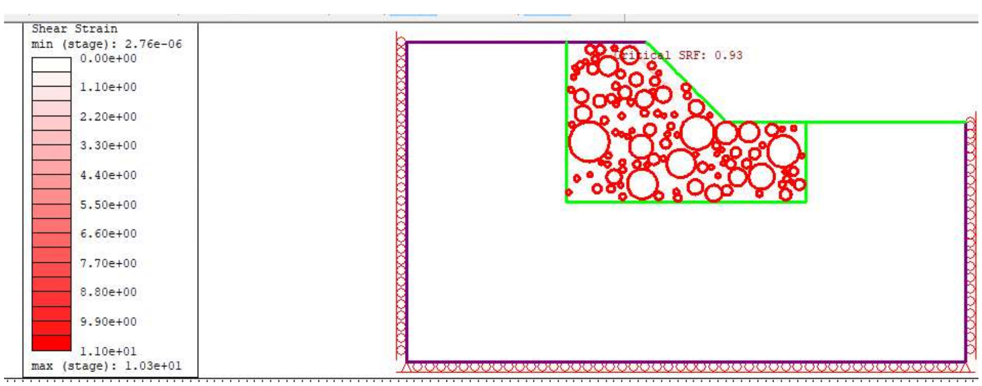

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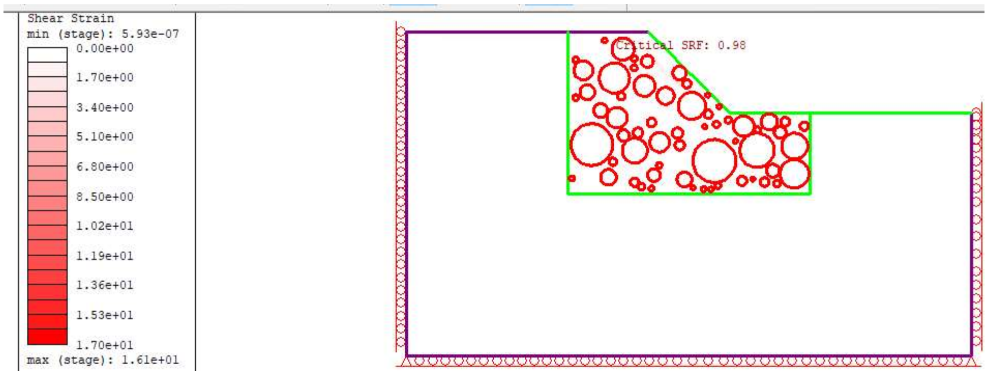

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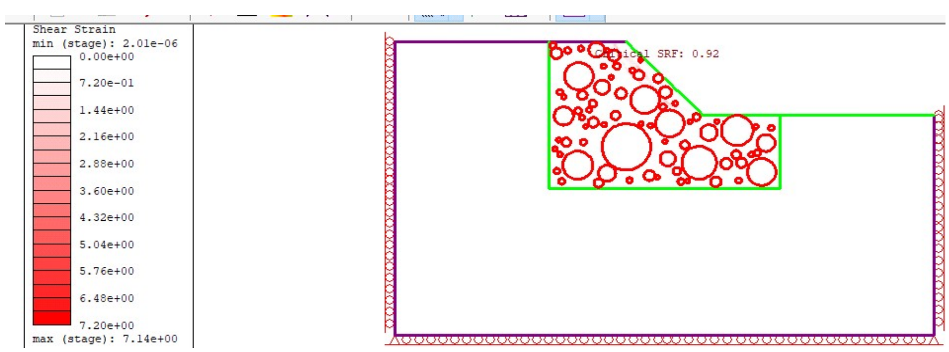

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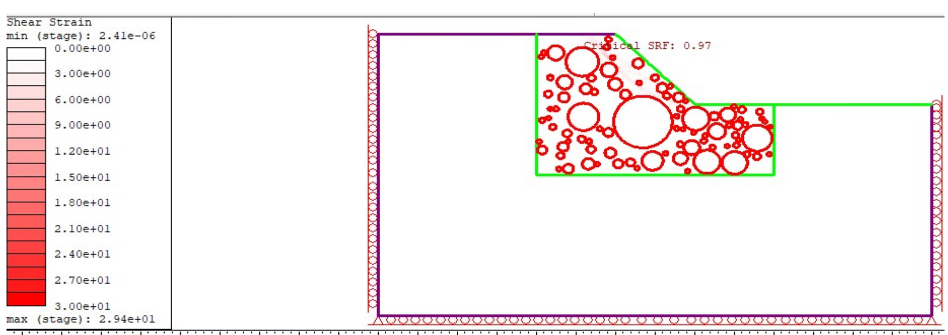
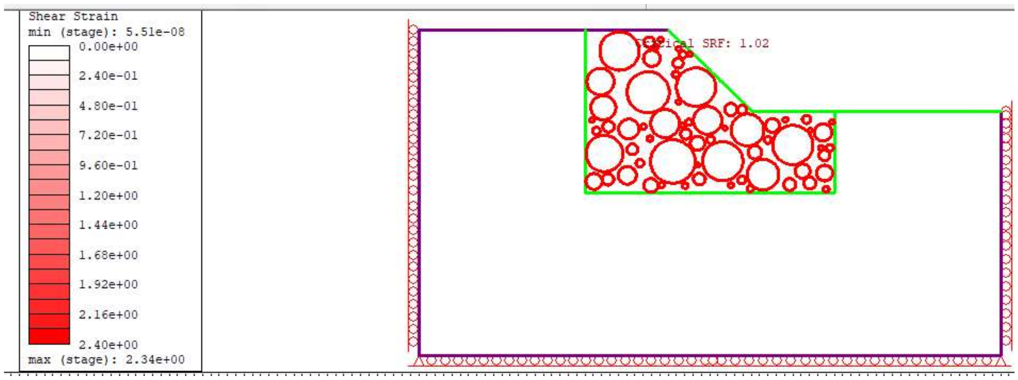


55%_1_FEM



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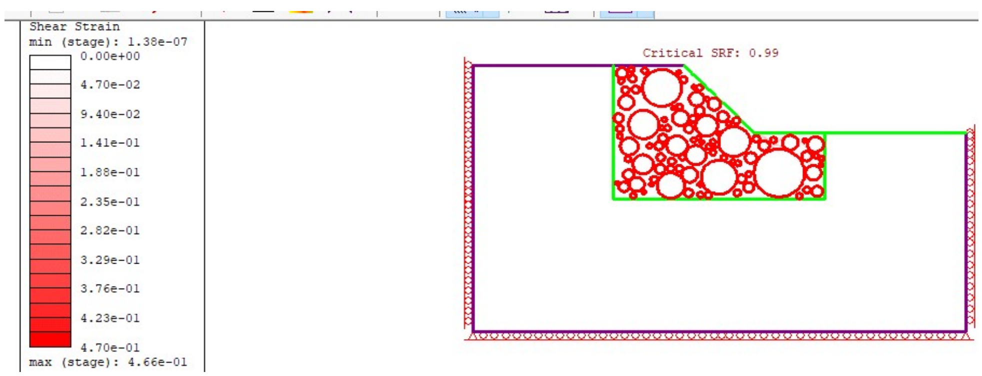
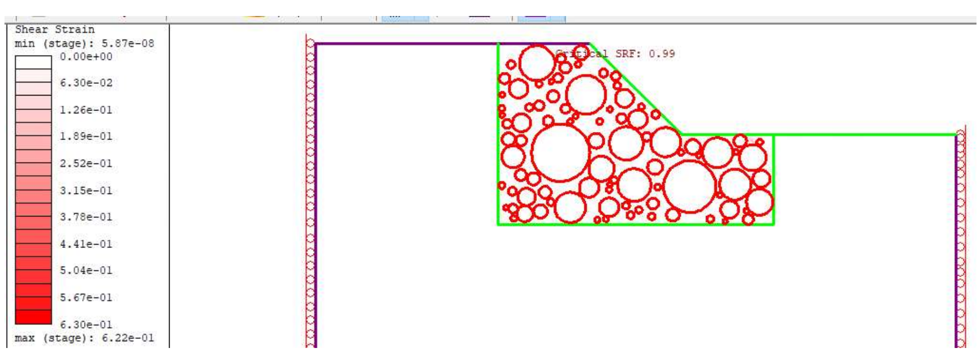
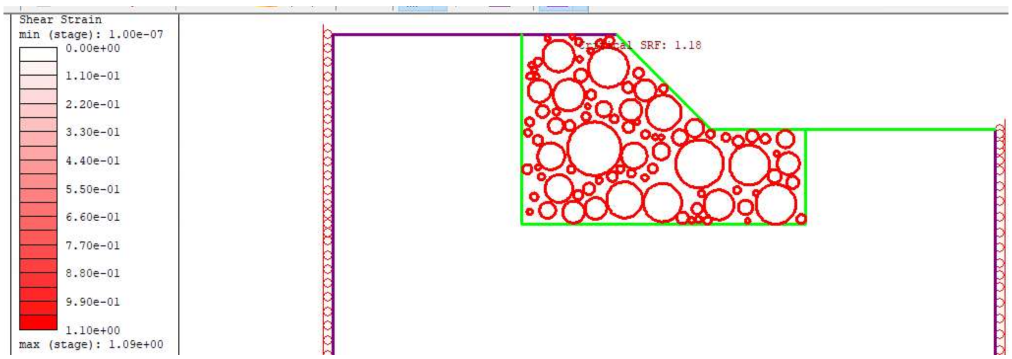


55%_3_FEM



55%_4_FEM



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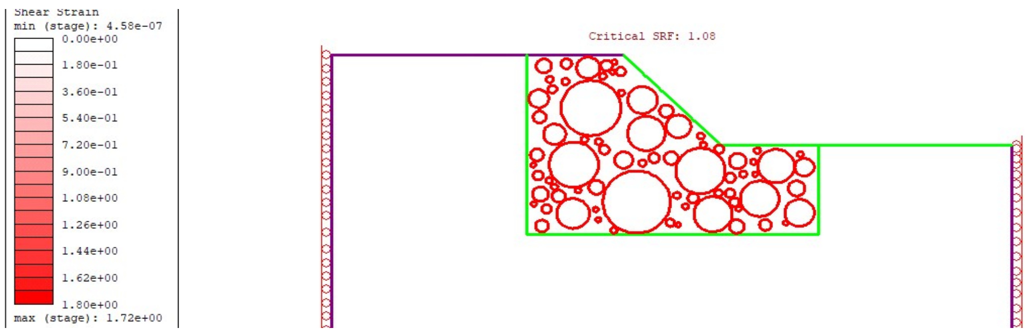
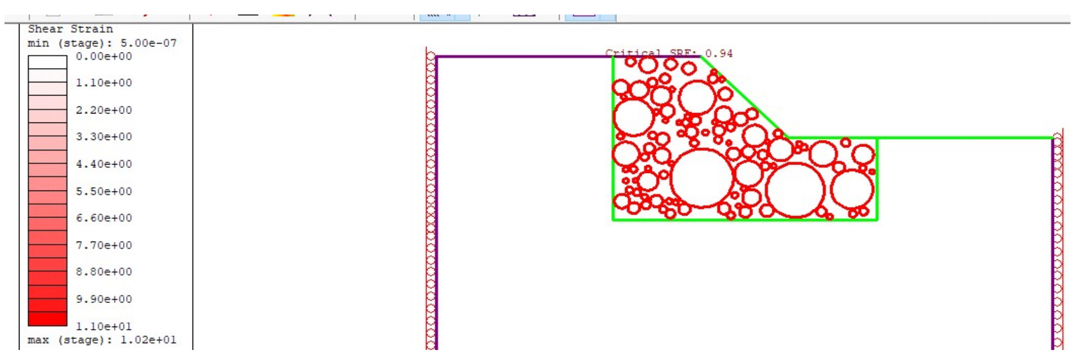
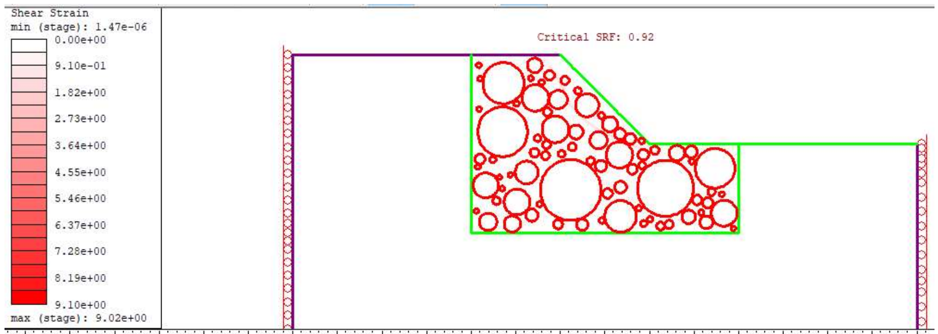


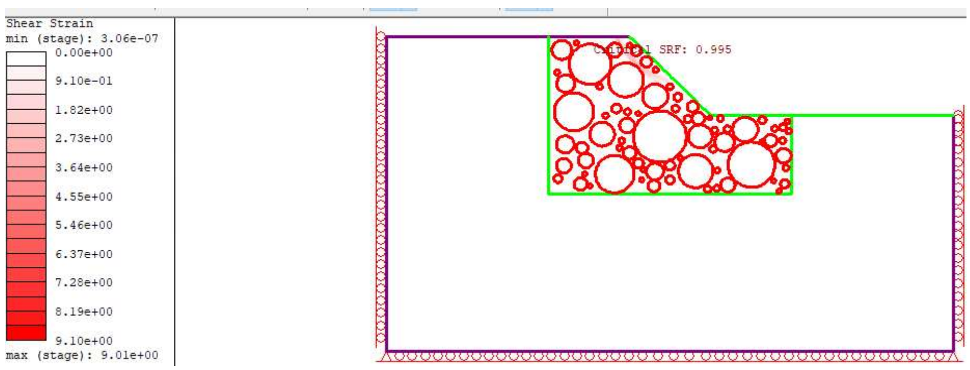
55%_6_FEM



55%_7_FEM



55%_8_FEM



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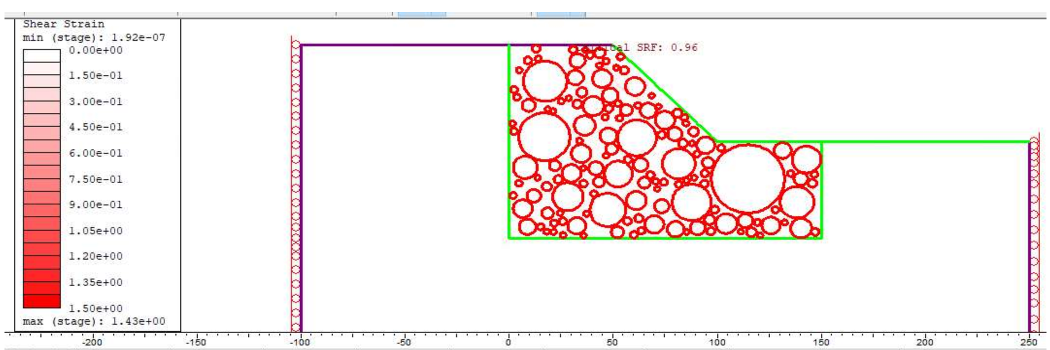

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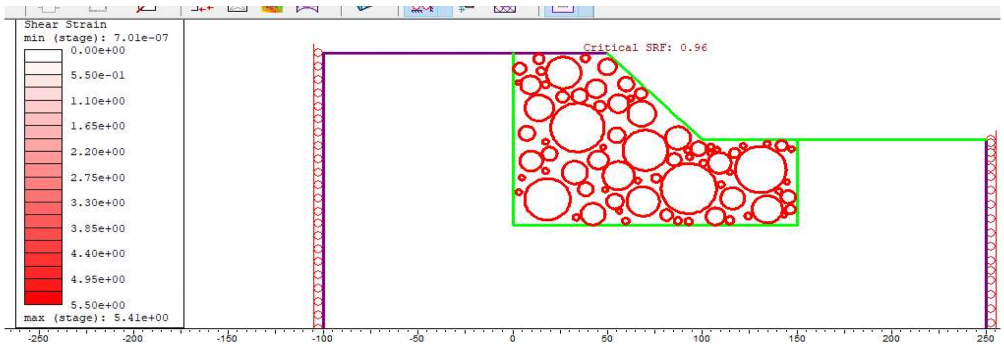

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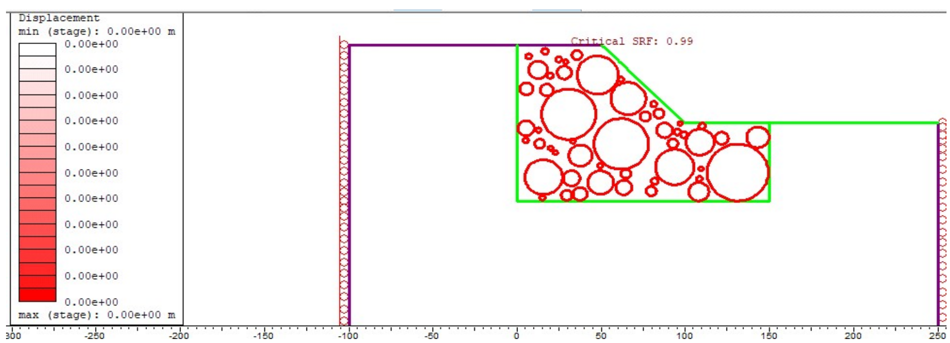
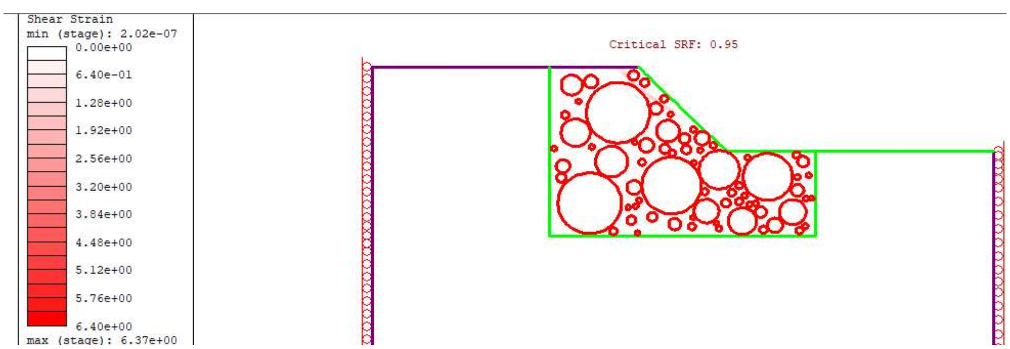


55%_12_FEM



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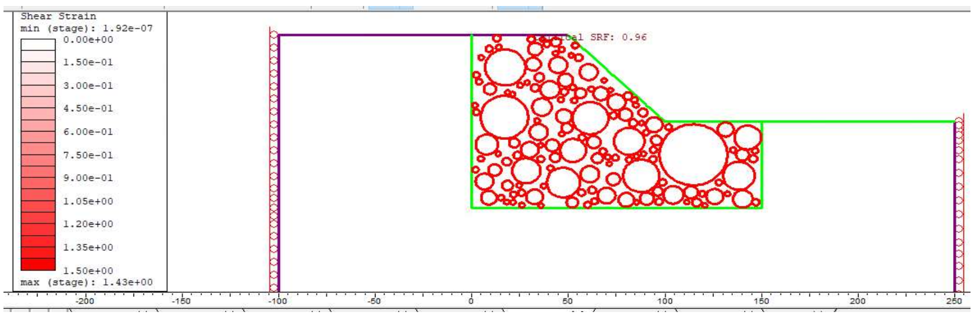
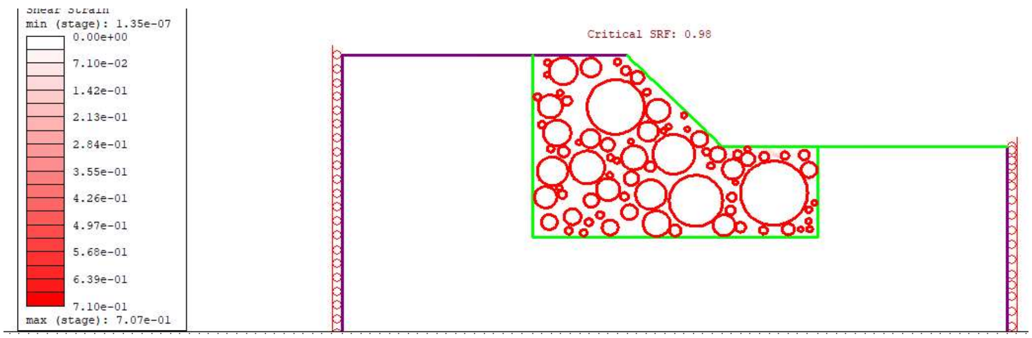


55%_14_FEM



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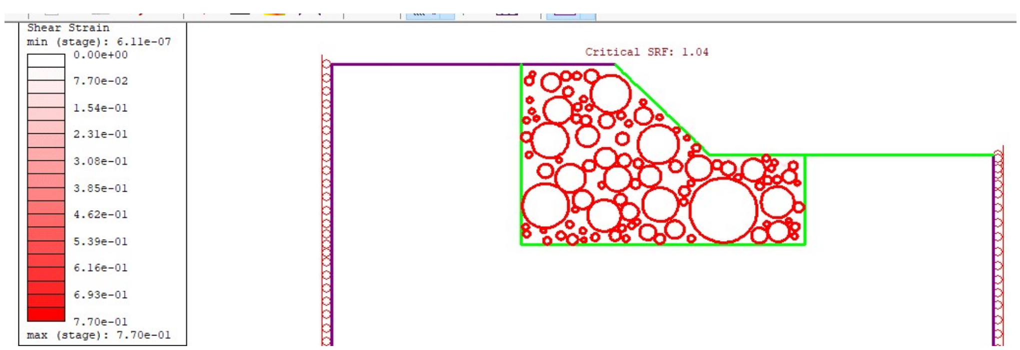
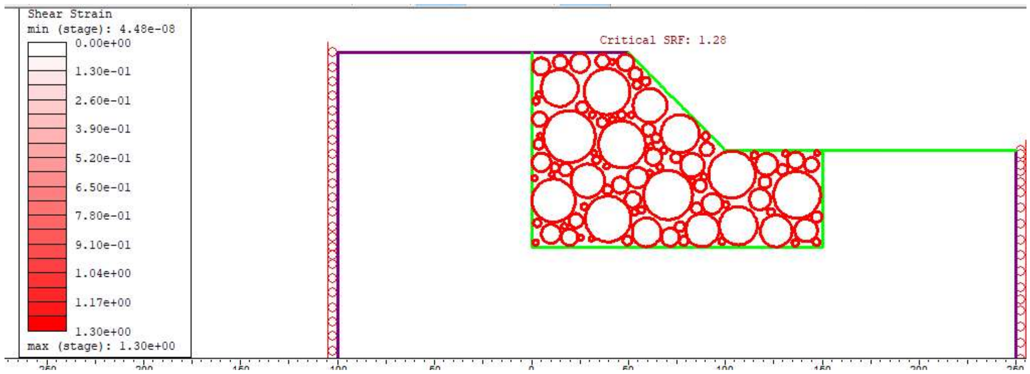
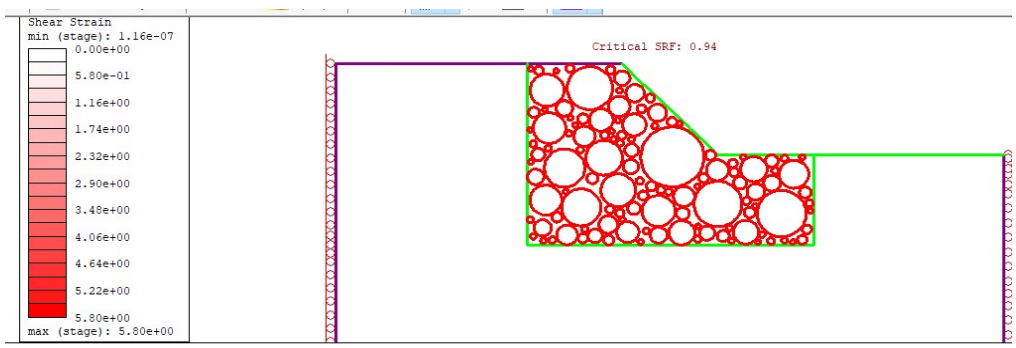


70%_1_FEM



70%_2_FEM



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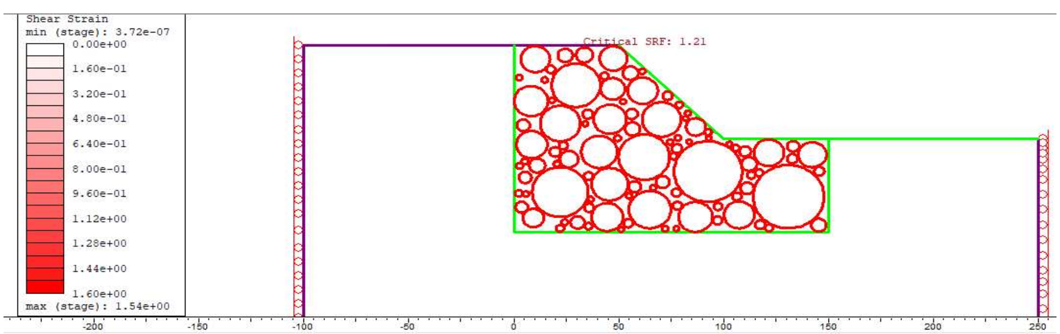
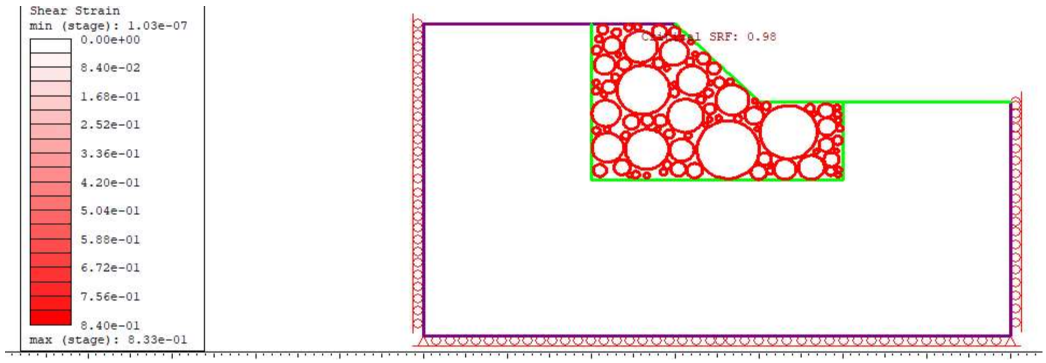
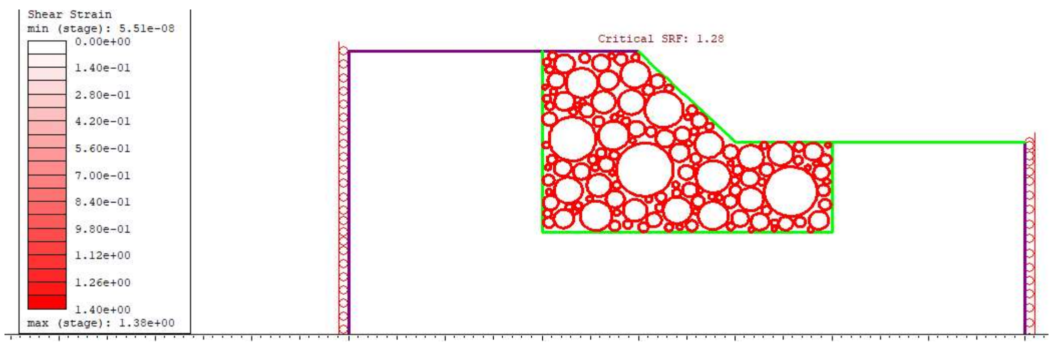


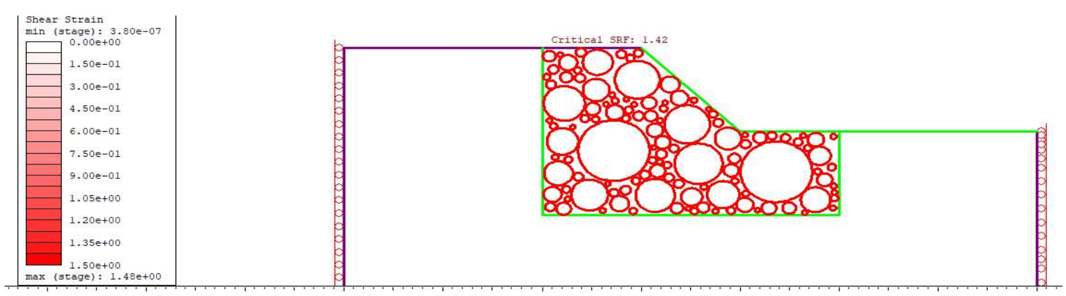
70%_4_FEM



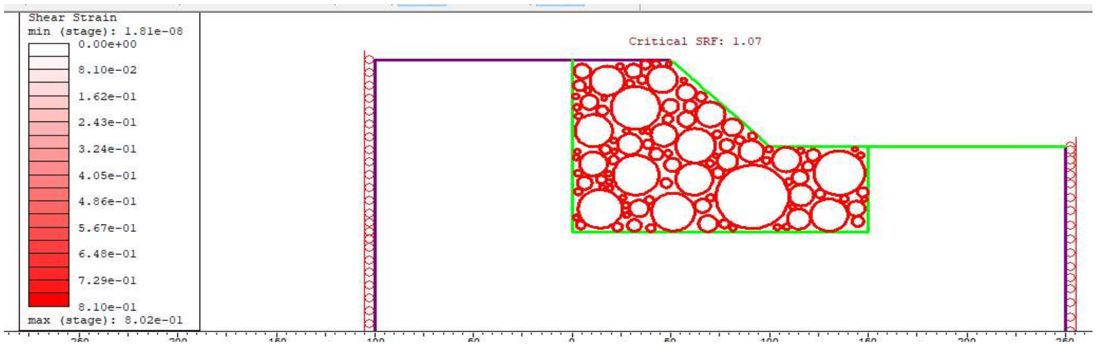
70%_5_FEM



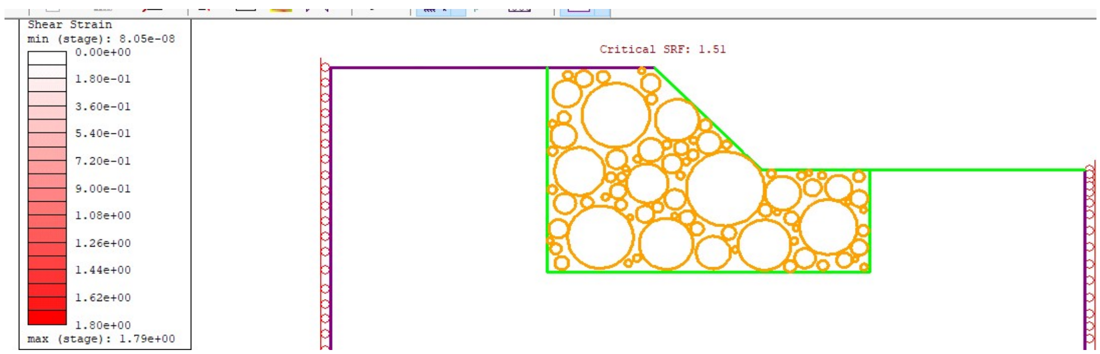
70%_6_FEM



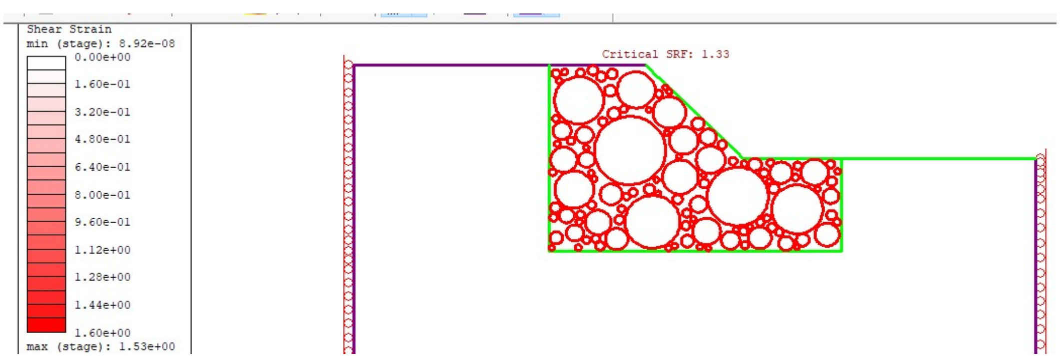
70%_7_FEM



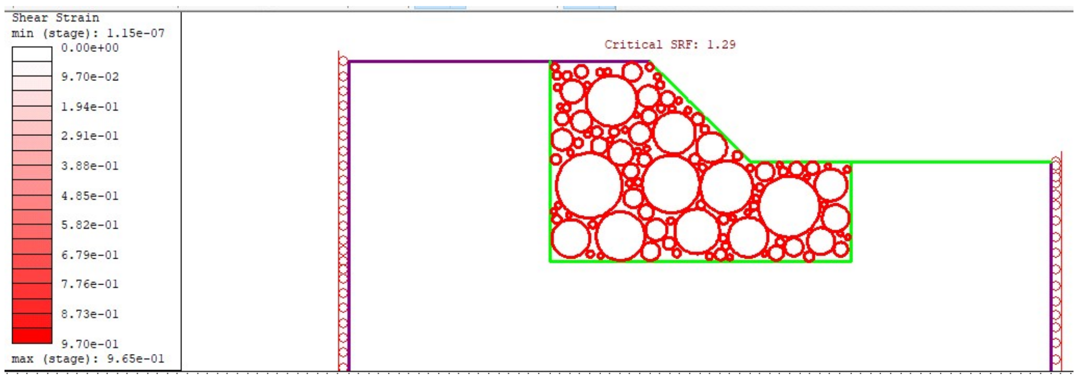
70%_8_FEM



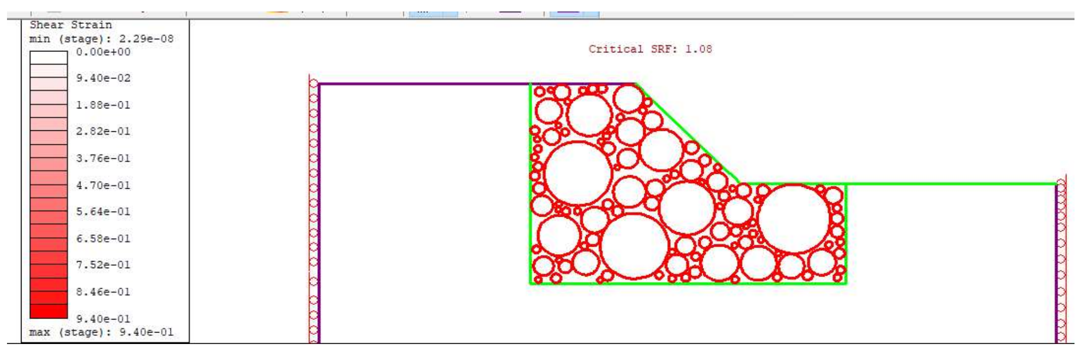
70%_9_FEM



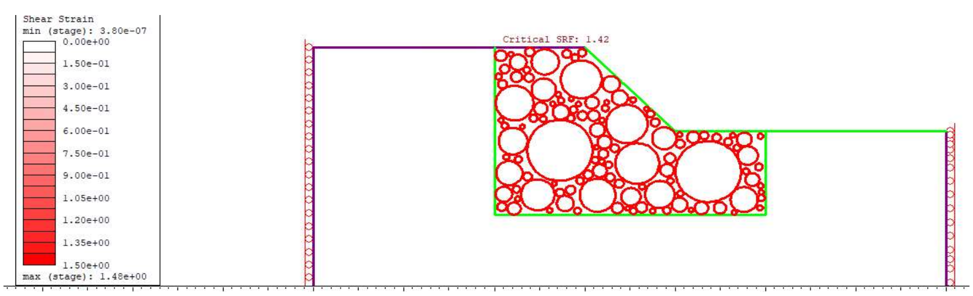
70%_10_FEM



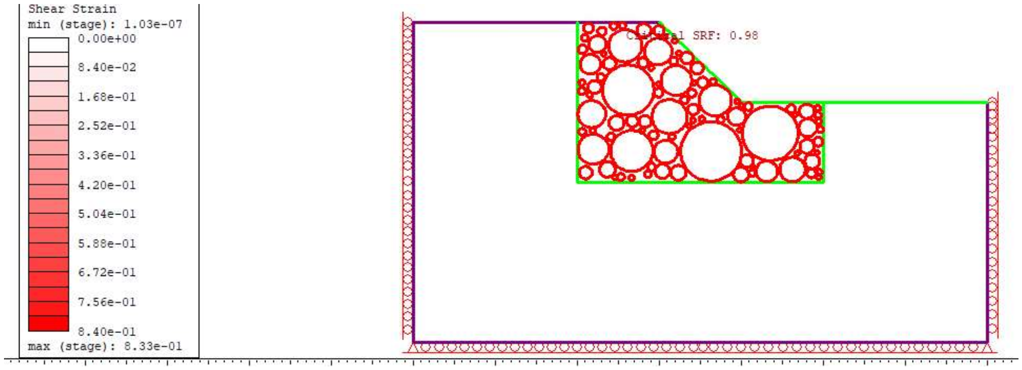
70%_11_FEM



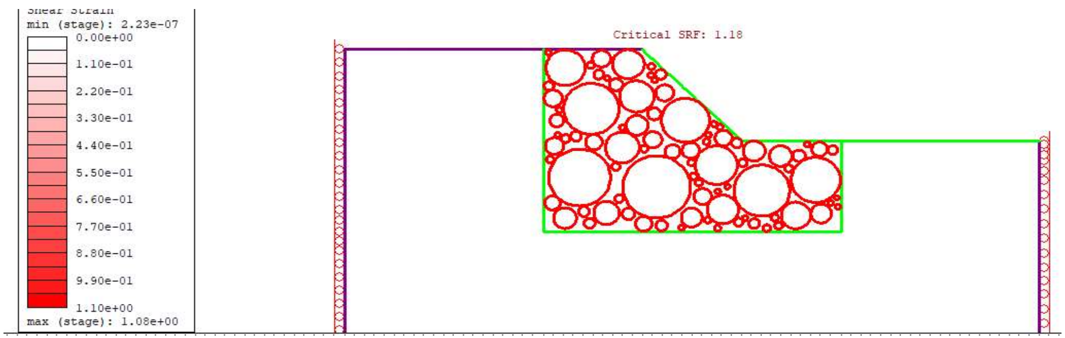
70%_12_FEM



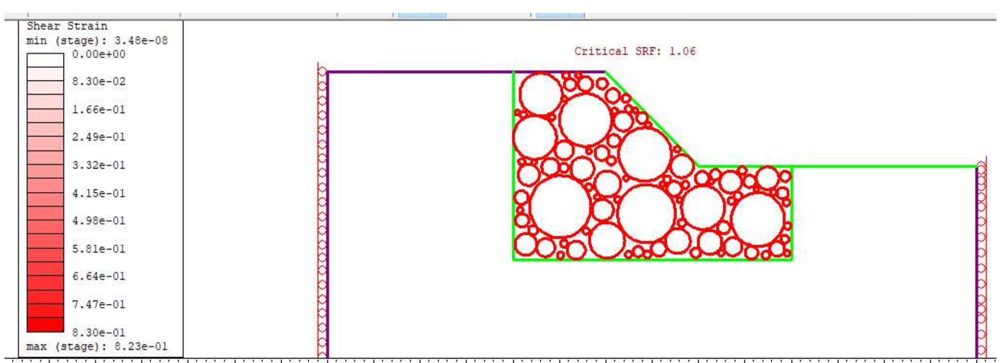
70%_13_FEM



70%_14_FEM

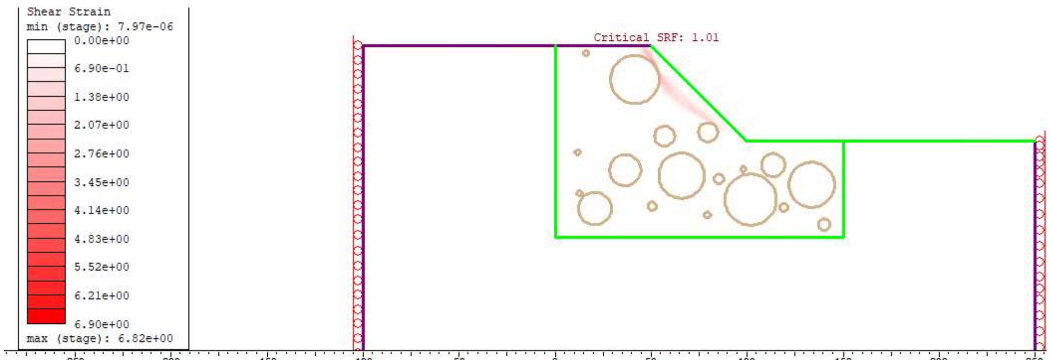


70%_15_FEM

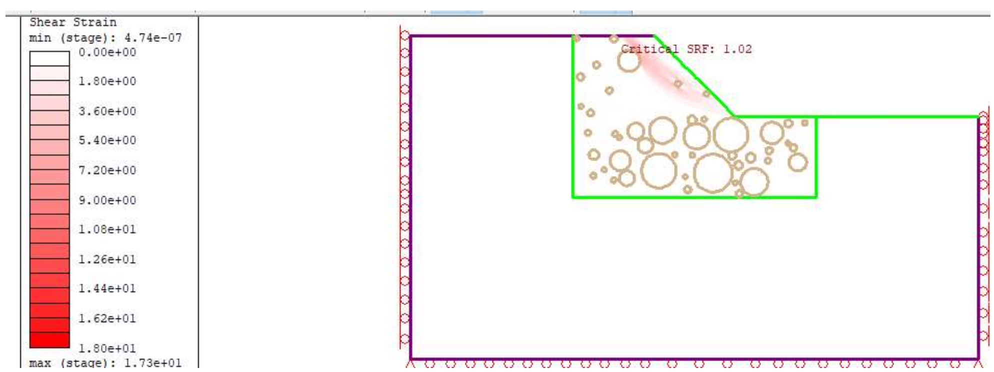


- <u>Results when the cohesion and the tensile strength of block- matrix interfaces are reduced by 100% (c= 0 MPa, φ = 24° , Tensile Strength= 0 MPa)</u>

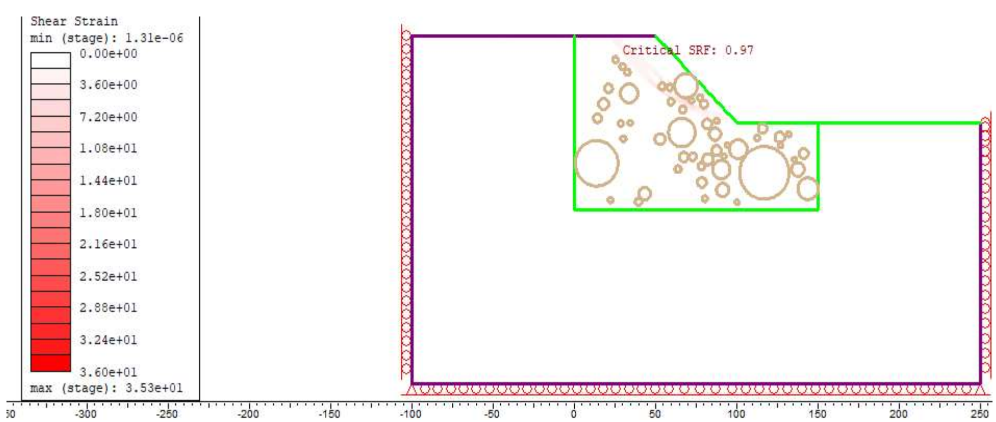
25%_1b_FEM



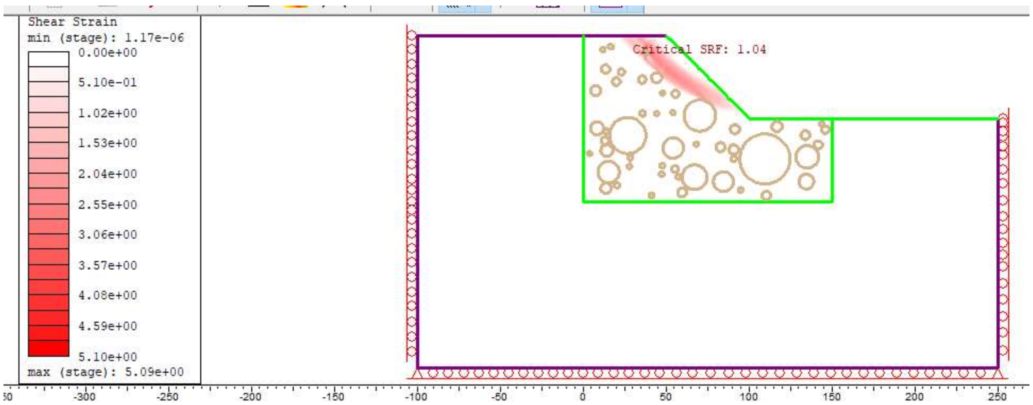
25%_2b_FEM



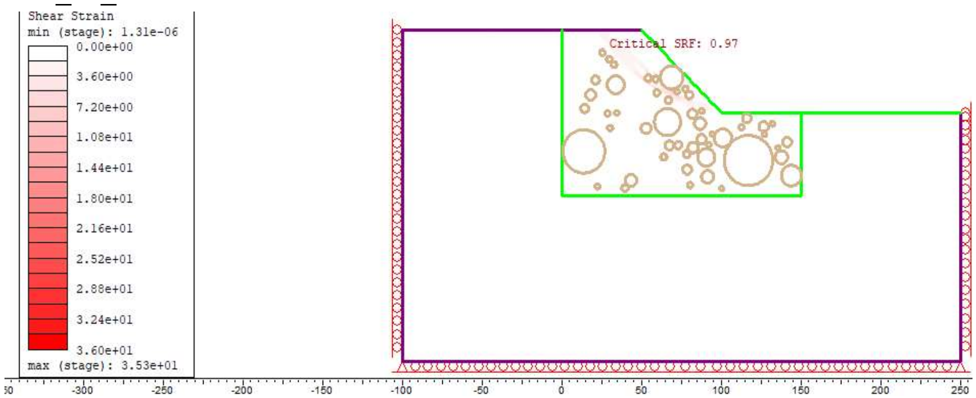
25%_3b_FEM



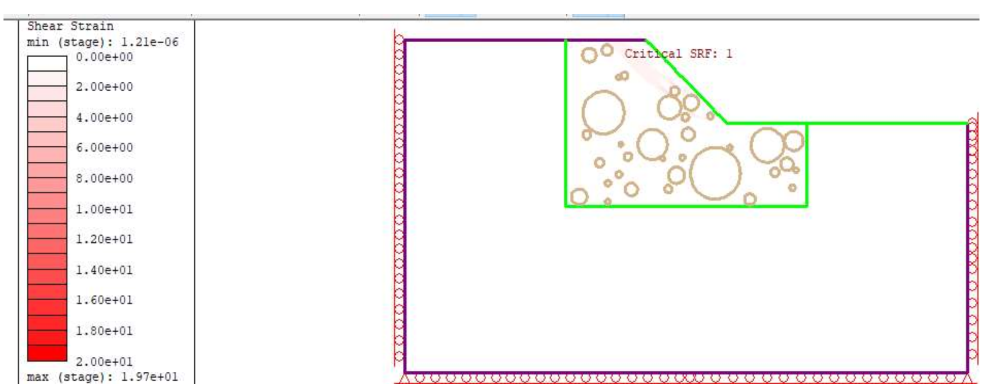
25%_4b_FEM



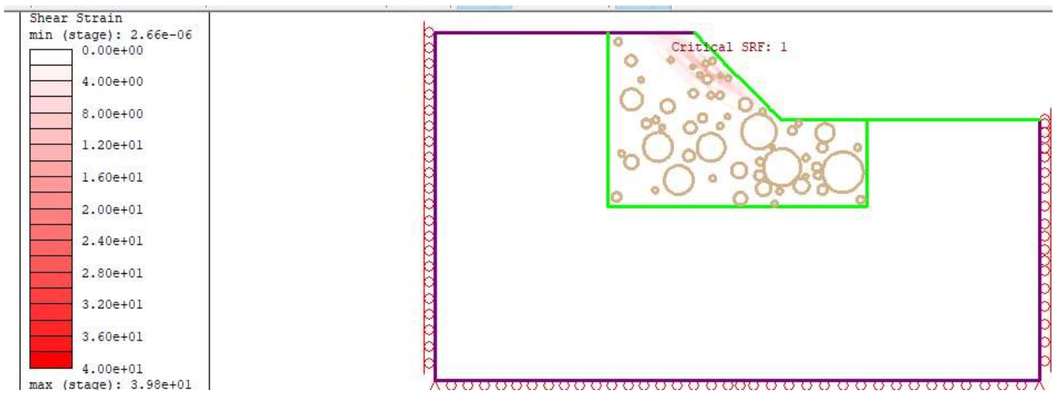
25%_5b_FEM



25%_6b_FEM



25%_7b_FEM



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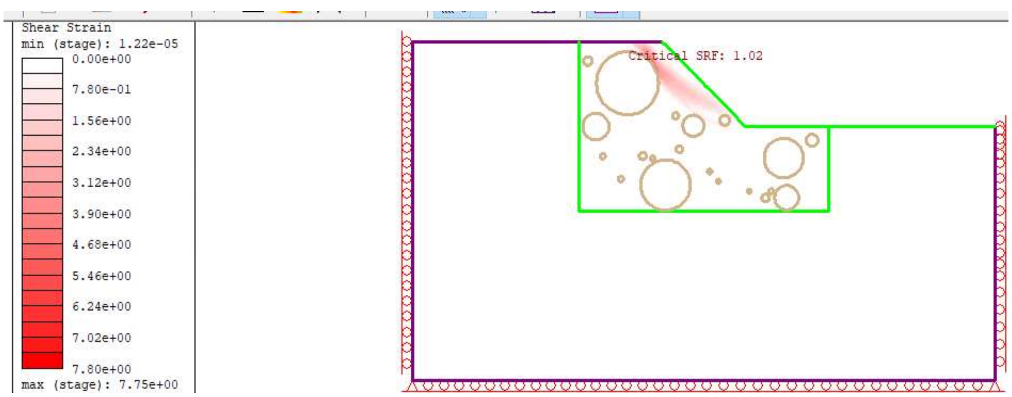

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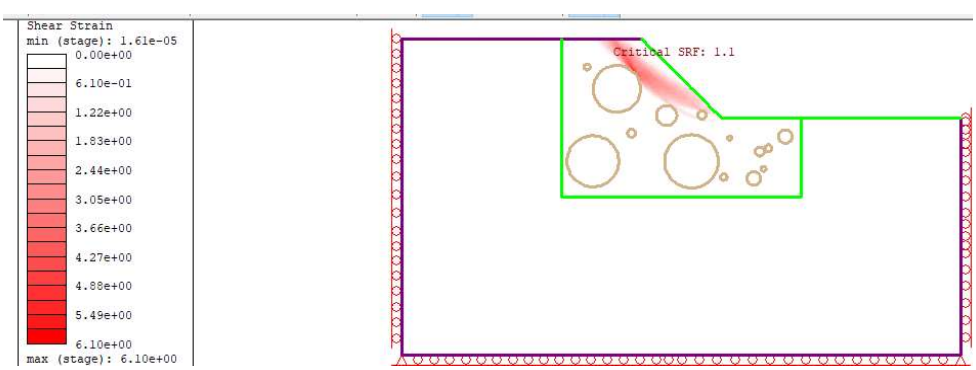

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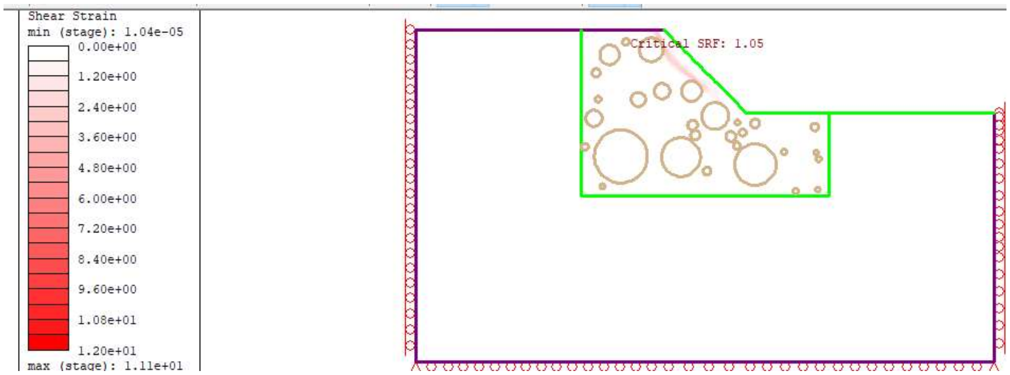

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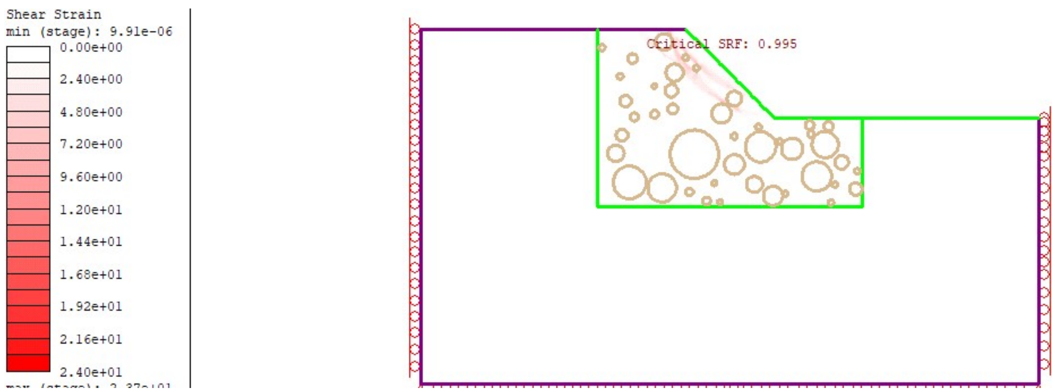

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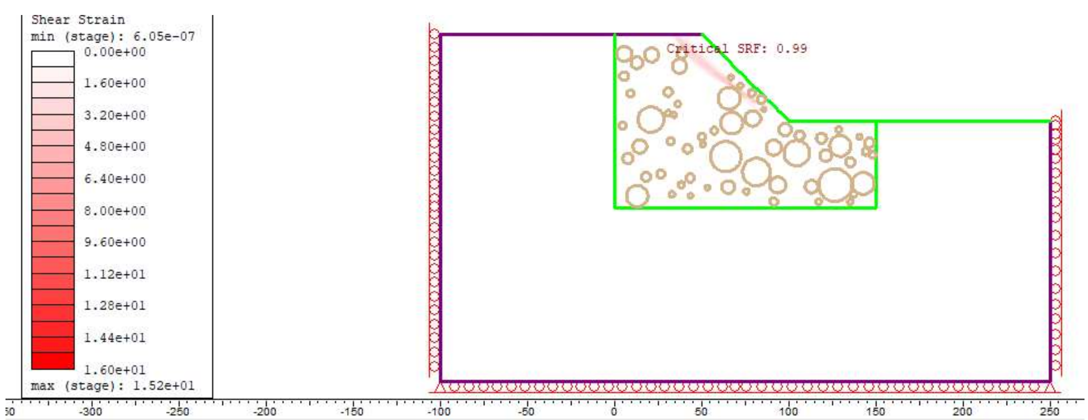

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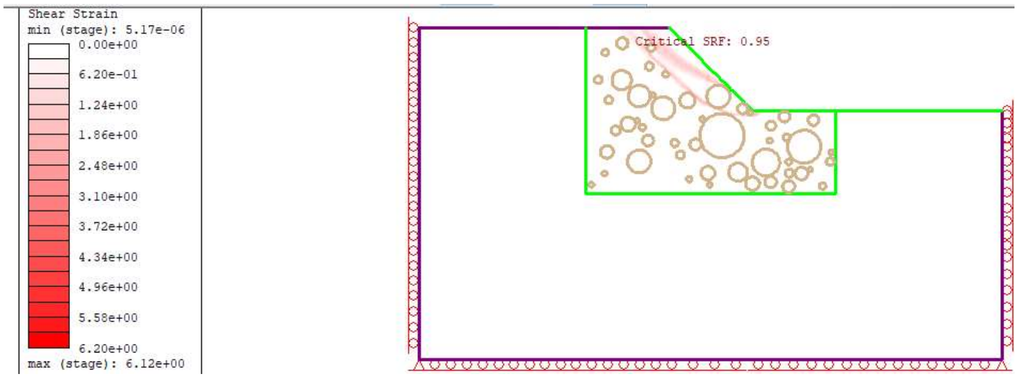

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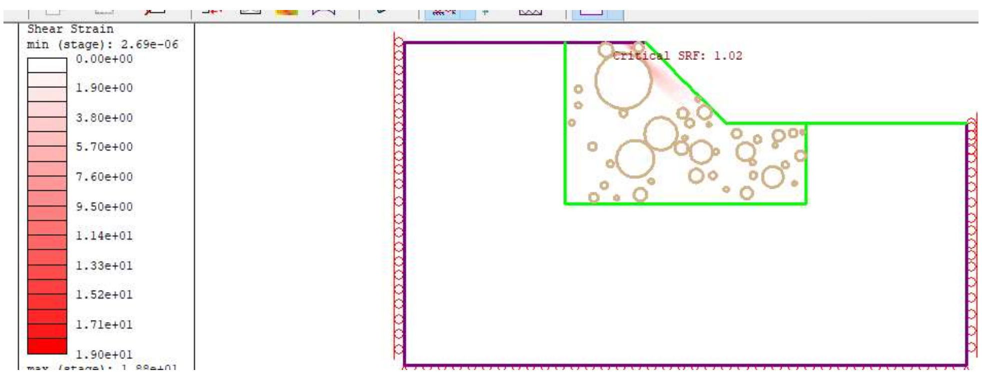
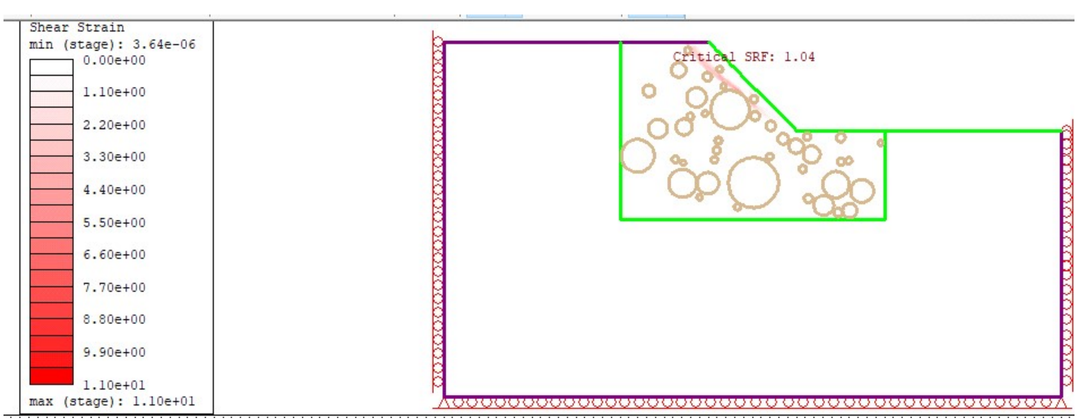
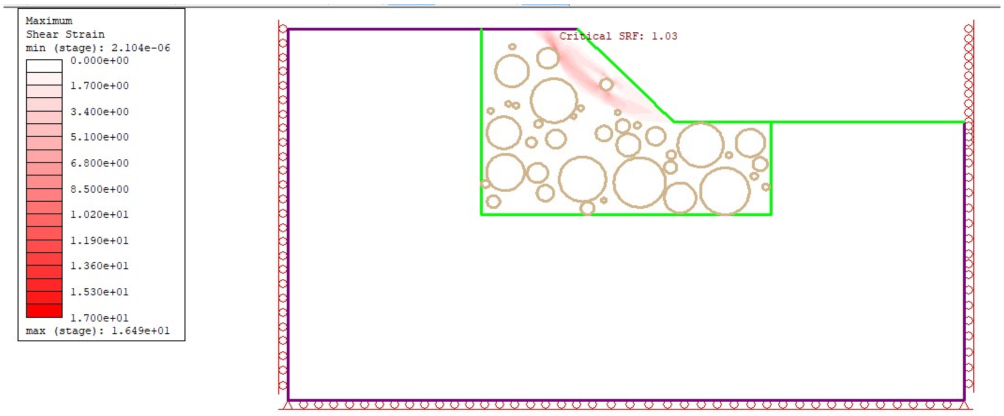


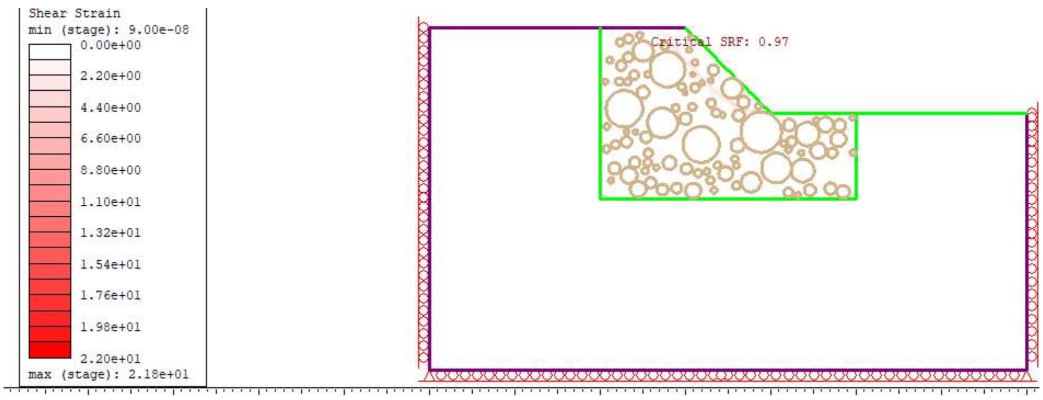
25%_15b_FEM



40%_1b_FEM



40%_2b_FEM



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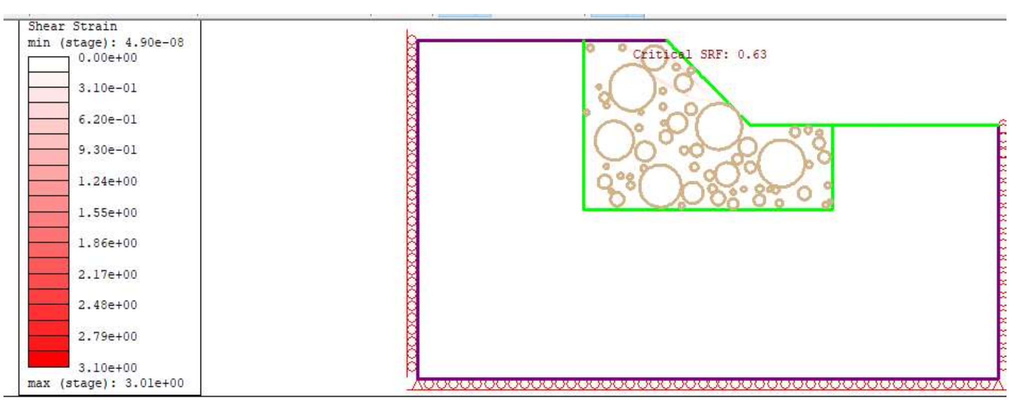

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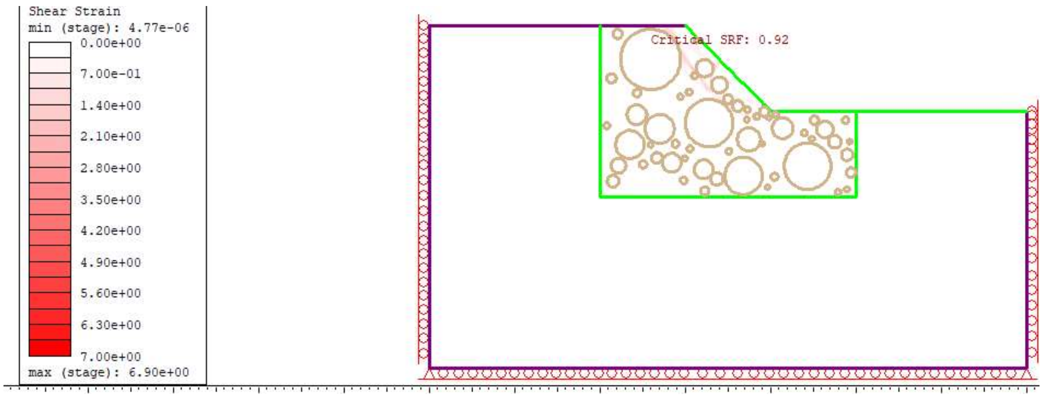
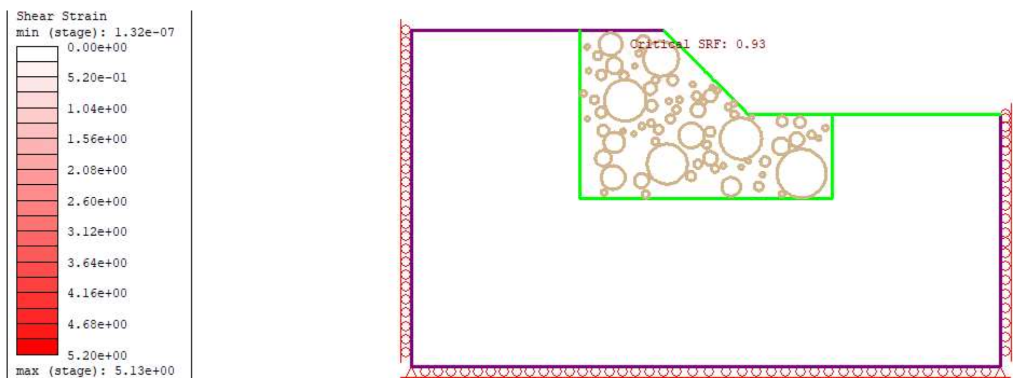
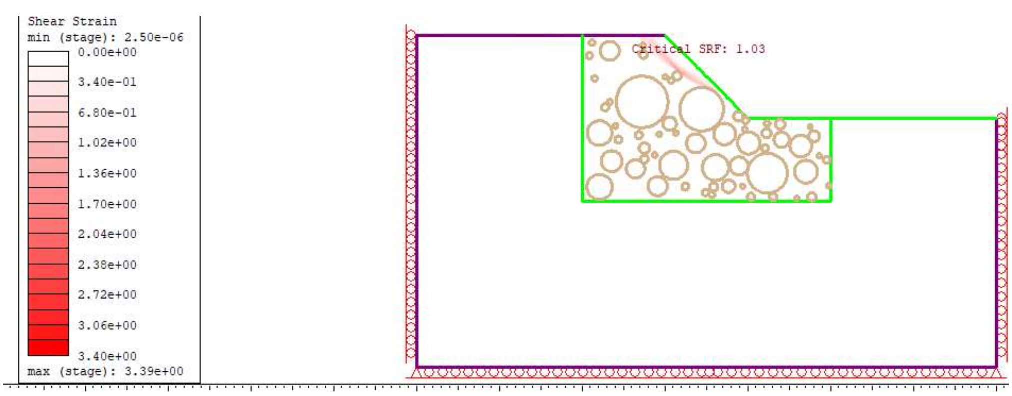


40%_5b_FEM



40%_6b_FEM



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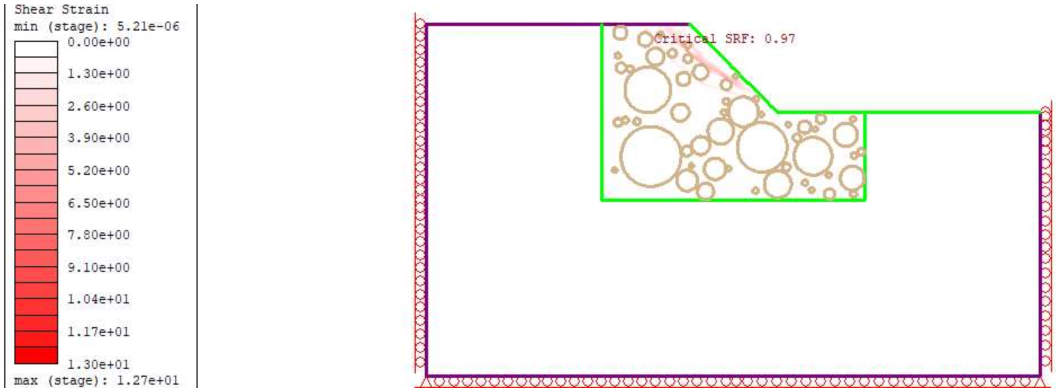

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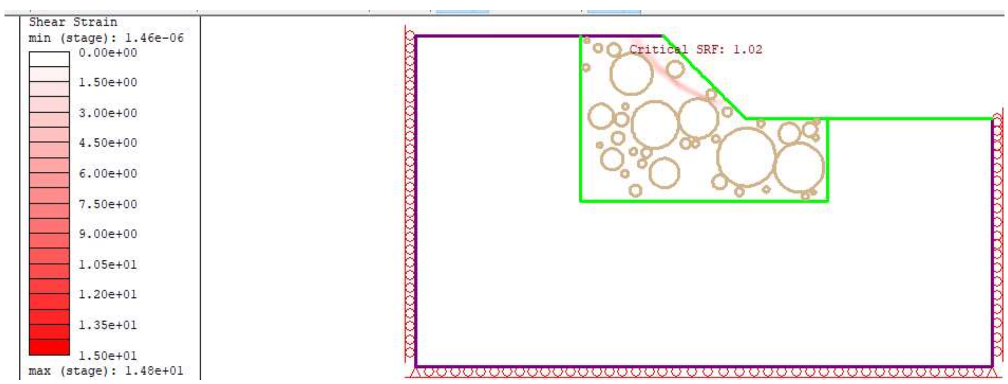

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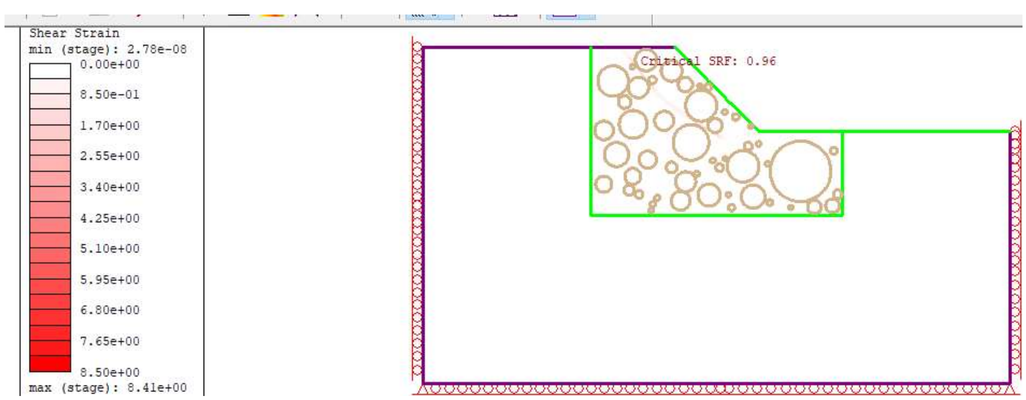

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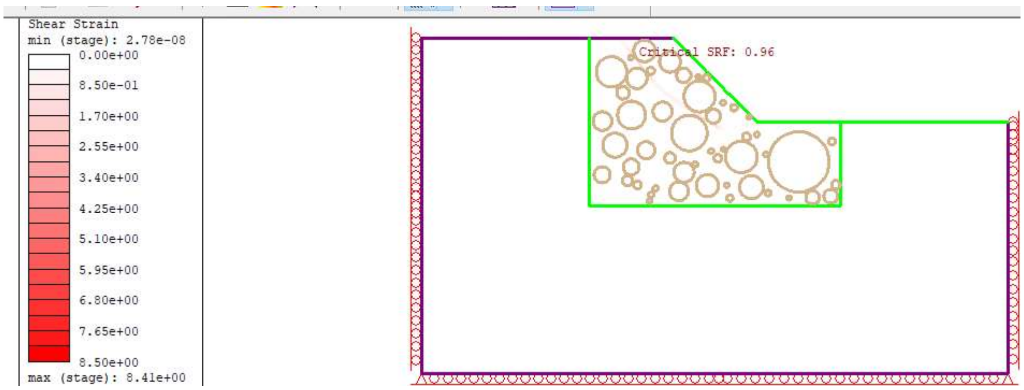

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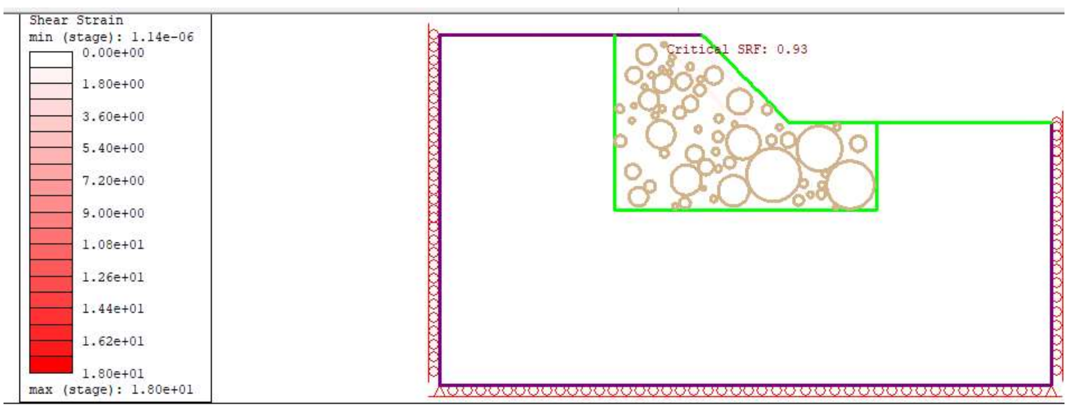

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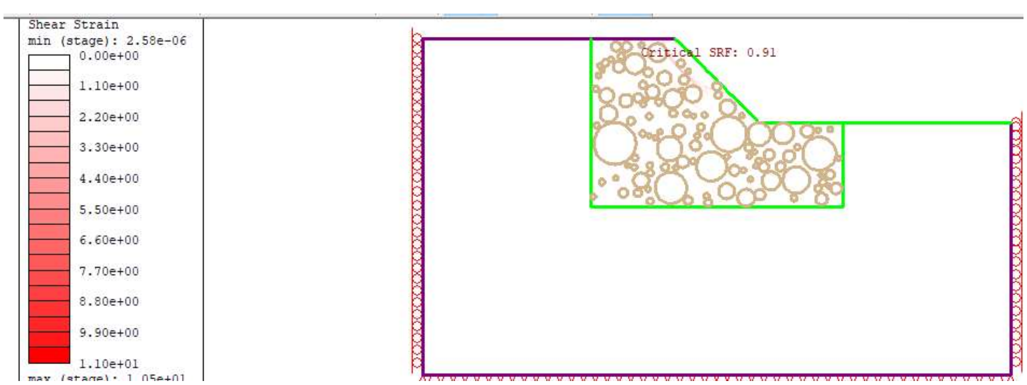

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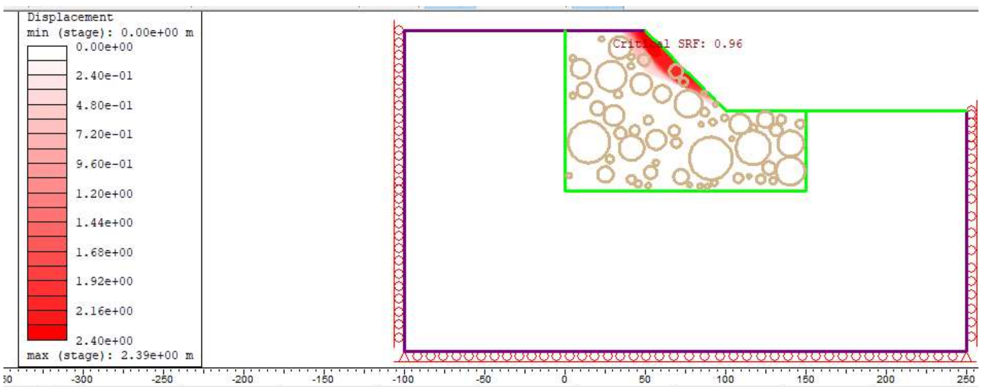

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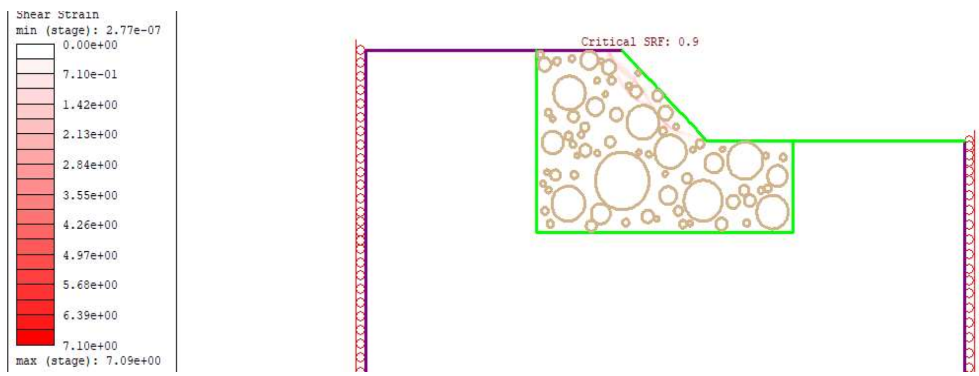

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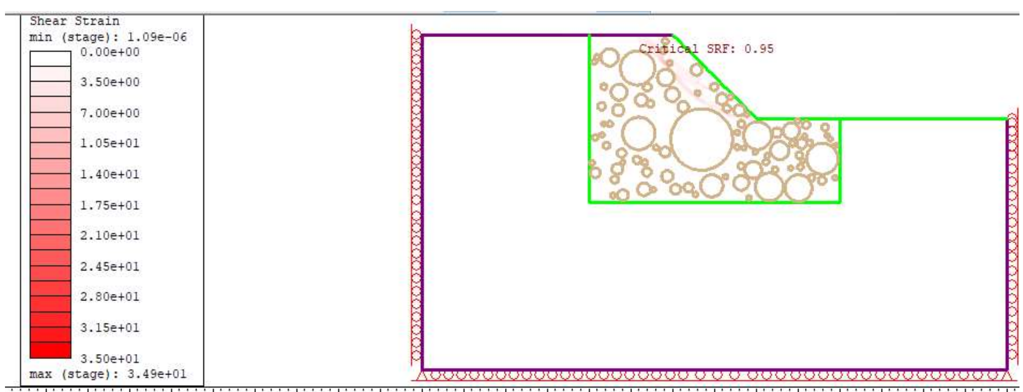

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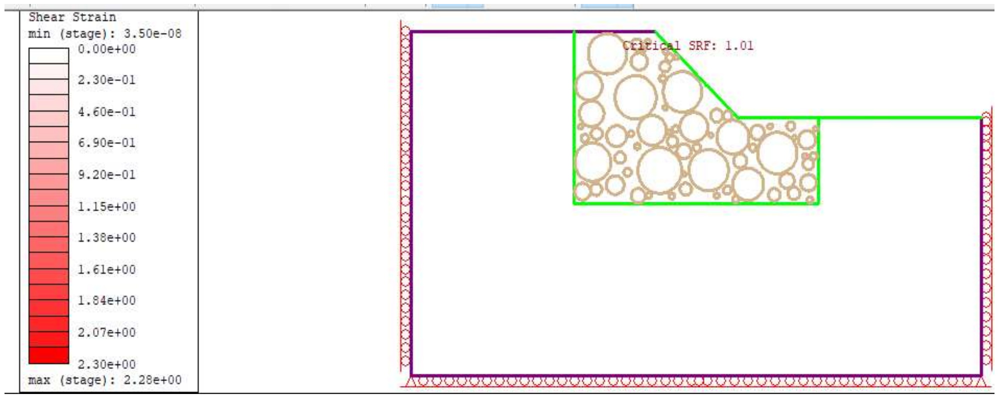
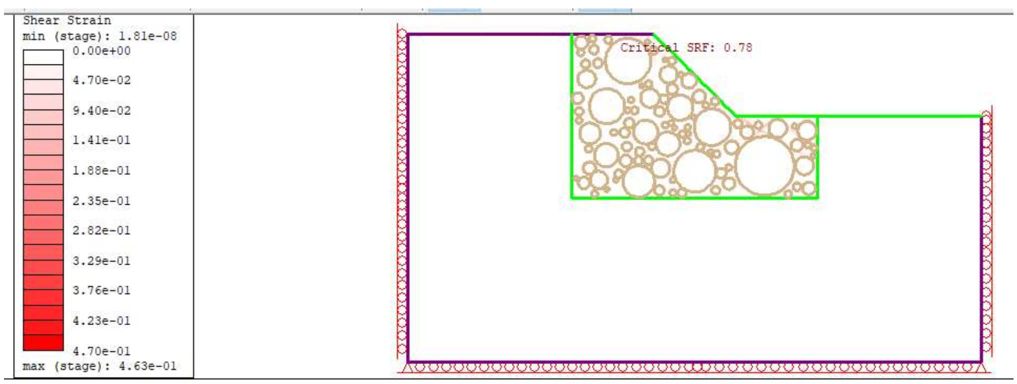


55%_2b_FEM



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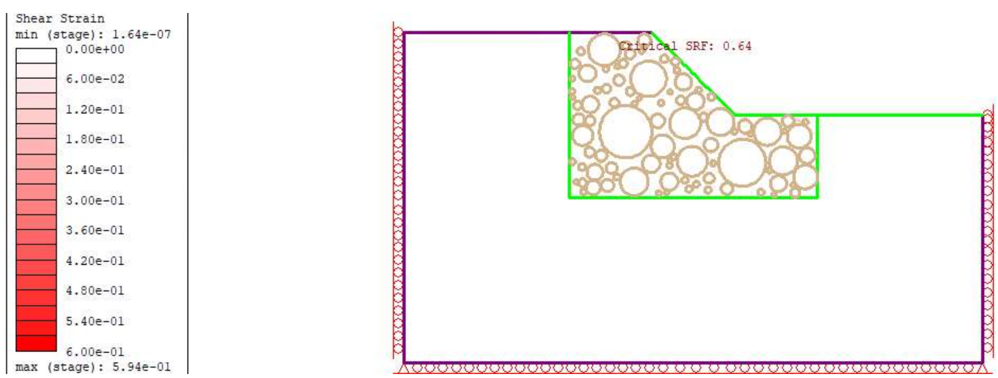

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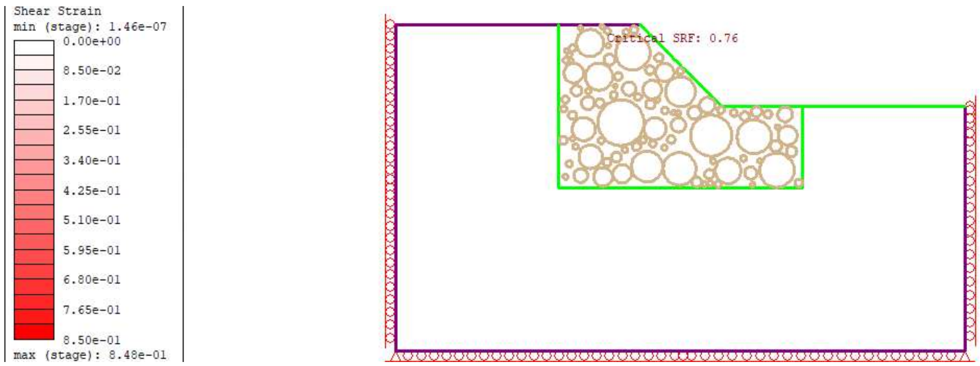

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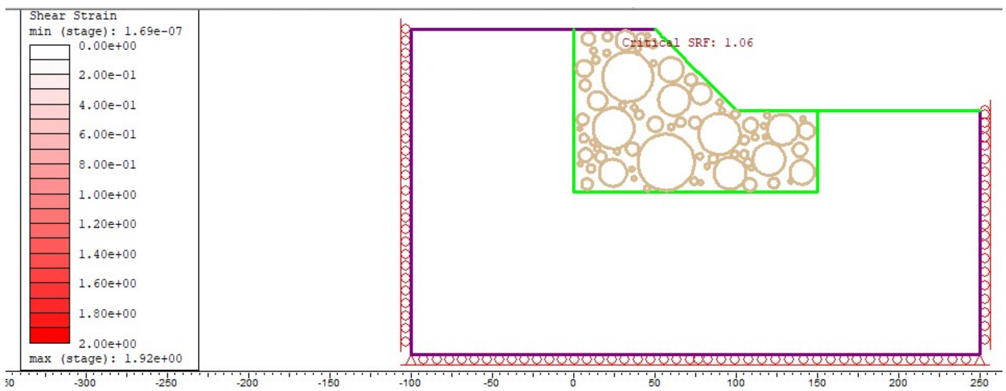

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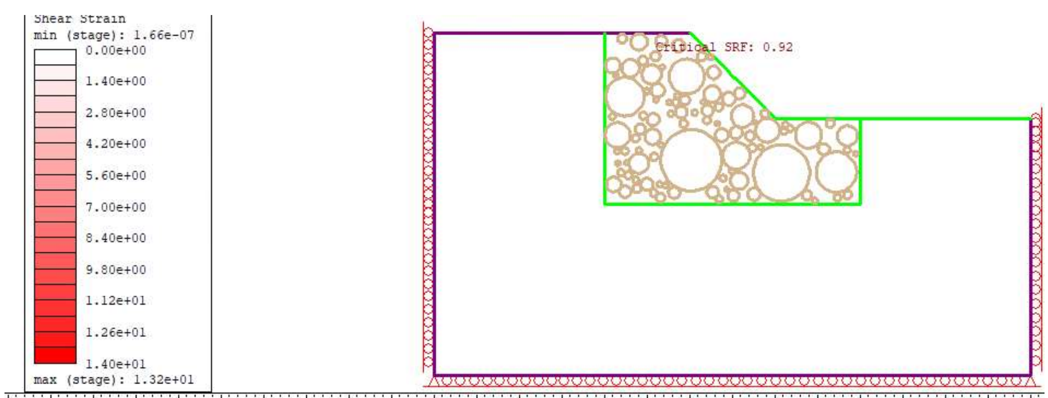

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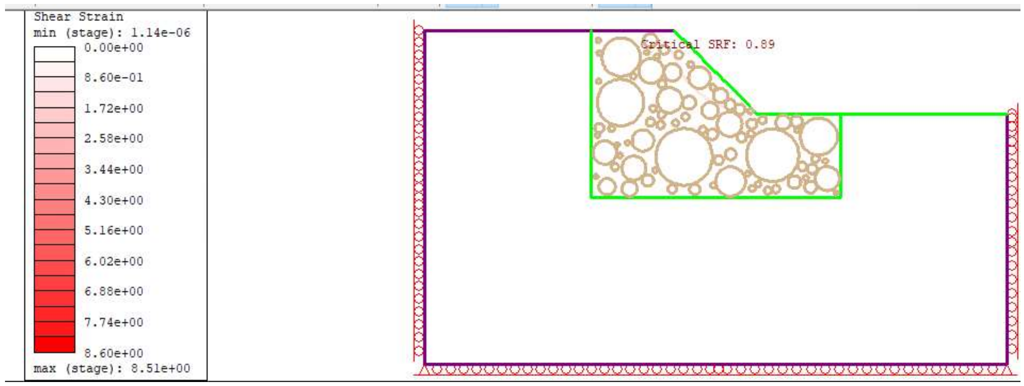

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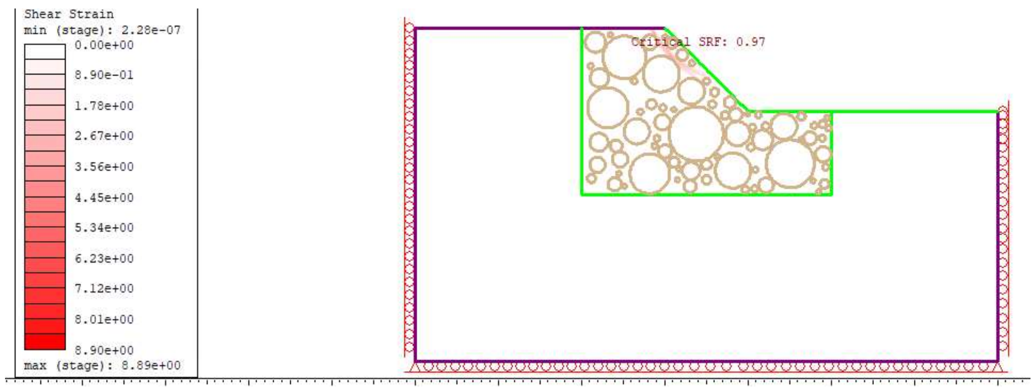

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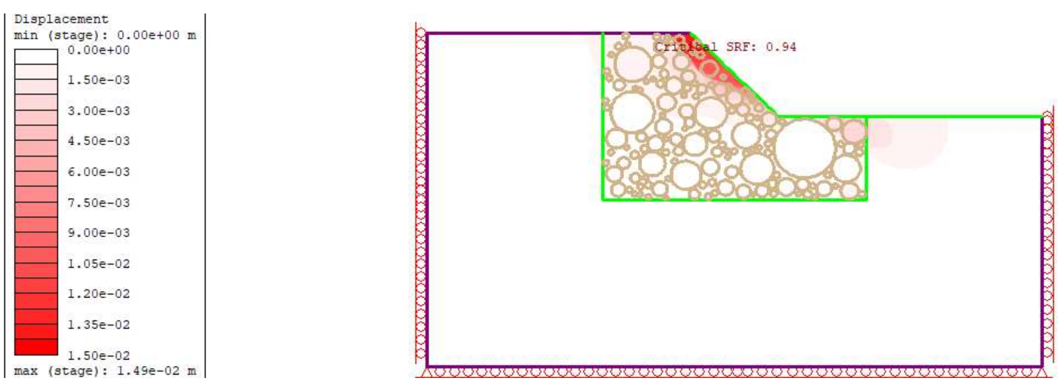

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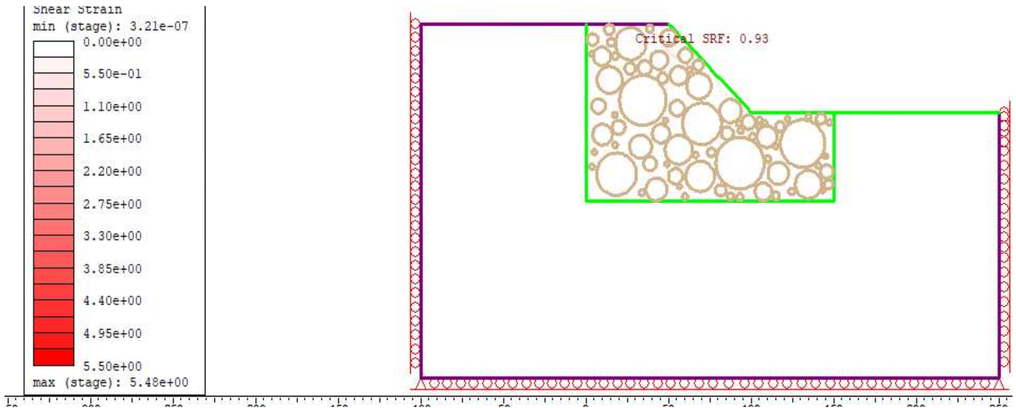

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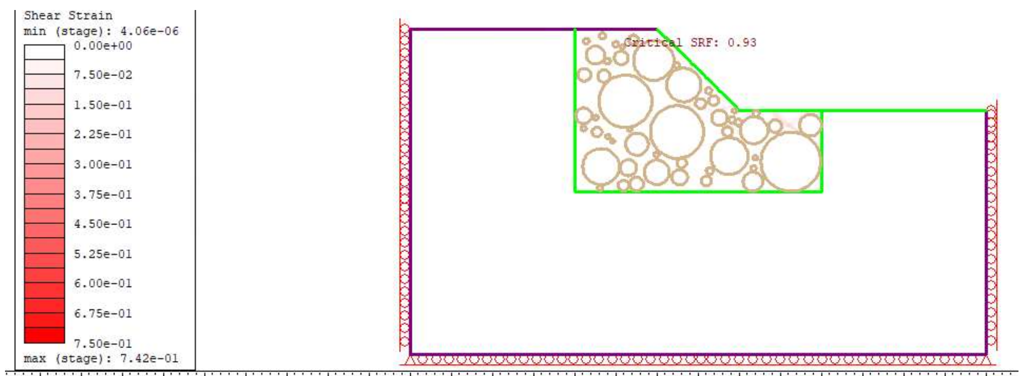

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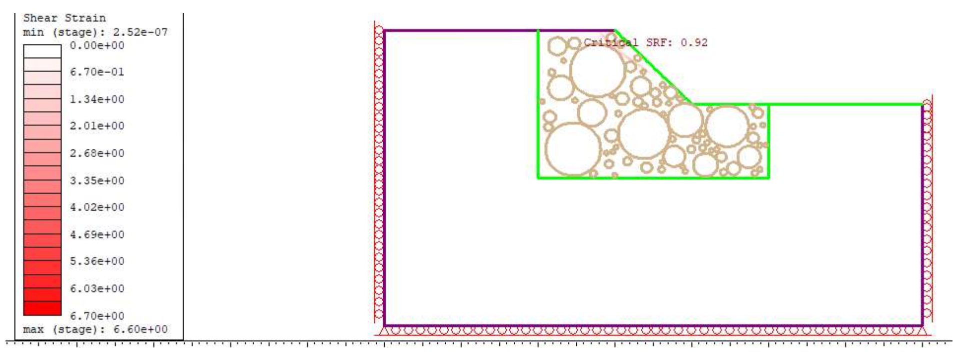

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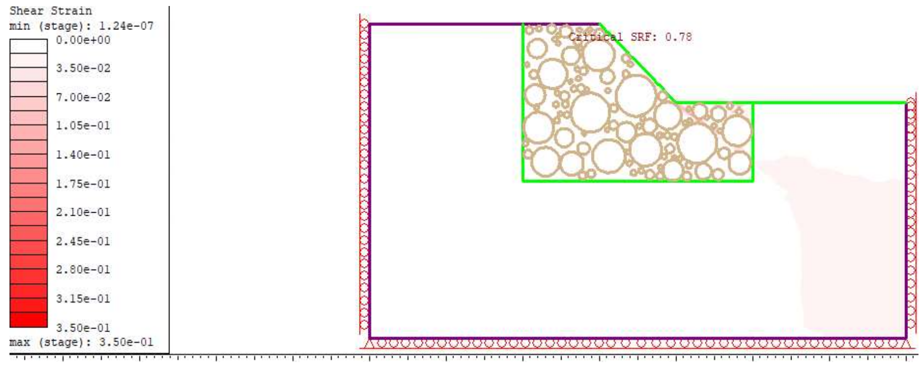

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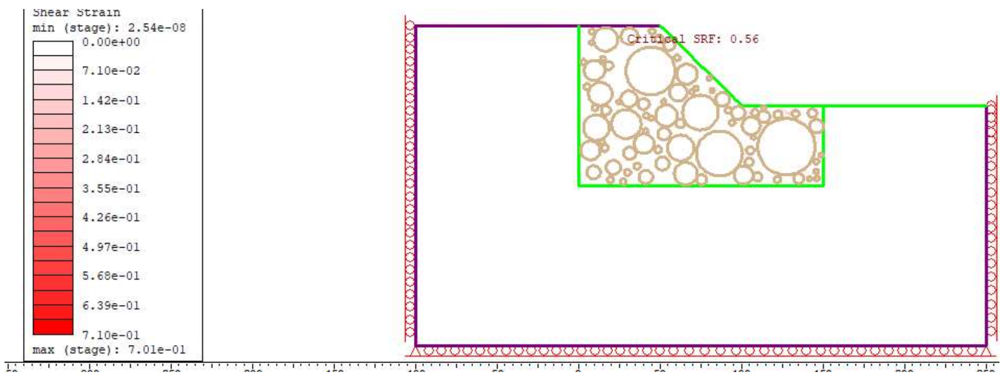
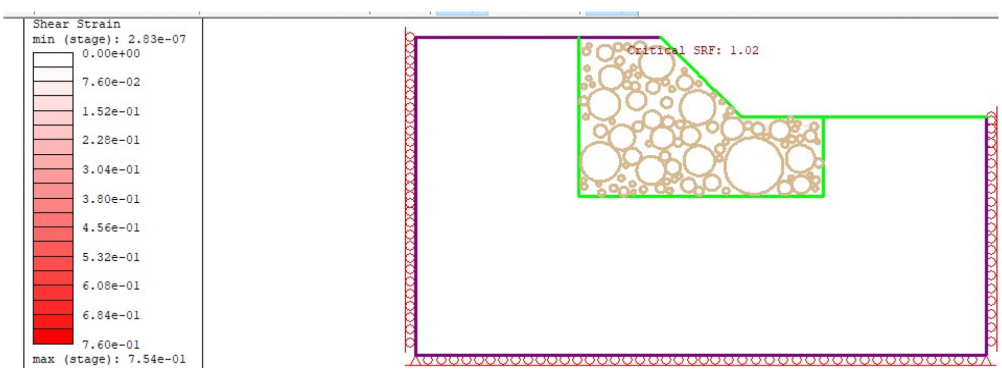
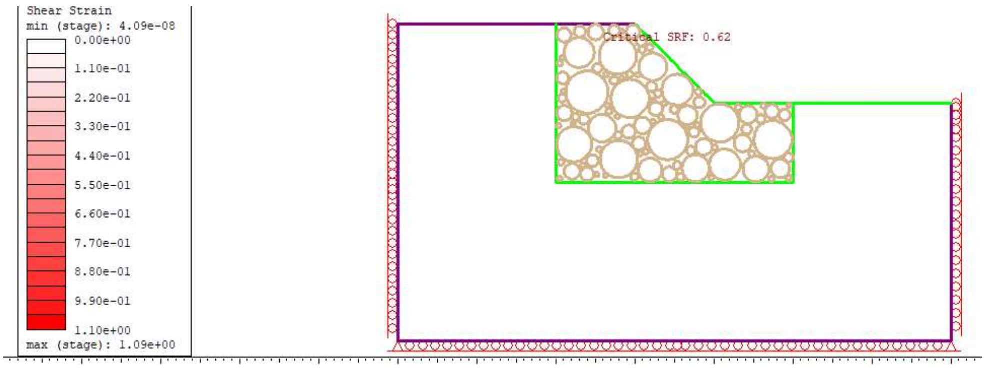


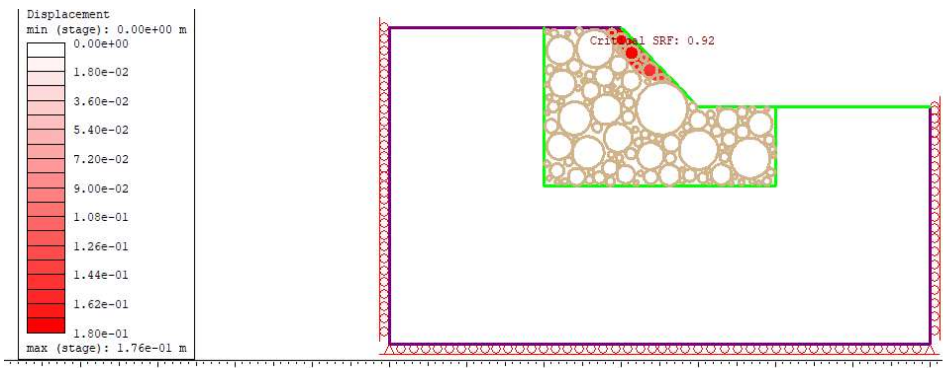
55%_15b_FEM



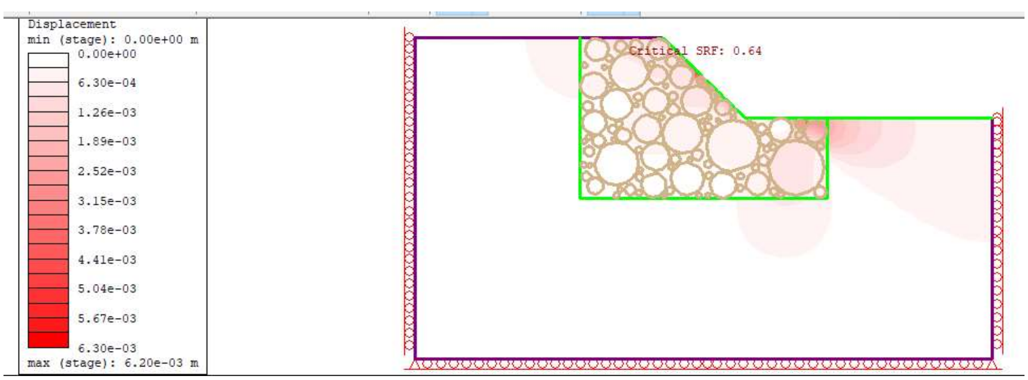
70%_1b_FEM



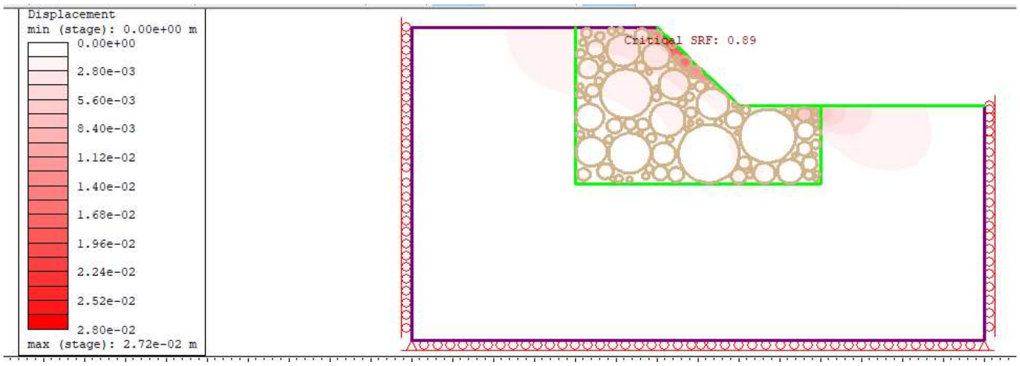
70%_2b_FEM



70%_3b_FEM



70%_4b_FEM



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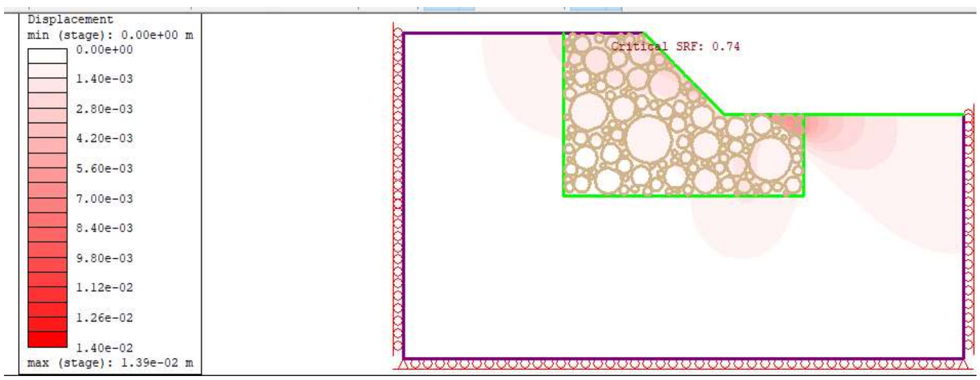
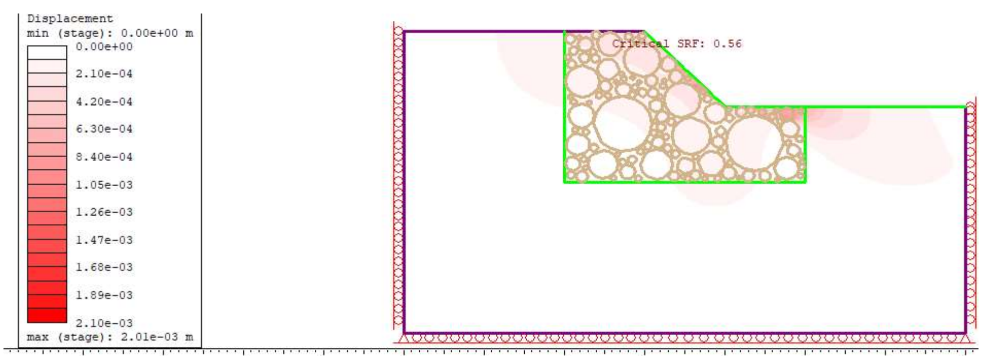


70%_6b_FEM



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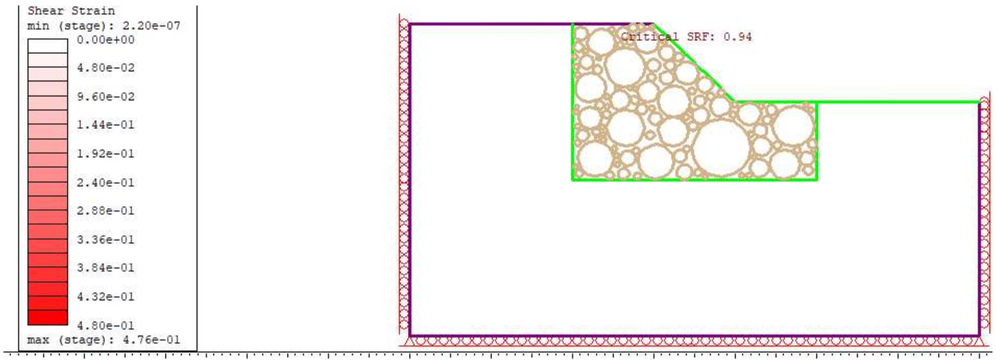
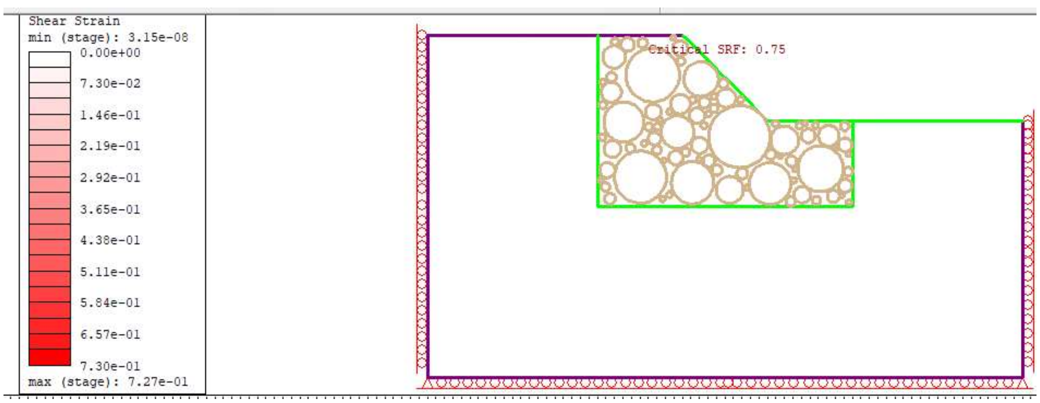
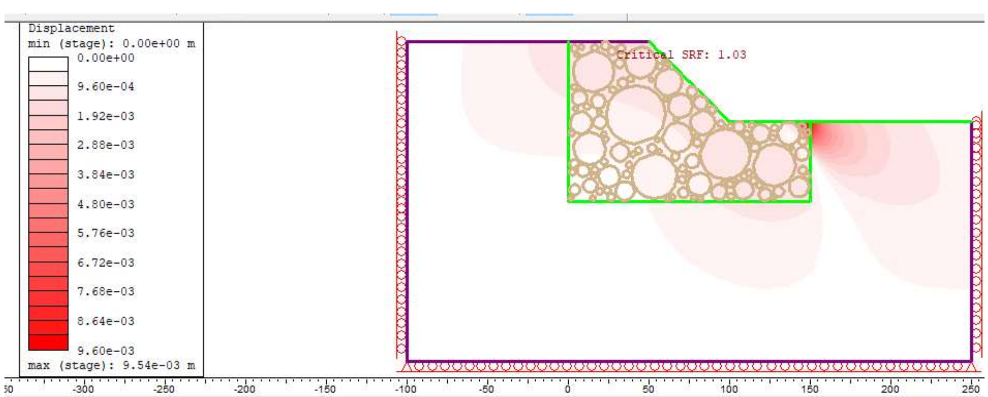


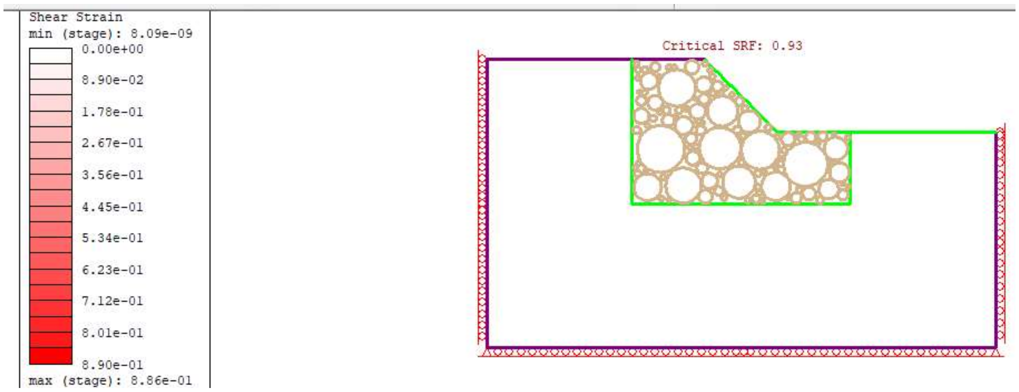
70%_8b_FEM



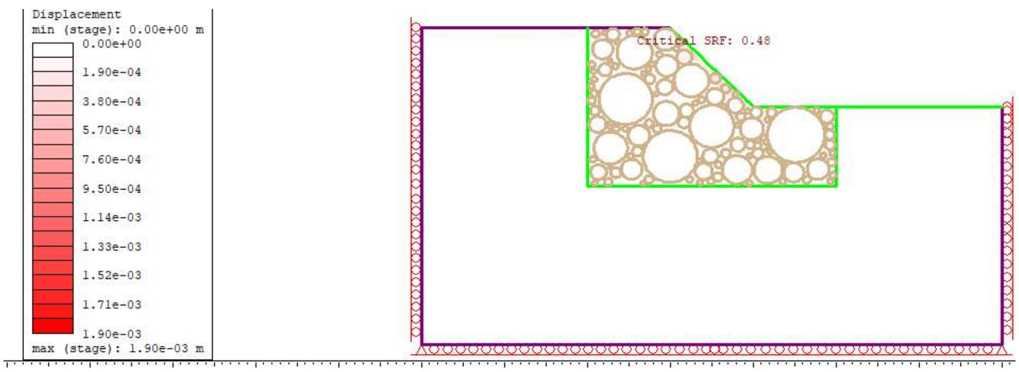
70%_9b_FEM



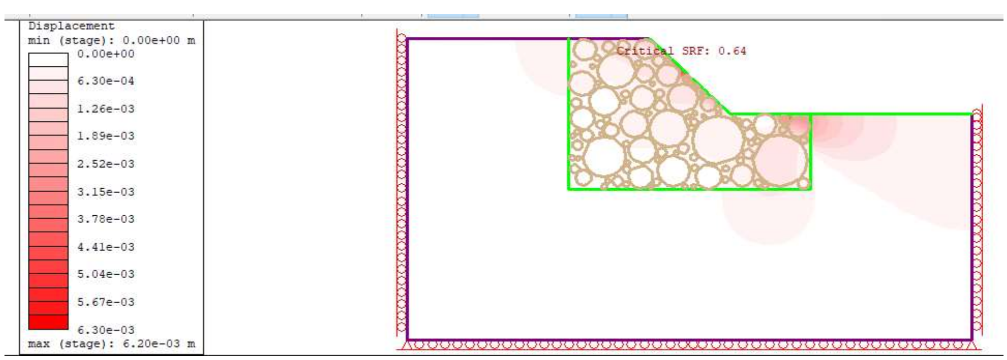
70%_10b_FEM



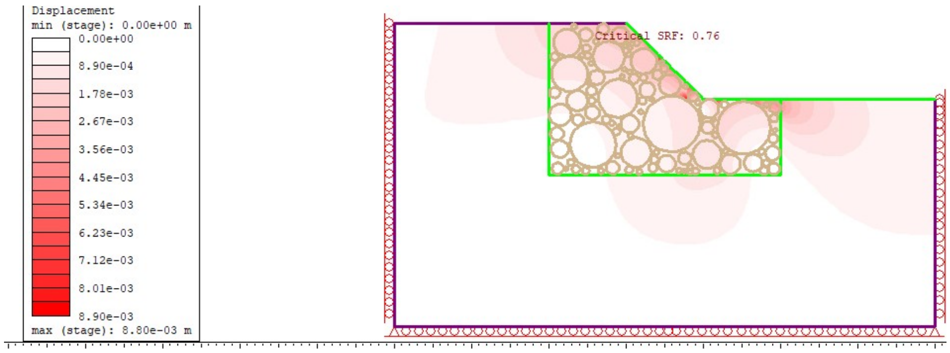
70%_11b_FEM



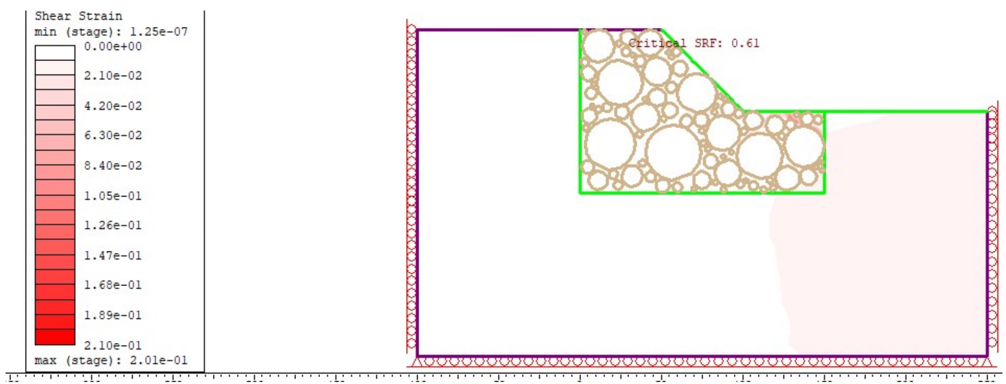
70%_12b_FEM



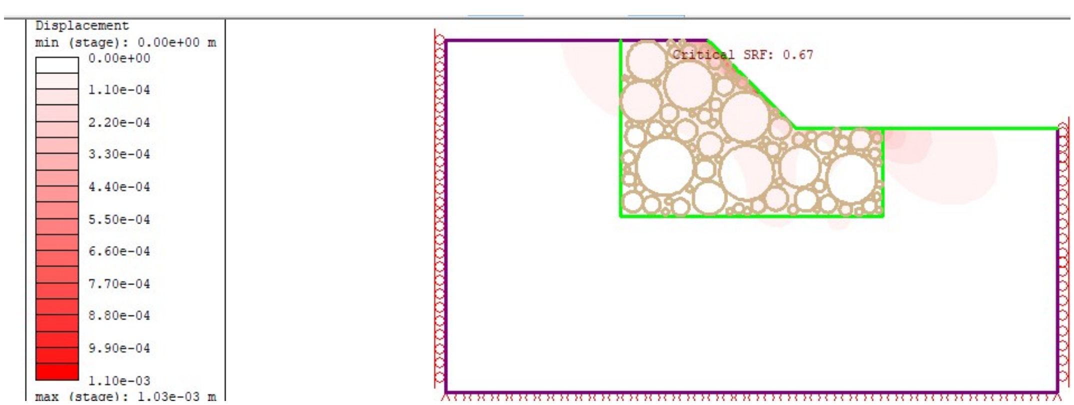
70%_13b_FEM



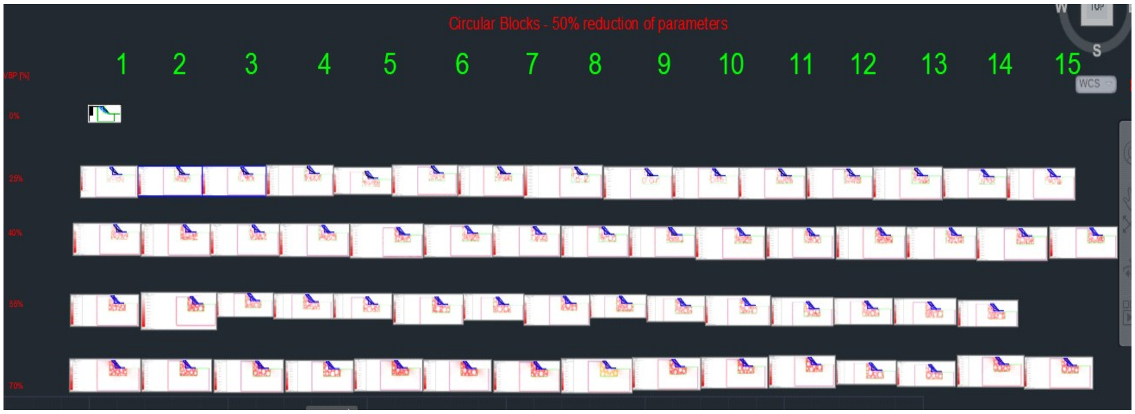
70%_14b_FEM



70%_15b_FEM

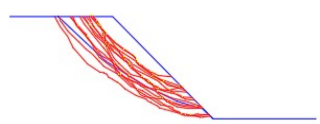


- <u>Comparison of failure surfaces when the cohesion and the tensile strength of block- matrix interfaces are reduced by 50%</u>

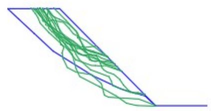


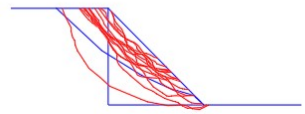
25% VBP

40% VBP

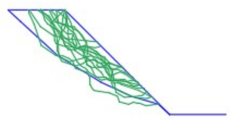


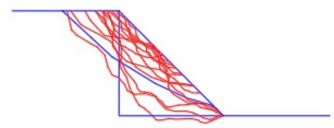
55% VBP



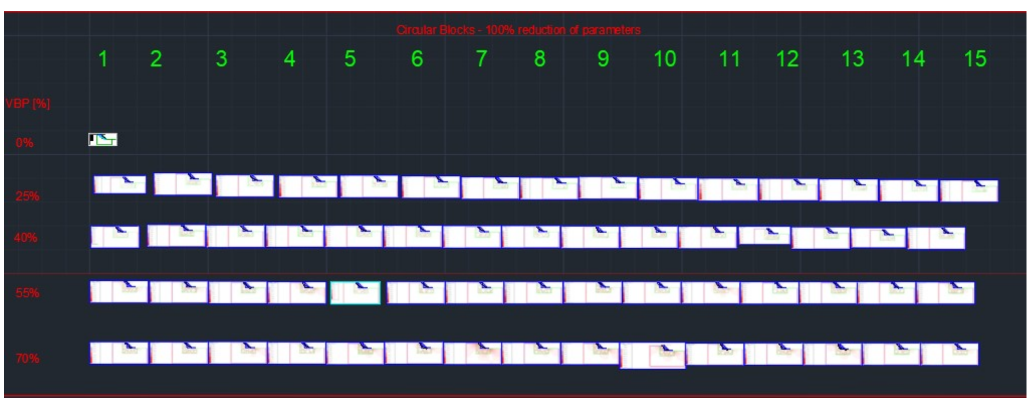


70% VBP

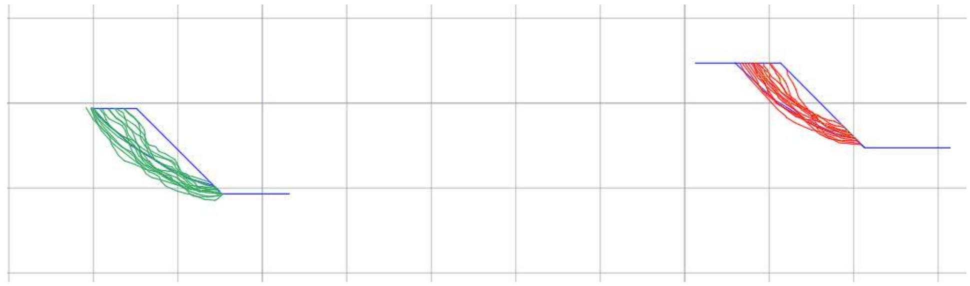




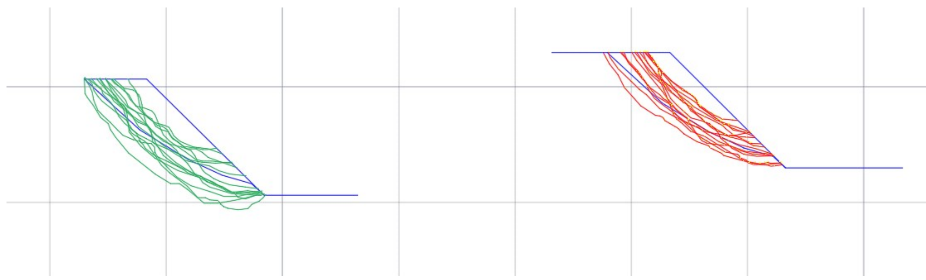
- <u>Comparison of failure surfaces when the cohesion and the tensile strength of block- matrix interfaces are reduced by 100%</u>



25% VBP

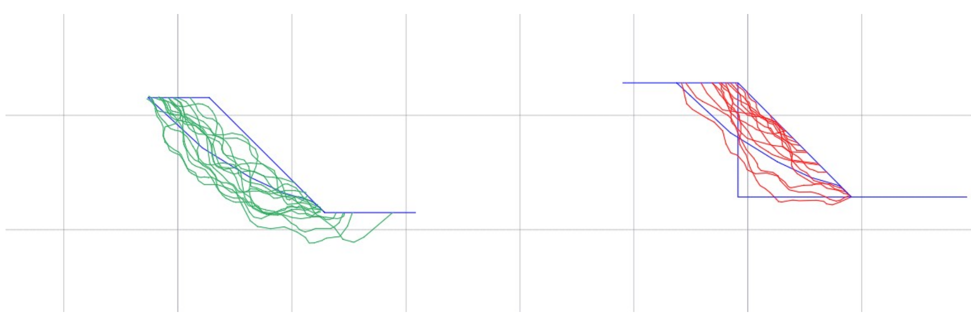


40% VBP



55% VBP

70% VBP



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