R-05-43

Strategy for a numerical Rock Mechanics Site Descriptive Model

Further development of the theoretical/numerical approach

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May 2005

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ISSN 1402-3091
SKB Rapport R-05-43

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Abstract

The Swedish Nuclear and Fuel Management Company (SKB) is conducting Preliminary Site Investigations at two different locations in Sweden in order to study the possibility of a Deep Repository for spent fuel. In the frame of these Site Investigations, Site Descriptive Models are achieved. These products are the result of an interaction of several disciplines such as geology, hydrogeology, and meteorology. The Rock Mechanics Site Descriptive Model constitutes one of these models.

Before the start of the Site Investigations a numerical method using Discrete Fracture Network (DFN) models and the 2D numerical software UDEC was developed. Numerical simulations were the tool chosen for applying the theoretical approach for characterising the mechanical rock mass properties. Some shortcomings were identified when developing the methodology. Their impacts on the modelling (in term of time and quality assurance of results) were estimated to be so important that the improvement of the methodology with another numerical tool was investigated.

The theoretical approach is still based on DFN models but the numerical software used is 3DEC. The main assets of the programme compared to UDEC are an optimised algorithm for the generation of fractures in the model and for the assignment of mechanical fracture properties. Due to some numerical constraints the test conditions were set-up in order to simulate 2D plane strain tests. Numerical simulations were conducted on the same data set as used previously for the UDEC modelling in order to estimate and validate the results from the new methodology.

A real 3D simulation was also conducted in order to assess the effect of the “2D” conditions in the 3DEC model.

Based on the quality of the results it was decided to update the theoretical model and introduce the new methodology based on DFN models and 3DEC simulations for the establishment of the Rock Mechanics Site Descriptive Model.

By separating the spatial variability into two parts, one depending on the geometry of the fracture system and one depending on the variation of the material parameters the determination of the rock mass properties are more straightforward.

Sammanfattning

För att studera möjligheterna att bygga ett djupförlagt lager för använt kärnbränsle utför Svensk Kärnbränslehantering AB (SKB) platsundersökningar på två olika platser i Sverige. Insamlade data från dessa platser tolkas och analyseras för att ge en samlad platsbeskrivning i form av en platsbeskrivande modell. Dessa modeller behandlar bland annat geologi, hydrogeologi, bergmekanik och ytnära ekosystem.

Under förberedande fasen för platsundersökningar utvecklades en numerisk metodik att uppskatta bergmassans mekaniska egenskaper som ingår i den bergmekaniska platsbeskrivningen. Den baseras på 3D diskret Spricknätsmodell (DFN) och 2D numerisk modellering med UDEC. Metodiken använder teoretiska materialmodeller för det intakta berget och sprickorna. Den framtagna metodiken testades på en begränsad del av data från undersökningarna vid Äspölaboratoriet. Dessa tester visade på vissa begränsningar i metodiken som kunde kopplas till den numeriska koden och som utgjorde en riskfaktor under platsundersökningarna. Deras inverkan på modelleringen (både i tid och i kvalitén av producerade resultat) bedömdes erfordra vidare undersökning med hjälp av andra numeriska produkter.

Den nu framtagna metodiken baseras fortfarande på 3D diskret Spricknätsmodell (DFN) men numeriska simuleringarna utförs med den 3D numeriska koden 3DEC. Valet av koden motiveras på följande grunder: 1) en algoritm har skrivits som automatiskt hanterar genereringen av sprickor i enskilda block; 2) en annan algoritm har utvecklats för att tilldela mekaniska egenskaper till sprickorna. Dessutom finns möjligheter att utföra några 3D numeriska modelleringar om behovet identifieras.

Antalet sprickor modellerade i en 3D diskret spricknätsmodell är väldigt högt och antalet korta sprickor är relativt sätt större än antalet stora sprickor. Det leder till ett stort antal block i 3DEC, varav några kan uppvisa komplex geometri. Den invecklade geometrin kan förhindra zonindelningen och därefter numerisk beräkning. Därför utformades testet i 3DEC som en belastningsförsök under ”2D” plant töjningstillstånd (plane strain). Den vidareutvecklade metodiken har validerats mot samma datauppsättning som användes för att kalibrera och validera ”UDEC” metodiken /Staub et al. 2002/. För att kunna uppskatta inverkan av plant töjningstillståndet på modellen utfördes jämförande simuleringar av ett riktigt 3D belastningsförsök.

Med hänsyn till de utvärderade jämförande simuleringarna har den uppdaterade teoretiska metodiken, baserad på 3DEC valts som verktyg för att svara på den teoretiska delen av den bergmekaniska platsbeskrivande modellen.

Genom att dela upp den rumsliga variationen i två delar, en del som beror på de geometriska egenskaperna hos spricksystemet och en del som beror på materialparametrarnas variation fås ett mer ändamålsinriktat förfarande att bestämma bergmassans egenskaper.

Contents

Symbols and abbreviations

c	cohesion of intact rock [MPa]
c_p	peak cohesion of fracture [MPa]
C-Y	Continuously-Yielding joint model
D	density [kg/m^3]
e_n	joint normal stiffness exponent
epsh	horizontal strain
epsv	vertical strain
epsx	strain in the X direction (horizontal)
epsy	strain in the Y direction (vertical)
epsz	strain in the Z direction
e_s	joint shear stiffness exponent
E	Young's modulus of the intact rock [GPa]
E_m	Young's modulus of the rock mass [GPa]
K_n	joint normal stiffness at expected normal stress [MPa/m]
K_s	joint shear stiffness at expected normal stress [MPa/m]
jr	material parameter for joint roughness [m]
Max K_n	maximum value of joint normal stiffness [MPa/m]
Max K_s	maximum value of joint shear stiffness [MPa/m]
sigma y	vertical stress [MPa]
$\Delta\sigma_y$	increment in stress along y-axis [MPa]
ε_x	strain in the X direction (horizontal)
ε_y	strain in the Y direction (vertical)
ϕ	fracture friction angle, total [°]
ϕ_i	fracture intrinsic friction angle [°]
$\phi_m^{(i)}$	fracture initial friction angle [°]
ν	Poisson's ratio of the intact rock
ν_m	Poisson's ratio of the rock mass
σ_t	tensile strength of fracture [MPa]
σ_{vmax}	maximal vertical stress [MPa]
τ	tensile shear strength [MPa]

1 Introduction

In the frame of SKB's site investigations a methodology for the establishment of the Rock Mechanics Site Descriptive Model has been developed. The results of the theoretical and numerical approach are presented in /Staub et al. 2002/.

The work presented in this report is a follow-up and further development of the numerical approach for the Rock Mechanics Site Descriptive Model. The aim of this activity is to improve the previous methodology in order to overcome the encountered problems and limitations. One of the problems that were encountered was that the automatic block generation procedure in UDEC does not include fractures ending inside blocks. A further comparison with 3D modelling was also recommended.

2 Presentation of the methodology

The Rock Mechanics Site Descriptive Model shall describe the initial stresses and the distribution of rock mechanical properties such as deformation and strength properties for the intact rock, for the fractures, for the deformation zones, and for the rock mass viewed as a unit consisting of intact rock and fractures. The evaluation of these properties can be achieved through the application of empirical relationships or by a theoretical approach based on numerical modelling. The methodology was developed in the purpose of characterising the mechanical properties of the rock mass, in any of the potential site, see /Andersson et al. 2002; Staub et al. 2002; Röshoff et al. 2002; Hakami et al. 2002/.

2.1 The theoretical approach in UDEC

The basis of the theoretical approach is to determine the mechanical properties by numerical modelling and using known parameters of the rock, i.e. fracture geometry, and mechanical properties for the intact rock and for the fractures, see /Staub et al. 2002/. The first task was to develop the methodology to use for modelling the rock mass behaviour. Then this methodology was applied in a "Test Case" on a limited set of real input data.

The input data must consider the fracture geometry, as well as mechanical properties of intact rock and fractures. Fracture geometry is often really complex and presents a non-linear spatial variability. This issue was handled by numerical stochastic modelling. Statistical data on fractures were used as input to simulate a three-dimensional Discrete Fracture Network (DFN) in the FracMan software. The numerical modelling was accomplished by using the two-dimensional code UDEC, and the rock block models were generated from 2D trace sections extracted from the 3D DFN model.

The numerical model was set-up to simulate a plane strain-loading test. Vertical and horizontal displacements, and vertical stresses were monitored during loading and used for the interpretation of deformation and strength properties. Different boundary conditions were applied on the model for simulating stress conditions (I) in the undisturbed rock mass, and (II) at the proximity of a tunnel.

The methodology was tested on a limited set of data coming from the Äspö Hard Rock Laboratory. Input data for the fracture network were mainly provided by tunnel mapping, input data for mechanical properties of intact rock and fractures were coming from results of laboratory tests conducted on core samples from 3 boreholes.

First, one model was run on one defined rock type to assess the influence of variation of input parameters on the outcome of the model, and refine the input parameters as interpreted from laboratory tests. The mechanical properties of the rock mass were evaluated for rock block models constituted of a homogeneous rock type. However, the geology in the "rock type" is most often composed of a combination of these different rock types. The determination of the mechanical properties of such mixture of rocks was achieved by means of Monte Carlo simulations from results obtained on homogeneous models. Special models were run for the determination of mechanical properties in deformation zones.

The theoretical methodology is reported in detail in /Staub et al. 2002/. The outcome of the Test Case are discussed and analysed in /Hudson (ed), 2002/, as part of the Rock Mechanical Site Descriptive Model.

2.2 Shortcomings of the UDEC approach

The methodology as established and tested in UDEC presented some limitations impeded to the software:

1. Generation of rock blocks. Quite many fractures are discarded or "shortened" when generating rock blocks by the process of meshing. As a matter of fact only fractures intersecting other elements (fractures or box boundary) at both ends are included in the process of generating the rock block model. This implies that fractures that do not intersect at all the box boundary or another fractures, and fractures that terminate in the rock, are discarded. This might lead to a distorted representation of the fracture network and to an overestimation of the rock mass parameters. To overcome this problem in UDEC all fractures extracted from the DFN model had to be manually prolonged so that they should intersect the box boundary or another fracture at both ends.
2. The prolonged sections of fractures can not be treated as real fractures when simulating. Hence sections of fractures that are real and fictitious must be identified and different mechanical properties must be assigned. The standard UDEC commands used for assigning mechanical properties to fractures do not work on statistical fracture networks, and some specific files must be written to determine a range along the fracture. It appears that the process of meshing can slightly move fractures at proximity of element nodes. Hence each model has to be checked in order to control that all fractures had been assigned mechanical properties. This process is highly time-consuming and not applicable during the Site Investigation programme.

3 Investigation for improvement of the methodology

The problems encountered during the Test Case enlightened the needs to improve the methodology, and specially automate the generation of rock block models from DFN models. Two main approaches might be undertaken: 1) the problems are solved in UDEC; or 2) another numerical code is used for determining the mechanical properties of the rock mass.

Regarding the nature of the problems and limitations encountered in UDEC the implementation of the methodology with an other numerical software appeared to be the most time-effective and promising solution.

3.1 Selection of the numerical software

Relying on the experience of UDEC and taking into account the numerical simulation programmes that are available for mechanical simulations two main softwares were thinkable:

- The 2D numerical code Fracod (FRACOM); the assets of this code might be also to consider propagation of fractures during the normal loading test.
- The 3D numerical code 3DEC (Itasca); recent developments and applications proved that the code might be suitable for generating rock block models from Discrete Fracture Network. Moreover developing the model in 3DEC provides a tool to run 3D simulations of the rock mass and to estimate the anisotropy.

Preliminary investigations and tests conducted with Fracod showed that the programme is actually not capable to handle the amount of fractures generated from the DFN model. The efforts needed to develop and adapt the programme for the purposes of this methodology were estimated too large to be worthwhile.

However the latest 3DEC version offered new possibilities. Some modules and functions have been developed in 3DEC version 3.0 that can overcome the shortcomings listed in section 2.2:

- Problems of discarded fractures (issue 1, section 2.2). By default the joints are also generated through the all model cube. However the commands HIDE and FIND available in 3DEC can help controlling the continuity of fractures /3DEC, 2003/. Based on these commands a FISH function has been written that limits the cuts only to the blocks that are intersected by the joint of a given radius /Damjanac, 2003/.
- Problems of assigning mechanical properties to fractures (issue 2, section 2.2). The 3DEC cut planes are still larger than the real fractures, meaning that we still have to deal with fictitious joints. A special function was written in order to assign different mechanical properties to different parts of the generated cut plane in 3DEC depending on the real fracture radius /Damjanac, 2003/. This implies that information is available when importing data in 3DEC.

3.2 Preliminary tests with 3DEC

Some preliminary tests were conducted on more or less complex fracture networks in 3DEC and illustrated that numerical simulations in 3D on rock blocks formed by a hundred of fractures are too time-consuming to be considered a standard solution for the site investigations. Moreover the high amount of fractures imported results in a complex geometrical network. Some realisations might not work as displacements and deformations of the blocks are too important. In some cases it is not even possible to execute the zoning of the model as the geometry of the blocks is to complex to be handled by 3DEC.

As a consequence a "simplified" 3D model has been developed. The model is built in a way to simulate conditions of a 2D plane strain test thus making numerical simulations quite similar to what was achieved with UDEC. The size of the alternative model is still 30×30 m in the XY plane but the width of the model in the Z direction is limited to 1 m. Moreover fractures were also generated from their traces as determined on a sampling plane, see /Staub et al. 2002/, but were extended perpendicularly to the XY plane.

4 Description of the implemented methodology

4.1 The 3DEC box region

The box region is 30×30×1 m which can be compared to a UDEC section with a 1 m thickness in the out of plane direction (Figure 4-1). The orientation of the 3DEC local model will be chosen in order to get sides parallel to the principal stresses. The model can be rotated in order to check the influence of the fracture pattern in the three directions of principal stresses.

4.2 Generation of fractures

The numerical model is aimed to simulate and represent the rock mass as identified in the site investigation area. The geological Site Descriptive model, composed of the deformation zones model, the rock domains model and the DFN model, constitutes the main information for the definition of the geometry of the mechanical numerical model.

The geometry of fractures is described by a Discrete Fracture Network which is generated in 3D. In the frame of the Site Investigations different DFN models might be defined in order to reflect the geological and structural heterogeneity of the rock mass. These should also be simulated in the rock mechanics model if their influence on the rock mass mechanical properties is estimated significant.

The different DFN models are then generated in FracMan. 20 Monte-Carlo simulations of the same DFN model are realised in order to catch the spatial variability and uncertainty of fracture orientation, fracture size distribution and fracture intensity. The DFN model is generated in a box which is larger than the 3DEC domain in order to avoid boundary effects when generating the fractures.

The 2D fracture traces required for the geometry of 3DEC are extracted on vertical sampling planes parallel to the principal stress(es). The 2D data are extrapolated to 3D by keeping constant the same orientation in the Z direction. The radius of the fracture is determined from the trace length given in the 2D fracture file.

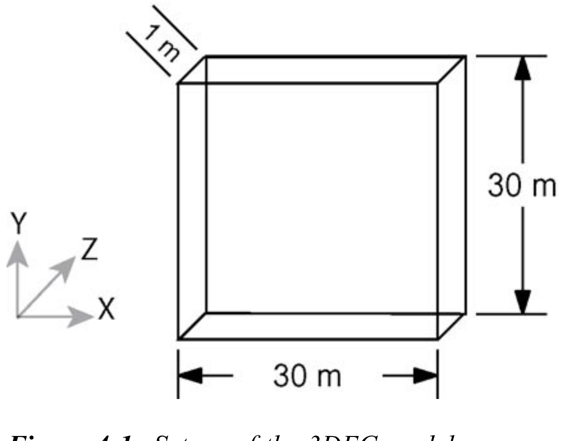

Figure 4-1. *Set-up of the 3DEC model.*

A special FISH function can be used in 3DEC version 3.00 to generate fractures according to their radius.

The basic structure in 3DEC is to generate fractures through a block, which means that the first fracture has to cut through the entire block model. When dealing with a stochastic fracture model representative of fracture size distribution and orientation in the rock mass the amount of generated fractures can increase very fast. This results in a very large amount of blocks in the 3DEC model. Nevertheless using the commands HIDE and FIND it is possible to control the extension of the fracture and limits its generation based to its radius to one or several identified blocks in the model. In order to automate the process an algorithm is written that looks in the model for the blocks that are cut by the next fracture. All other blocks are hidden, and the extension of the fracture is limited to the visible blocks of the model. Before to go to next fracture all blocks are activated and made visible.

Most often the fractures generated in 3DEC are still larger than the given radius but all fractures do not cut through the all model. This enables to decrease the amount of blocks in the model and to build a more time-effective model. In order to optimise this process the fractures are sorted by radius and the larger ones are generated first.

4.3 Definition of boundary conditions

The boundary conditions are of two types, velocity and stress. The boundary conditions are related to the type of simulated test. The boundary conditions presented in this section are set for a "2D" plane strain test.

4.3.1 Stress boundaries

The stress boundaries are applied to reflect the in situ stress field. The values can be adjusted to take into account variations with depth or with "rock domain".

In situ stresses are applied on the 6 sides of the model and only normal stresses are used as the model is oriented perpendicularly to the principal stresses (Figure 4-2).

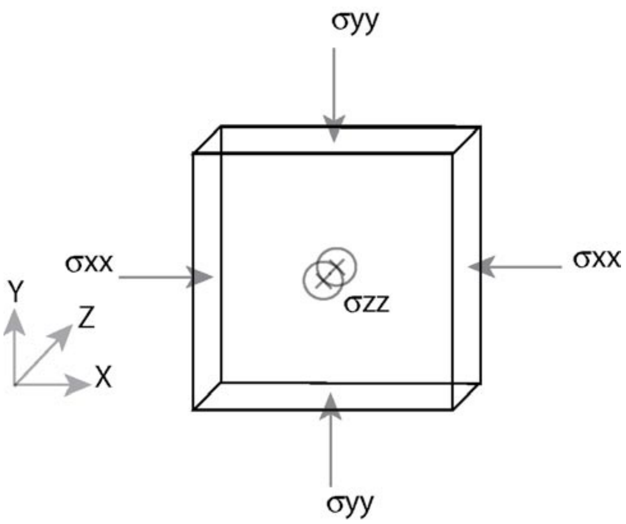

Figure 4-2. *Set of stress boundaries applied to the model.*

A linear gradient is applied on the vertical stress in the vertical direction. Before starting the load test the model is run into equilibrium with the in situ stresses.

In order to simulate the plane strain loading test confining stresses must be applied on the vertical faces of the model, which are consistent to the in situ stresses.

4.3.2 Velocity boundaries

Two types of velocity boundaries are defined: zero velocity and constant velocity. They are applied as follows:

- The zero velocity is used for locking the model in one or two directions. Vertical displacement is disabled on the bottom face of the model during applying the in situ stresses. Horizontal displacements in the Z-direction and X-direction are disabled in the centre of the bottom and upper faces of the model. Horizontal displacements in the Z-direction are disabled on both XY vertical planes of the model (Figure 4-3).
- The constant velocity is applied on the horizontal boundaries for simulating loading during the "2D" plane-strain test. The loading velocity is a function of the model size and is defined as modelsize*12e-5 (Figure 4-4).

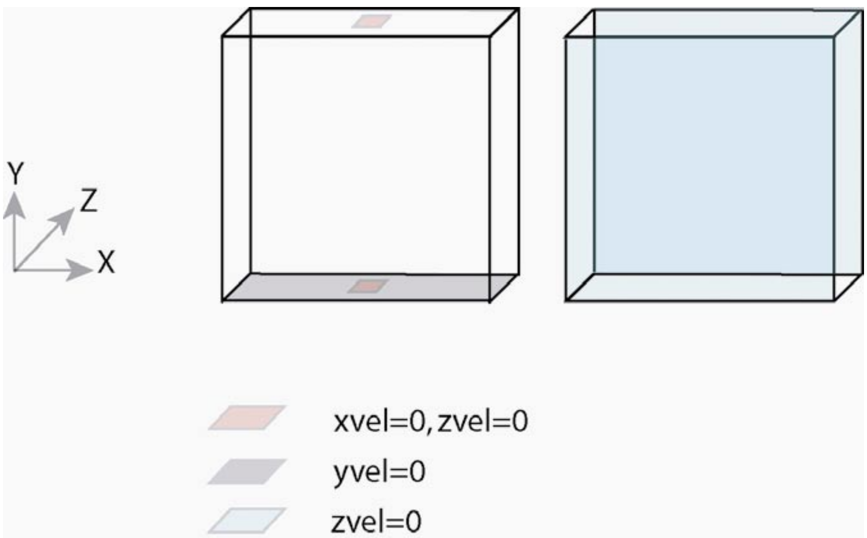

Figure 4-3. *Set of zero velocity boundaries applied to the model before loading.*

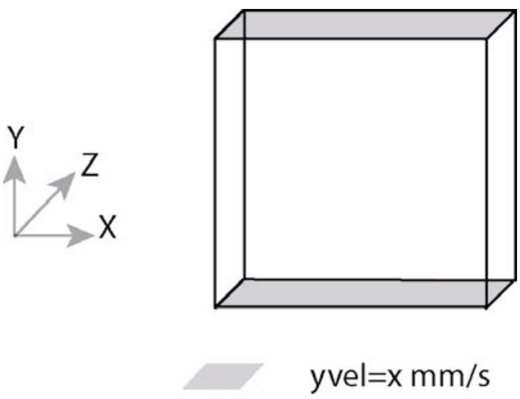

Figure 4-4. *Set of constant velocity boundaries applied during the "2D" plane strain test.*

4.3.3 Assignment of properties to the fractures

An algorithm based on contacts and sub-contacts between the blocks in the model is run for assigning mechanical properties to the fractures. The module is written such as all contacts and sub-contacts identified outside of the real fracture area are assigned specific properties for fictitious joints. For the contacts and sub-contacts identified inside the real fracture area the real mechanical properties of the fractures are assigned (Figure 4-5).

Different numbers are defined in the algorithm file in order to identify the different groups of properties. At that time up to 5 different mechanical properties can be assigned to real fractures in the model.

Depending on the geological analysis and mechanical signification of the different sets and minerals, fracture group might be defined according to different criteria (fracture set, mineralization group,…). Each fracture group is identified by a specific material identification number associated to specific mechanical parameters.

The process of defining fracture group has to be undertaken in connection with geologists. Appropriate mechanical properties for fractures are evaluated from laboratory tests.

The properties assigned to the fictitious joints are related to the mechanical properties of the intact rock in order to minimise the influence of these fractures on the model.

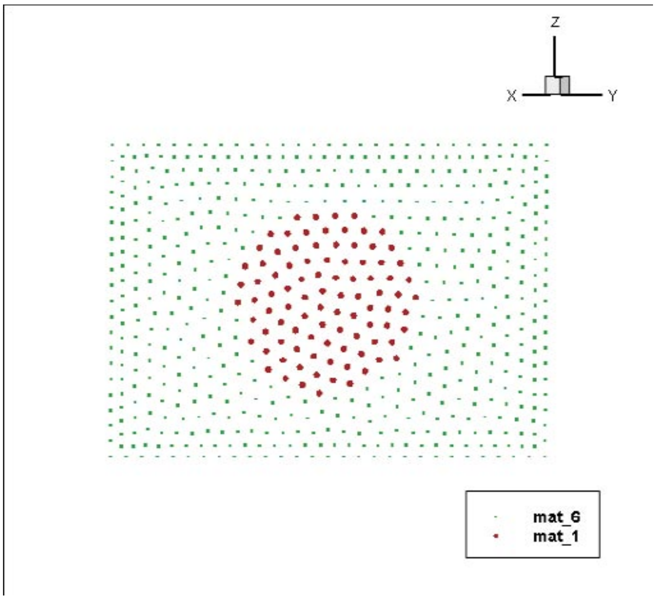

Figure 4-5. Illustration of the assignment of properties on a fracture; mat_1 is for the real fracture, mat_6 is outside the real fracture area.

4.4 The computations

Before starting the load test the in situ stresses are applied and the model is run into equilibrium.

The mechanical plane strain test is simulated by a vertical loading applied on both horizontal sides of the model at constant velocity. Horizontal displacements in X and Z directions are not allowed along these 2 faces (Figure 4-6). The constant velocity is applied during a specified number of computational cycles. Even if the stress boundary conditions are such that the model is in an initial force-equilibrium state before alteration, the equilibrium state is checked before performing the vertical loading.

The vertical loading is applied to the model beyond the elastic behaviour of the rock material and fractures.

Deformation and stresses are monitored in the model during loading. Sampling lines are defined along the vertical and horizontal borders of the domain in the XY plane (Figure 4-7). The measurement sections are located in the centre of the model in the Z direction. Deformation and stress are monitored at vertices distributed regularly along

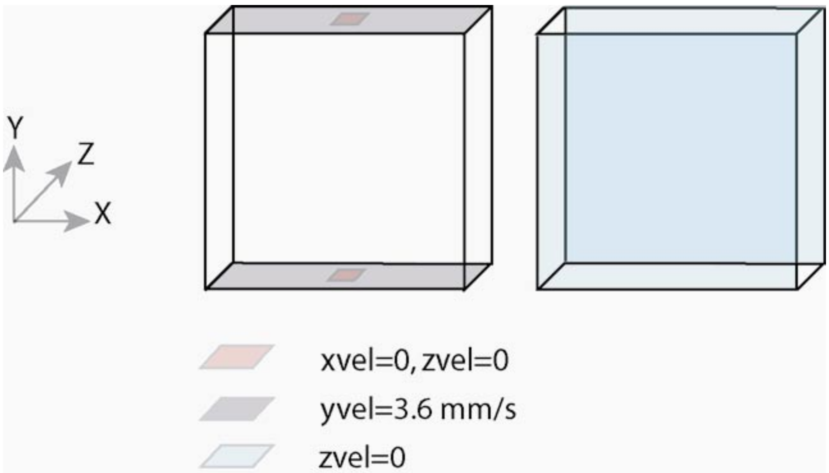

Figure 4-6. *Velocity boundary conditions applied during loading.*

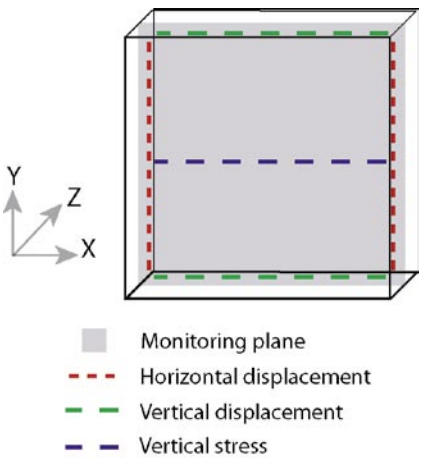

Figure 4-7. *Illustration of the monitoring plane and the monitoring plines.*

the measurement profile. The values are collected at the vertex nearest to the given point coordinates for horizontal and vertical deformation or at the zone nearest to the given point coordinates for vertical stresses. The amount of points is related to the model size.

The mean of the values obtained at each point along each profile are calculated at each loading stage, thus obtaining horizontal and vertical deformation as well as stress increase in the model during the loading test. The strain in both directions, ε_x and ε_y, is also calculated at each loading stage.

The Poisson's ratio and deformation's modulus of the rock mass are calculated according to the following equations:

$$\nu_m = \frac{1}{1 + \varepsilon_y / \varepsilon_x} \tag{1}$$

$$E_m = \left(1 - \nu_m^2\right) \cdot \Delta\sigma_y \cdot 1 / \varepsilon_y \tag{2}$$

Equations (1) and (2) are derived from Hooke´s law for plane strain loading. The monitored stress and calculated strain are plotted in order to evaluate the deformation's modulus, Poisson's ratio and the maximal vertical stress at failure of the rock mass. When evaluating the Poisson's ratio and the deformation's modulus of the rock mass, the initial linear part of the recorded curves is used, see Figure 4-8.

The maximal vertical stress at failure is evaluated from the intersection of the best fit curves on both sides of the breakpoint of the vertical strain/vertical stress curve (Figure 4-9).

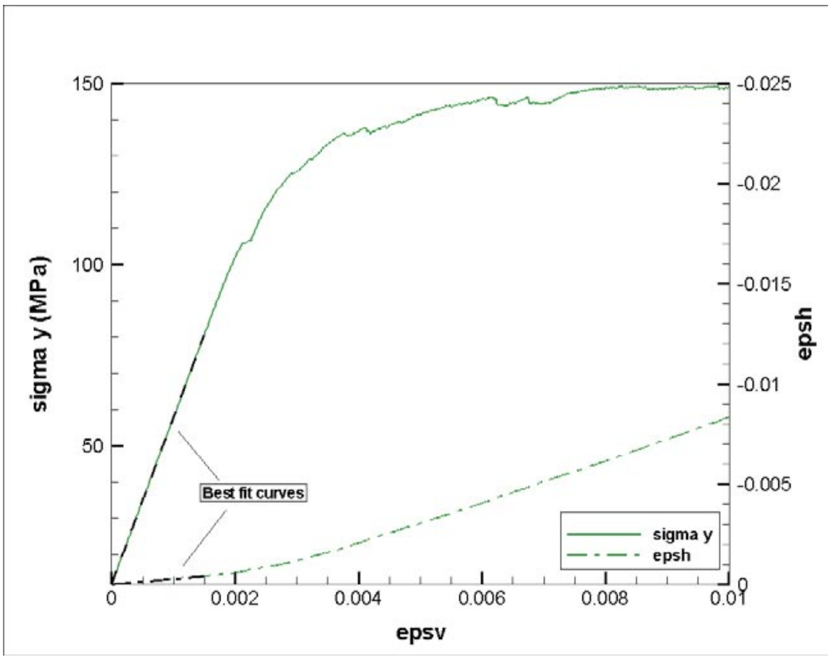

Figure 4-8. *Evaluation of the deformation's modulus and the Poisson's ratio.*

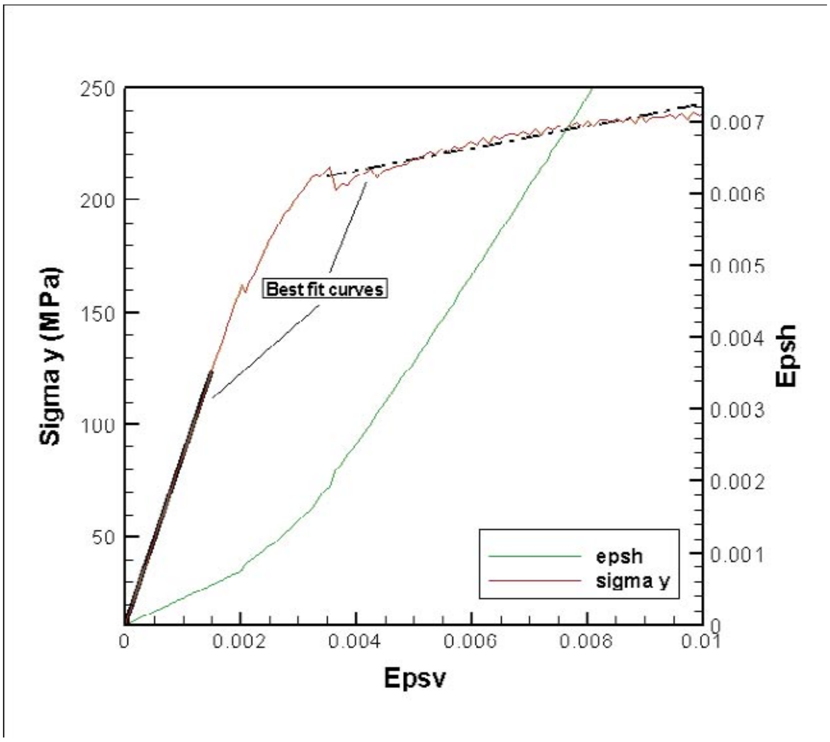

Figure 4-9. *Evaluation of the maximal vertical stress at failure.*

5 Comparison 3DEC/UDEC

The 3DEC model was calibrated against the UDEC model as presented in /Staub et al. 2002/. The aim is to validate the outcome of the rock mechanical model as implemented in 3DEC.

5.1 Generation of the model

5.1.1 The rock block model

The DFN model used for the comparison is based on information collected in the Zedex tunnel in the Äspö Hard Rock Laboratory, /Hermansson et al. 1998/. Table 5-1 presents a summary of the parameters used for the generation of the fracture network. The fracture radius distribution is assumed to follow a lognormal distribution.

Based on these parameters several realisations of the geometrical network of fractures are generated in 3D. The fracture traces used as input to the UDEC model had been extracted along sampling planes parallel to the principal stresses.

For the comparison test one realisation of the DFN model was selected. The results of this model are already available for the UDEC numerical code. The same 2D fracture trace file is used for the preliminary 3DEC model. The fractures have been extended in the Z direction perpendicularly to the XY section plane.

Figure 5-1 is an illustration of the fracture traces extracted on a 2D plane from the 3D DFN model. Figure 5-2 presents the rock block models generated from this trace file both in UDEC and 3DEC. The same fracture traces are used as input to both UDEC and 3DEC simulations.

Table 5-1. Fracture data for DFN model.

	Pole to fracture plane			Size, m		P_{32}, m^2/m^3
	Dip direction, °	Dip, °	Fisher coefficient	Mean	Std dev.	
Set 1	348.2	4.2	8.69	0.25	0.25	0.40
Set 2	46.4	7.4	10.50	0.50	0.25	0.87
Set 3	142.8	63.7	8.99	0.25	0.25	0.40

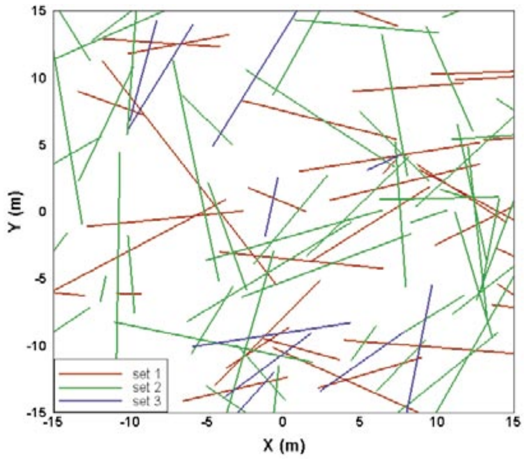

Figure 5-1. *2D fracture traces extracted from the DFN model with differentiation of the 3 fracture sets.*

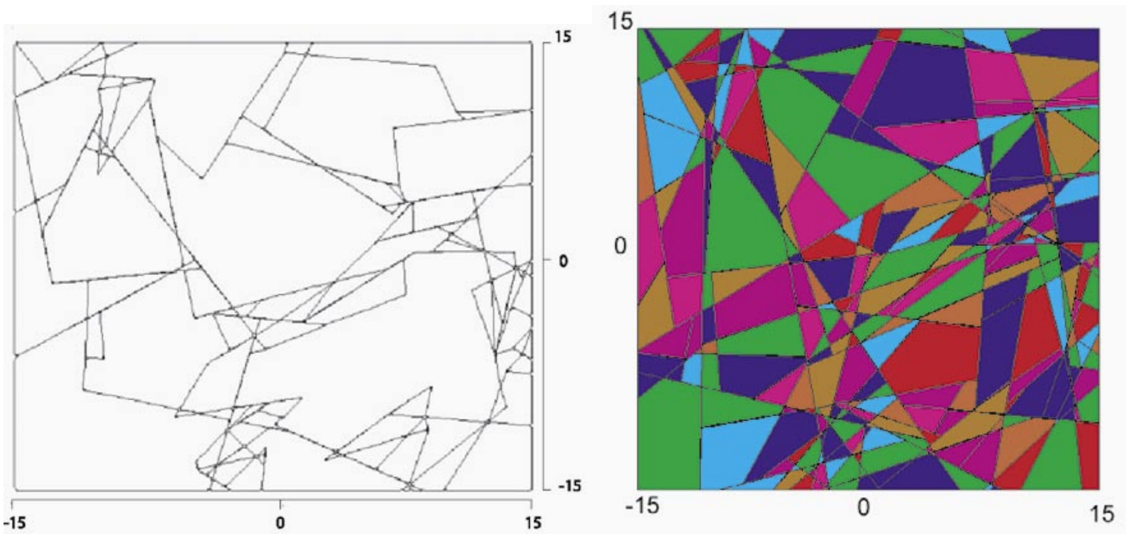

Figure 5-2. *The UDEC and 3DEC rock block model obtained from the same fracture trace. View in the XY vertical plane.*

5.1.2 In situ stresses and boundary conditions

The magnitude and orientation of the in situ field stresses for the comparison purposes are presented in Table 5-2. The magnitude of the stresses is given for a depth of –470 to –500 m. The evaluation of the stress tensor is presented in /Hakami et al. 2002/.

The confining stresses applied to the model are consistent to the in situ stress field.

Table 5-2. Principal stress magnitude and orientation.

	Magnitude, MPa	UDEC,	3DEC,
σ_1	22.4	Horizontal,	Horizontal, x-direction
σ_2	13.1	Out-of plane	Horizontal, z-direction
σ_3	11.7	Vertical	Vertical

5.1.3 Mechanical properties

Mechanical properties of intact rock

Tests in the Test Case had been conducted on 4 different rock types commonly mapped in the Äspö HRL. Only the diorite which is the most abundant rock in the area is considered in this section. The Mohr-Coulomb plasticity block model is used to specify the intact rock behaviour. The mechanical properties used for the simulations are summarized in Table 5-3.

Mechanical properties of fractures

The Barton-Bandis joint constitutive model was mainly used in the precedent methodology /Staub et al. 2002/. Some sensitivity analyses and comparisons were conducted applying the Continuously-Yielding joint constitutive model.

The Barton-Bandis joint constitutive model is not implemented in 3DEC. However, a similar model, the Continuously-Yielding joint constitutive model, is available. This model too is estimated to provide an appropriate description of the behaviour of the joints, accounting for the increase of stiffness with stress. Therefore this model has been used for the verification tests in 3DEC.

Due to limitations in the 2D numerical model presented in /Staub et al. 2002/ the same parameters were assigned to the three sets of fractures. In order to limit the divergences between the two models, the same mechanical parameters were applied to all fracture sets also in 3DEC. The input parameters are summarized in Table 5-4.

As mentioned in section 4.3.3 sections of the fractures generated in the model are considered to be fictitious. Specific mechanical properties must be assigned to these sections of "fractures" that are related to the properties of the intact rock. Table 5-5 presents the mechanical properties assigned to fictitious joints in this case. The Coulomb-slip joint constitutive model is chosen to simulate the behaviour of these "fractures".

Table 5-3. Mechanical properties of the diorite, input to the M-C rock model.

Density, kg/m³	Young's modulus, GPa	Poisson's ratio	Friction angle, °	Cohesion, MPa	Dilation angle, °	Tensile strength, MPa
2,750	73	0.27	49	31	0	14.8

Table 5-4. Mechanical properties of real fractures, input to the C-Y joint constitutive model.

Kn, MPa/mm	en	Max Kn, MPa/mm	Ks, MPa/mm	es	Max Ks, MPa/mm	$\phi_m^{(i)}$, °	ϕ_i, °	jr, m
10.4e3	0.46	44e3	5.7e3	0.53	30e3	35	40	0.002

Table 5-5. Mechanical properties of fictitious fractures, input to the Coulomb-slip joint constitutive model.

	Kn, MPa/mm	Ks, MPa/mm	ϕ, °	C_p, MPa	σ_t, MPa
Fictitious joints	321.1e4	29.2e4	49	31	14.8

Even if all fracture sets possess the same mechanical properties in the comparison test, the different group numbers are kept and illustrate how 3DEC deals with different groups of fractures when assigning mechanical properties. Figure 5-3 illustrates how mechanical properties are assigned to fractures with consideration to their expected radius (process described in section 4.3.3). This sketch can be compared to Figure 5-2 which represents the original fracture traces.

Figure 5-4 represents the contacts located beyond the fracture area. Properties for fictitious joints are assigned to these contacts.

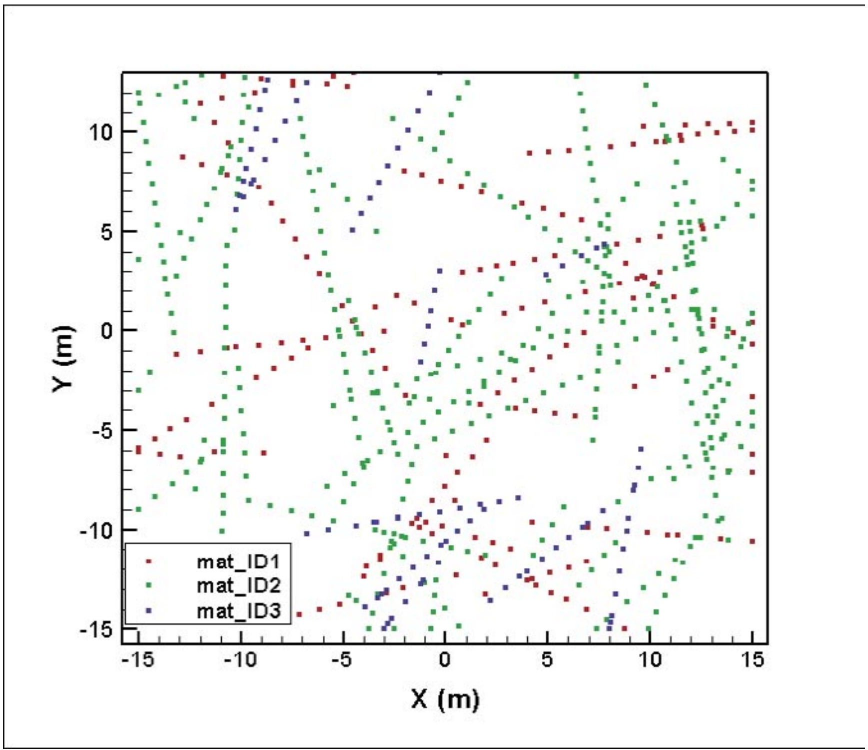

Figure 5-3. *Identification of the material number assigned to contacts in the model; mat_1 to mat_3 represent the properties assigned to different sets of fractures (in this case the properties are the same).*

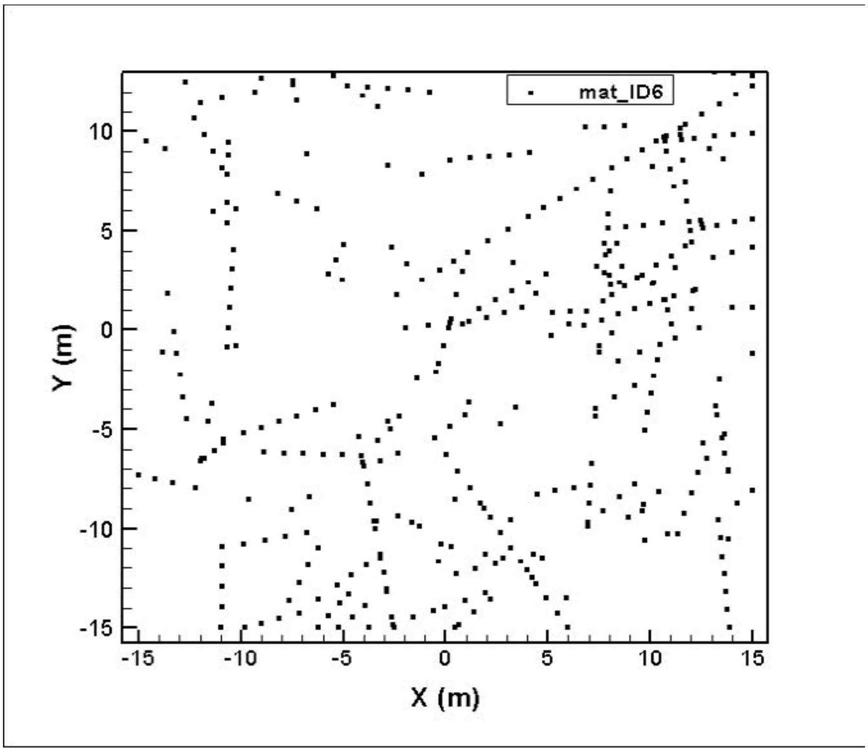

Figure 5-4. Visualisation of the contacts identified beyond the fracture radius.

5.1.4 Results

Different parameters were plotted at the end of the loading test in order to illustrate the deformation of the rock during loading: displacement vectors (Figure 5-5) and indication of failures in the rock (Figure 5-6). These figures illustrate the complexity of the deformation in the rock mass due to the complex fracture network.

Figure 5-7 illustrates the strain calculated in x and y direction as well as the vertical stress increase measured during loading. The evaluated mechanical parameters are presented in Table 5-6. The results illustrate that the deformation modulus (and in some extent the Poisson's ratio) is quite insensitive to the methodology used. However the maximal vertical stress is about 35% lower in the 3DEC model than in the UDEC model.

The differences observed between both models might be due to the farther more complex geometrical network generated in 3DEC (by retaining all fractures when generating blocks), see Figure 5-2.

Table 5-6. Comparison 3DEC/UDEC mechanical parameters for a 30 m model.

Case	E_m, GPa	ν_m	σ_{vmax}, MPa
3DEC A19_30	43.46	0.21	135.64
UDEC A19_30	44.31	0.25	185.69

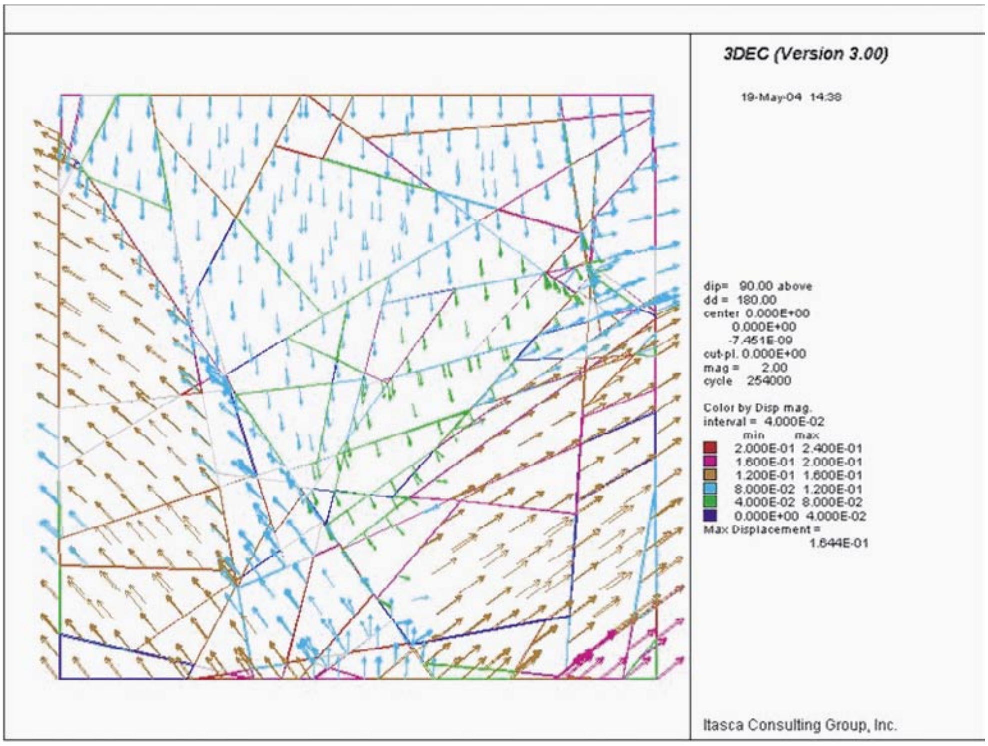

Figure 5-5. *Displacements monitored during plane strain testing of the case 19_30m.*

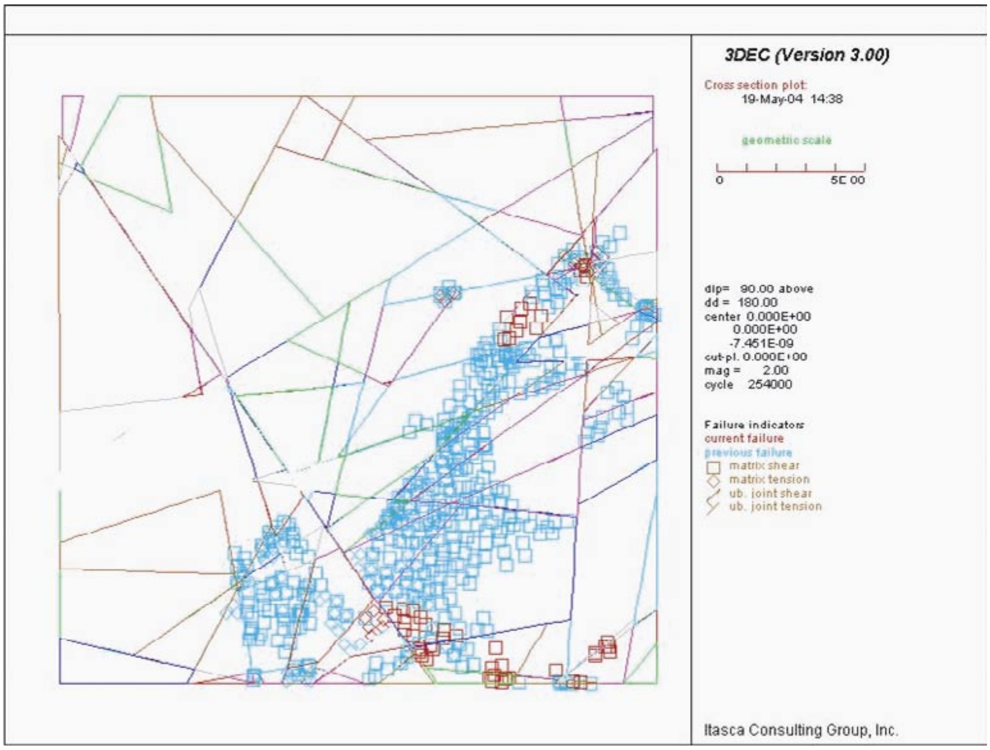

Figure 5-6. *Indications of failure (shear and tension) monitored during plane strain testing of the case 19_30m.*

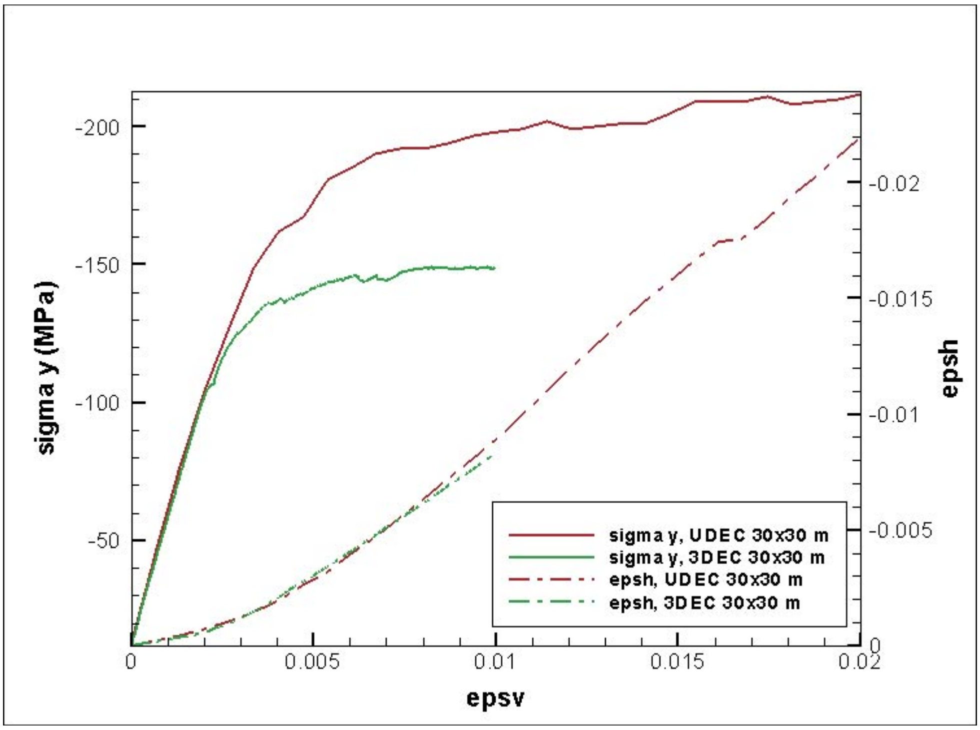

Figure 5-7. *Stress-strain curves for the 3DEC and UDEC 30×30 m model.*

5.2 Influence of model size

As had been done with UDEC smaller model sizes built on the same fracture trace data have been simulated. Figure 5-8 and Figure 5-9 illustrate the fracture geometry used as input for the 10×10 and 20×20 m 3DEC models. This geometry is extracted from the fracture geometry illustrated in Figure 5-2 for the 30×30 m model.

Looking at these patterns illustrate clearly that the size of the model will influence on the fracture intensity and therefore on the amount of blocks generated in 3DEC.

The same procedure as described in section 5 was used for the simulations. Figure 5-10 and Figure 5-11 illustrate the displacements and indications of failures monitored on the 10×10 m model.

These plots, and their comparison to Figure 5-6 and Figure 5-7, illustrate clearly the implication of the density and spatial disposition of fractures on the behaviours of the rock block model.

Figure 5-12 presents the strain and stress curves obtained for the 10×10 and 20×20 m model, as well as the curves presented previously for the 30×30 m model for comparison.

Table 5-7 presents the evaluated parameters for the rock mass for different model sizes. The figures presented in the table illustrate decreasing values for the rock mass with decreasing model size.

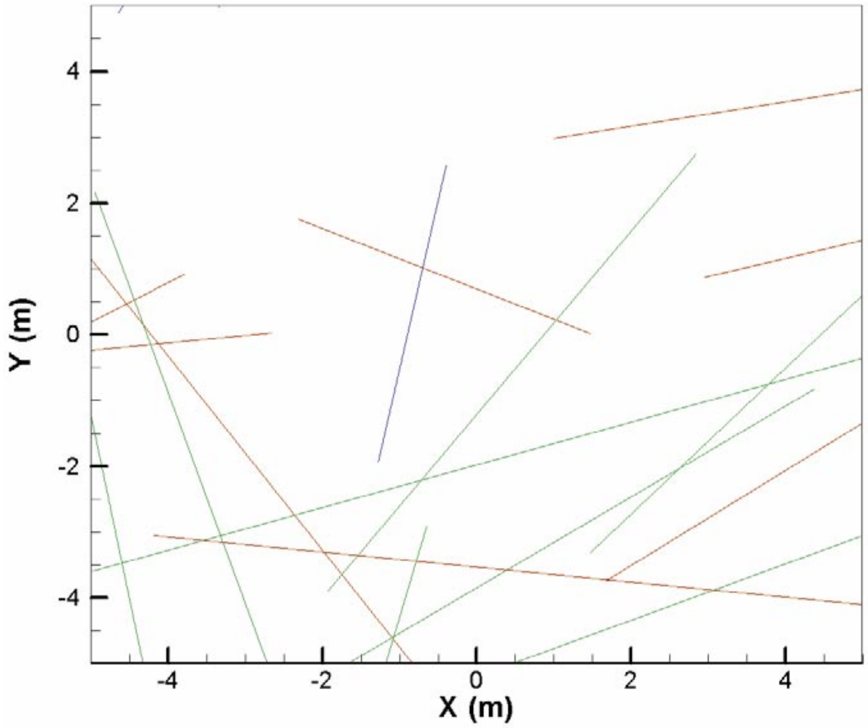

Figure 5-8. Fracture traces used for the 3DEC 10×10 m model.

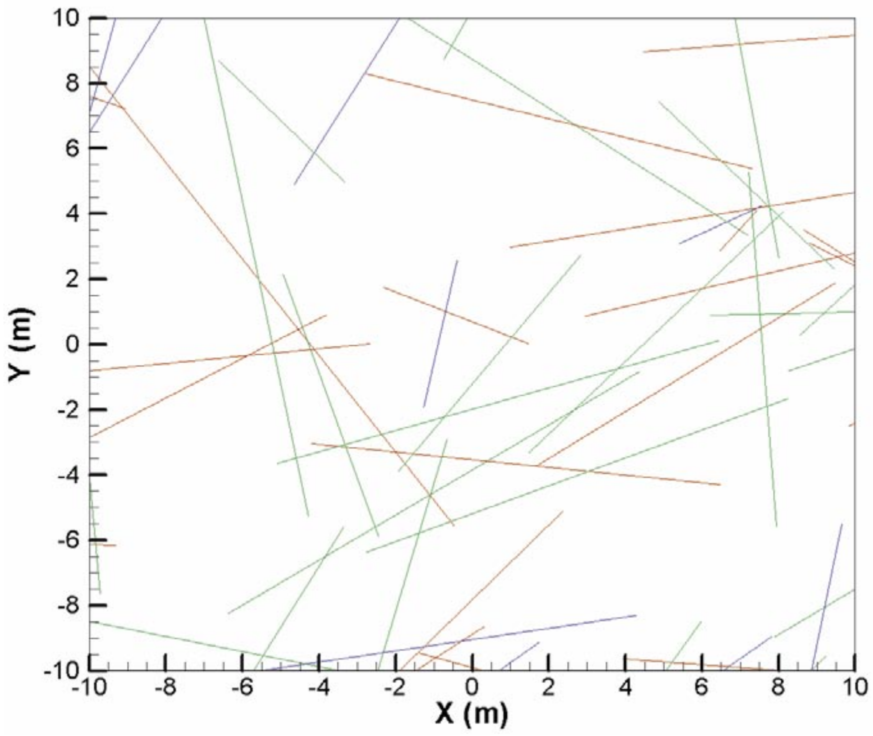

Figure 5-9. Fracture traces used for the 3DEC 20×20 m model.

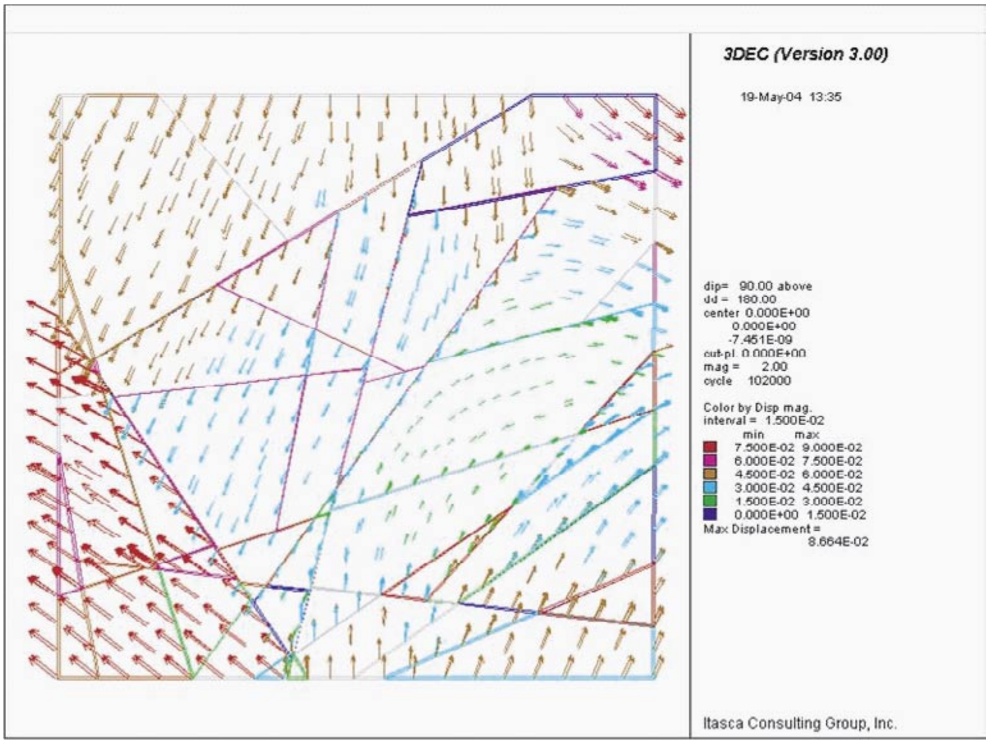

Figure 5-10. *Deformation and displacements monitored during plane strain testing of the case 19_10m.*

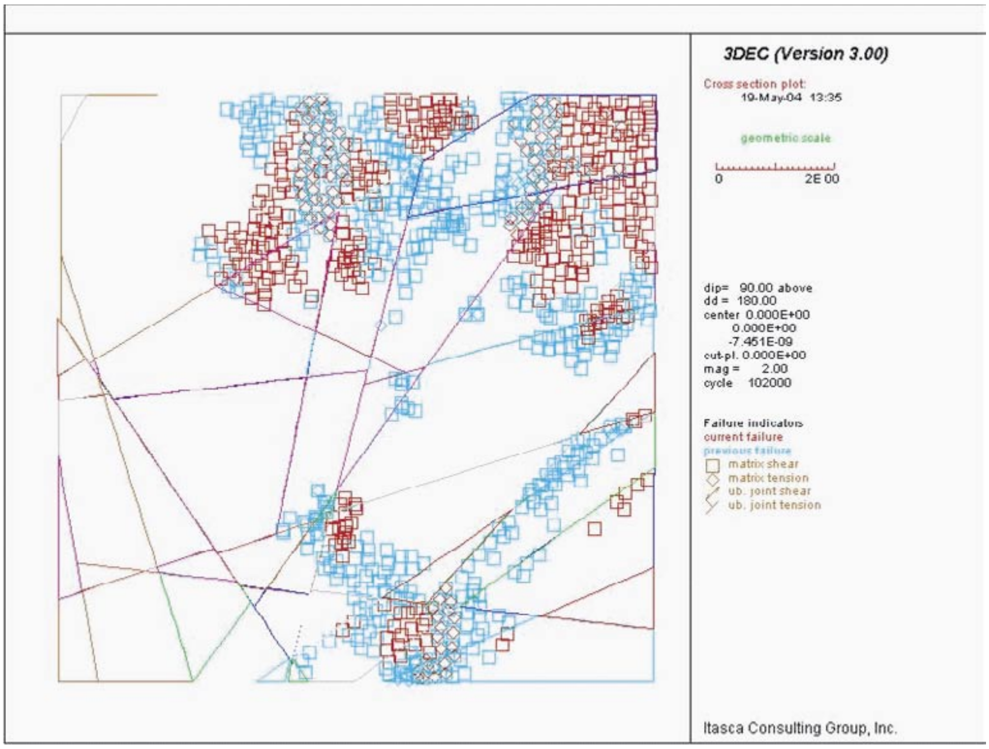

Figure 5-11. *Indications of failure (shear and tension) monitored during plane strain testing of the case 19_10m.*

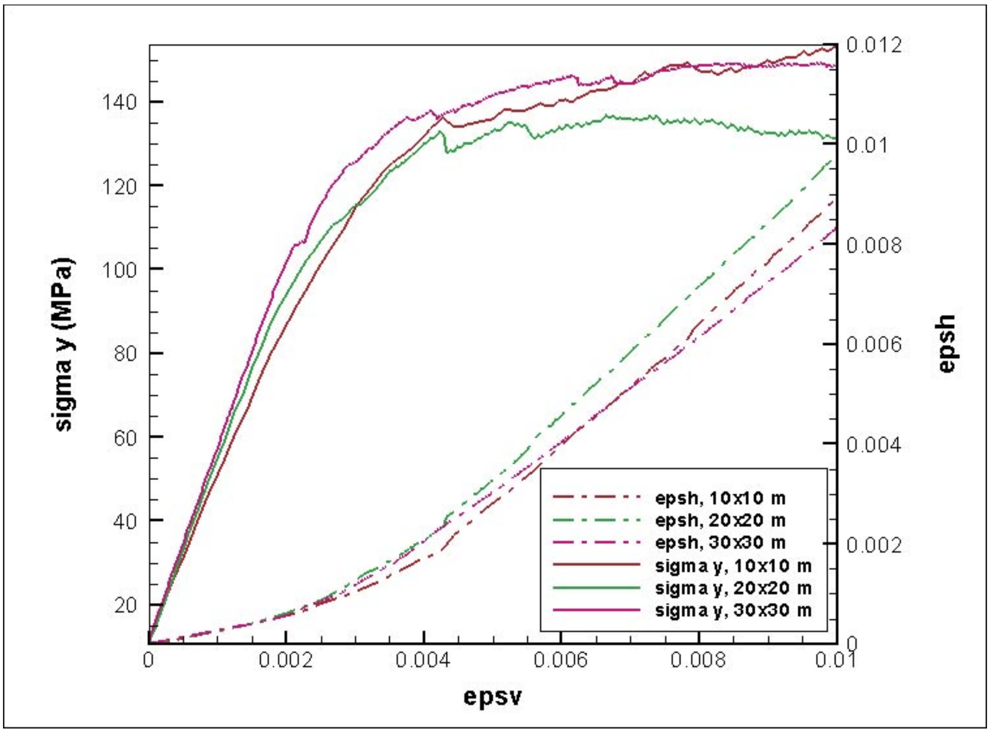

Figure 5-12. *Stress-strain curves for three different sizes of the 3DEC model.*

Table 5-7. Rock mass parameters obtained for different model sizes in 3DEC.

Case	E_m, GPa	ν_m	σ_{vmax}, MPa
3DEC A19_10	36.67	0.22	130.77
3DEC A19_20	41.30	0.22	132.38
3DEC A19_30	43.46	0.21	135.64

Table 5-8. Rock mass deformation properties and principal stress at failure for different model sizes tested in UDEC.

Case	E_m, GPa	ν_m	σ_{vmax}, MPa
UDEC A13_20	43	0.28	193.5
UDEC A13_30	47.3	0.27	189.4
UDEC A13_40	47.2	0.26	168.7
UDEC A13_60	44.3	0.26	167.3

The decrease in rock mass mechanical parameters observed is most significant for the deformation's modulus than for the principal vertical stress at failure.

Similar analyses conducted in UDEC on one fracture model extracted at different model sizes could not enlighten such a trend, see Table 5-8 and /Staub et al. 2002/. These tests had also been conducted applying the Continuously-Yielding joint constitutive model.

For the 3DEC models the maximal vertical stress at failure increases with the model size while it shows the opposite trend in the UDEC model.

6 3D simulations

In order to validate the assumptions made for the 2D plane strain model run in 3DEC and to quantify the eventual overestimation of the deformation's modulus some comparisons were made by running a real 3D model.

First computations simulating the intact rock have been conducted. These were done in order to check the algorithms and the conceptual model in plane strain conditions and in 3D. Then simulations on a rock block model generated from a stochastic fracture network were conducted. Due to problems in executing the zoning of the model for blocks with complex geometry, the fracture network used as input in 3DEC has been limited to 18 fractures in a 10×10×10 m block.

6.1.1 Short description of the 3D loading test

The procedure is basically the same as described for the "2D" plane strain test in 3DEC with some exceptions:

- Real orientation of fractures is used for generating the 3D rock block model. The real orientation of fractures is also the input for the "2D" plane strain model used for the comparison purpose. However the width of the model for plane strain is so restricted (0.5 m) that the influence of the real orientation compared to the process described in section 4 is estimated to be negligible.
- The monitoring points for measuring deformation and stresses during loading are scattered on the surfaces of the block model (see section 4.4 for comparison with the conditions in the "2D" plane strain test). However the same procedure is used to obtain data at each gridpoint and obtain the mean value at each stage for the different surfaces.
- Preliminary simulations showed that the software could not handle the contrast of mechanical properties assigned to real and fictitious fracture as listed in Table 5-4 and Table 5-5. The normal and shear stiffness of the real fractures had to be modified.
- The Poisson's ratio is equivalent to $\varepsilon_h/\varepsilon_v$, and is evaluated from the first linear section of the curve. The deformation's modulus is equivalent to $\Delta\sigma_y/\varepsilon_y$, which is evaluated at the first linear section of the stress-strain curve.

6.1.2 Tests on the intact rock

Simulations were conducted on a 10×10×10 m block model constituted only of intact rock. No fractures at all were generated. This test is run in order to validate the behaviour of the model, and estimate the validity of the monitoring procedure, by comparing the estimated mechanical parameters to the known mechanical properties of the intact rock.

The input parameters for the intact rock are presented in Table 5-3.

Figure 6-1 illustrates the strain and stress curves obtained under "2D" plane strain conditions and 3D strain tests. In 3D the model is free to move in the X and Z direction, and the loading is applied in the Y direction. The conditions for the "2D" plane strain test are described in section 4.

The mechanical properties evaluated from these curves are summarized in Table 6-1.

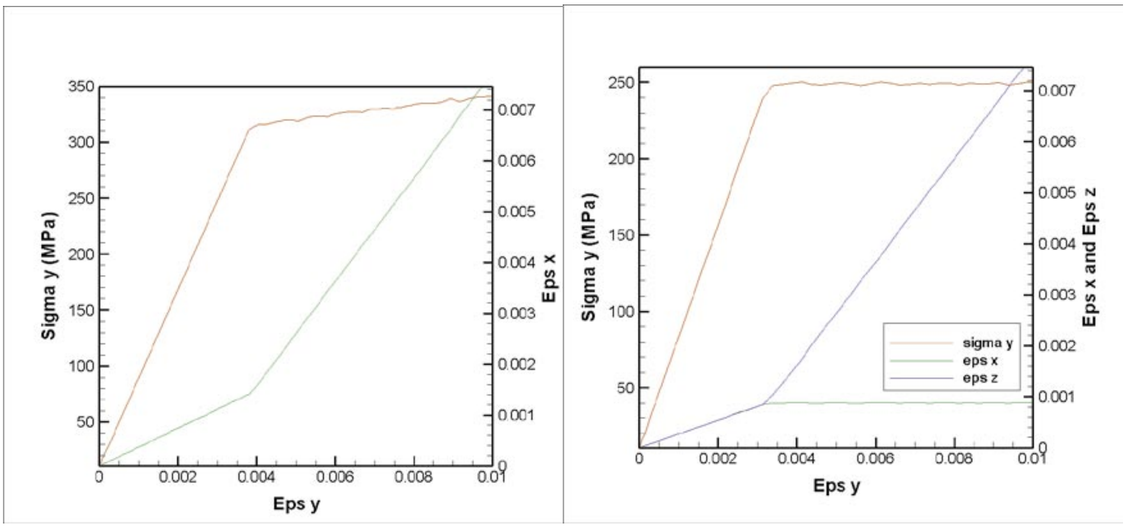

Figure 6-1. Strain and stress curves obtained for a) the 2D plane strain conditions and b) the real 3D strain test.

Table 6-1. Mechanical parameters of the intact rock evaluated from the simulations.

	E, GPa	v	σ_{ymax}, MPa	Theoretical stress at failure, MPa
Plane strain	73.2	0.27	315.5	313.2
3D loading	73.1	0.27	248.7	248.1

The Young's modulus and Poisson's ratio evaluated from both simulations are very consistent and similar to the input parameters for the intact rock, see Table 5-3. Nevertheless some discrepancies are noticed on the maximal vertical stress at failure. The value obtained in 3D is much lower than the one evaluated from the plane strain test. This was expected and can be compared to the differences in theoretical stress at failure for both tests, Table 6-1. The curves in Figure 6-1 illustrate clearly that the failure will first occur in the direction of minimal horizontal stresses (Z direction) which is locked during the "2D" plane strain loading test.

Both simulations could reproduce the behaviour of the intact rock and validate the test and monitoring procedure.

6.1.3 Rock block model

The stochastic fracture network used to generate the 3D rock block model includes 18 fractures. For the 3D loading test real orientation of fractures (based on dip and dip direction) was used. The rock block model generated is presented in Figure 6-2.

The procedure described in section 4 and used for the construction of the rock block model for the plane strain test has been slightly modified for the purpose of the comparison test. A vertical section parallel to the XY plane has been extracted from the model illustrated in Figure 6-2. Its extension in the Z direction is 0.5 m centred in the rock block model. This implies that the fractures are integrated in the "2D" model with their true orientation, as was done for the 3D model. However by reducing the width of the model to 0.5 m the influence of the true orientation of fractures should be negligible. The "2D" rock block model generated in 3DEC is illustrated in Figure 6-3.

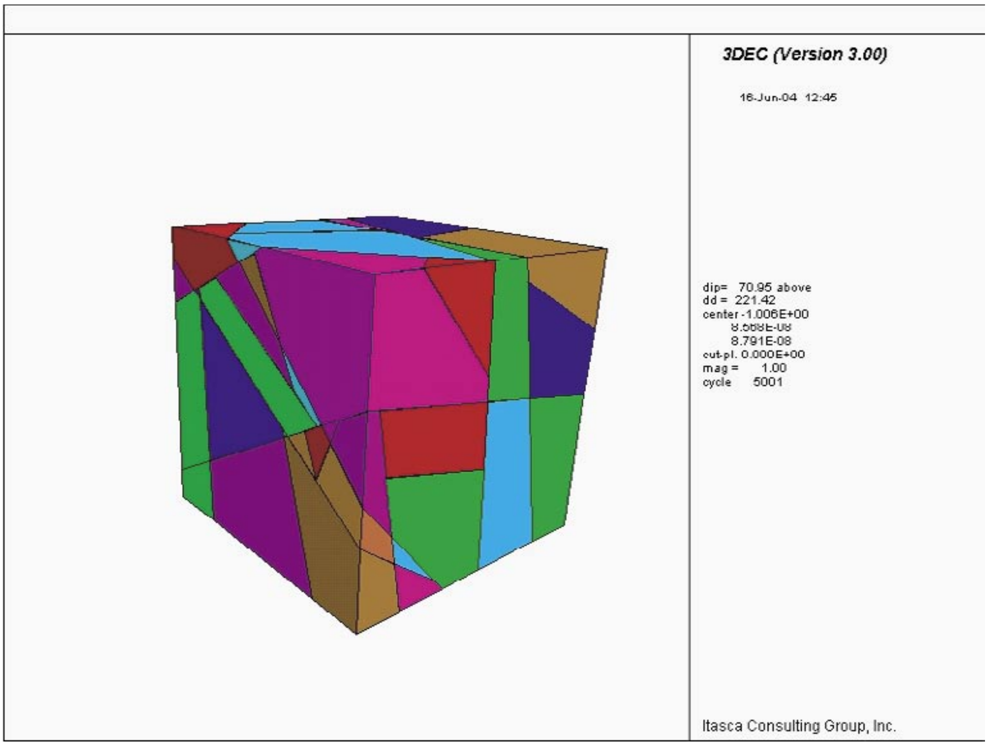

Figure 6-2. *The rock block model generated for the 3D loading test.*

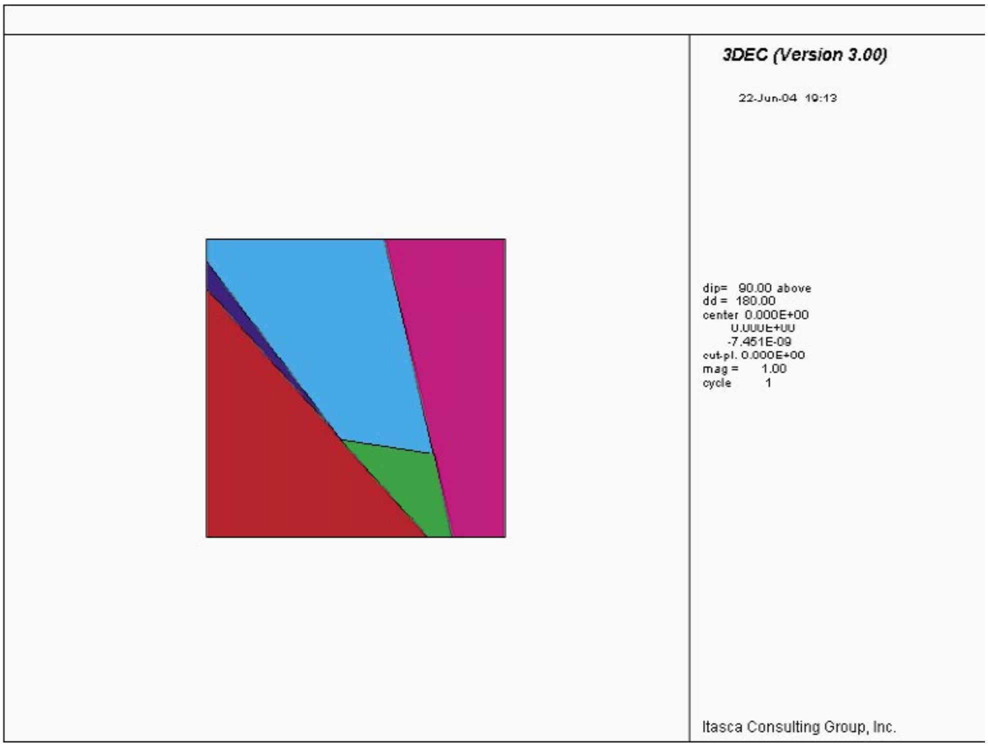

Figure 6-3. *The rock block model generated for the plane strain test.*

The mechanical properties used for the intact rock are presented in Table 5-3. Table 6-2 summarizes the mechanical properties used as input for real and fictitious fractures. The Coulomb-slip constitutive model is used for both types of fractures. The properties applied to real fractures might lead to an overestimation of the deformation's modulus but the maximal vertical stress at failure should be fairly affected.

Deformation and stress curves are presented in Figure 6-4 to Figure 6-6. Figure 6-4 simulates a real 3D loading test. Figure 6-5 simulates a 3D loading test locked in the Z direction to simulate plane strain conditions. Figure 6-6 simulates a "2D" plane strain loading test on a 10×10×0.5 m block model, which is similar to the model used for the descriptive model described in section 4.

The rock mass mechanical properties evaluated from these tests are presented in Table 6-3. The results show that the deformation's modulus is lowest when simulating a real 3D model and highest for the "2D" plane strain model. Variations on the Poisson's ratio do not show a clear trend. The maximal vertical stress at failure is lowest for the 3D loading test which was predictable. The discrepancy between the "2D" plane strain test and the 3D test locked in the Z direction is fairly significant in the order of 1.5%.

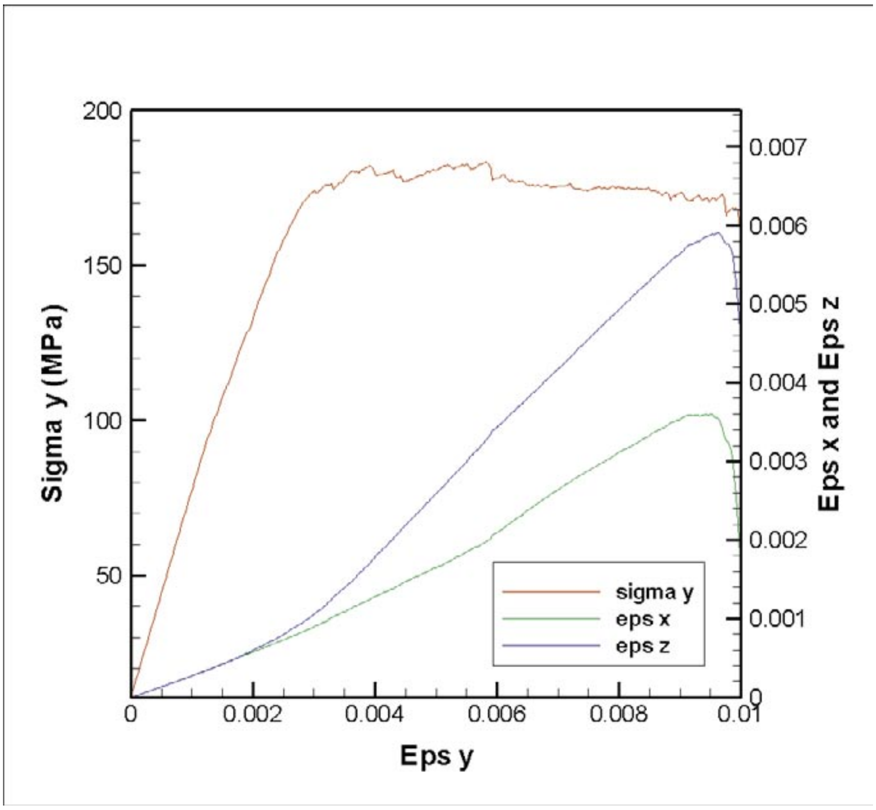

***Figure 6-4.** Strain and stress curves obtained for the 3D loading test. Displacements are free in the X and Z direction, loading is in the Y direction.*

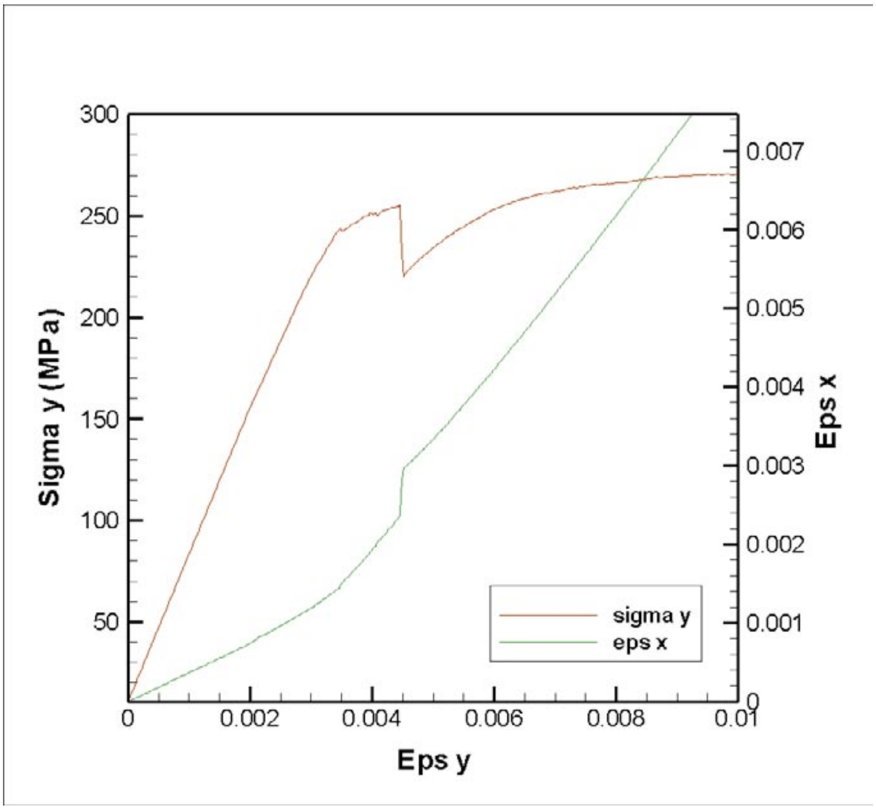

Figure 6-5. *Strain and stress curves obtained for the 3D loading test. Displacements are free in the X direction but locked in the Z direction, loading is in the Y direction.*

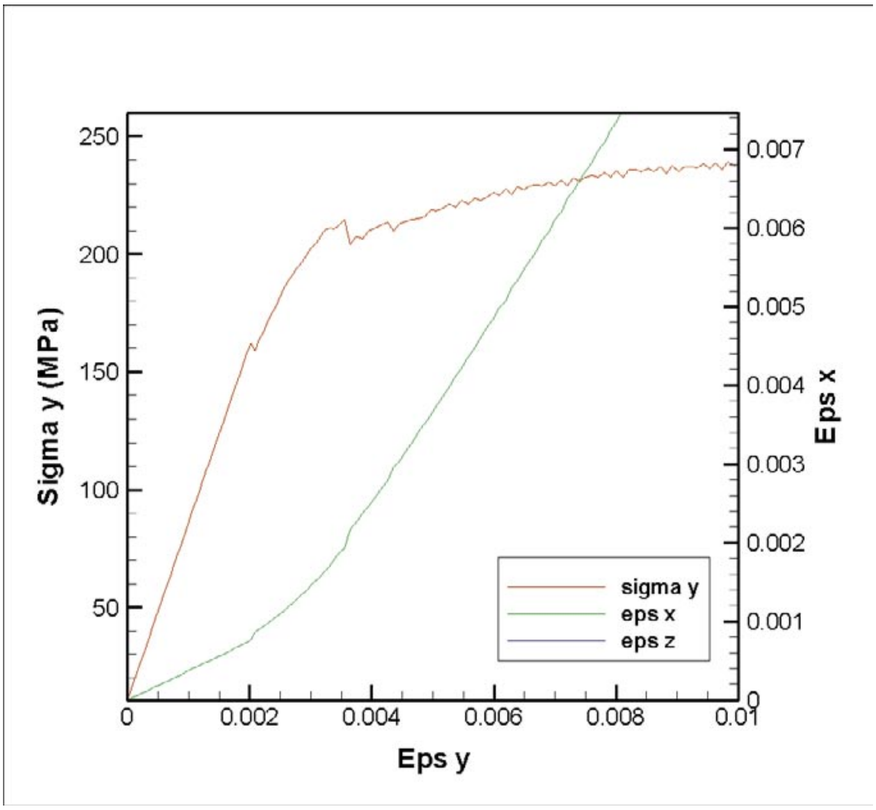

Figure 6-6. *Strain and stress curves obtained for the plane strain loading test. Displacements are free in the X direction but locked in the Z direction, loading is in the Y direction.*

Table 6-2. Mechanical properties of rock fractures used as input.

	Kn, MPa/mm	Ks, MPa/mm	ϕ, °	C_p, MPa	σ_t, MPa
Real	321.1e4	29.2e4	30	–	–
Fictititious	321.1e4	29.2e4	49	31	14.8

Table 6-3. Rock mass mechanical properties evaluated from the simulation tests.

	E_m, GPa	ν_m	σ_{ymax}, MPa
Plane strain test 10×10×0.5	68.2	0.31	206
3D loading test locked in Z direction	66.8	0.28	203
3D loading test	62.4	0.30	178

7 Spatial variability

The uncertainty of a model can be separated in conceptual uncertainty, data uncertainty and spatial variability.

The conceptual uncertainties originate from an incomplete understanding of the principal structure of the analysed systems and its interacting processes. This uncertainty is not discussed further in this section.

Data uncertainty concern uncertainty in the values of the parameters in a model. Data uncertainties may be caused by measuring errors, interpretation errors, or the uncertainty involved in extrapolation when the parameters varies in space.

Spatial variability concerns the variation in space of a parameter value. Spatial variability is not an uncertainty but is of course often a cause for data uncertainty.

The data uncertainty and spatial variability are often expressed in statistical terms as mean value, standard deviation and type of distribution. In our case the spatial variability can be separated into the spatial variability of the geometry of the fractures, the spatial variability of the parameters describing the properties of the intact rock and the fractures.

The spatial variability of the fracture system is described by the DFN model.

The data uncertainty and the spatial variability of the material parameters for a specific rock type are expressed by the measured mean value, standard deviation and type of distribution.

A common way to get the statistical parameters for a model with many input parameters that can be expressed in statistical terms is to run Monte Carlo simulations. One set of parameters is randomly chosen according to the statistical distributions of the parameters and the response of the model with these parameters is calculated. By running a lot of simulations and by treating the outcome in a statistical way the mean and the standard deviation of the outcome from the model can be estimated.

In order to minimise the number of numerical calculations with 3DEC a simplified way of doing the Monte Carlo simulations is proposed compared with the method of approach in /Staub et al. 2002/.

- The influence of the geometry of the fracture system is estimated by running 3DEC calculations with 20 realisations of the fracture system with values of all other parameters equal to the mean values. The result is statistically treated.
- The influence of the data uncertainty and the spatial variability of the material parameters are analysed for one DFN realisation by vary one parameter a time and keep all other parameters equal to the mean values. The result is statistically treated.
- The combined effect of DFN geometry-induced variability and the material property-induced variability is estimated by Monte Carlo simulations using the GoldSim system.

In Figure 7-1 is the effect of the spatial variability of the fracture system on the deformation modulus of the rock mass determined by 20 DFN realisations and load tested in 3DEC.

In Figure 7-2 is the effect of the spatial variability of the material parameters on the deformation modulus of the rock mass. The influence is given as deviation from the mean value for one DFN realisation.

During the Monte Carlo simulation one value from each distributions, Figure 7-1 and Figure 7-2 are draw and added to get the combined effect of geometry of fracture system and the material parameter variation. The resulting values are stored for statistical treatment. In Figure 7-3 the resulting distribution is shown.

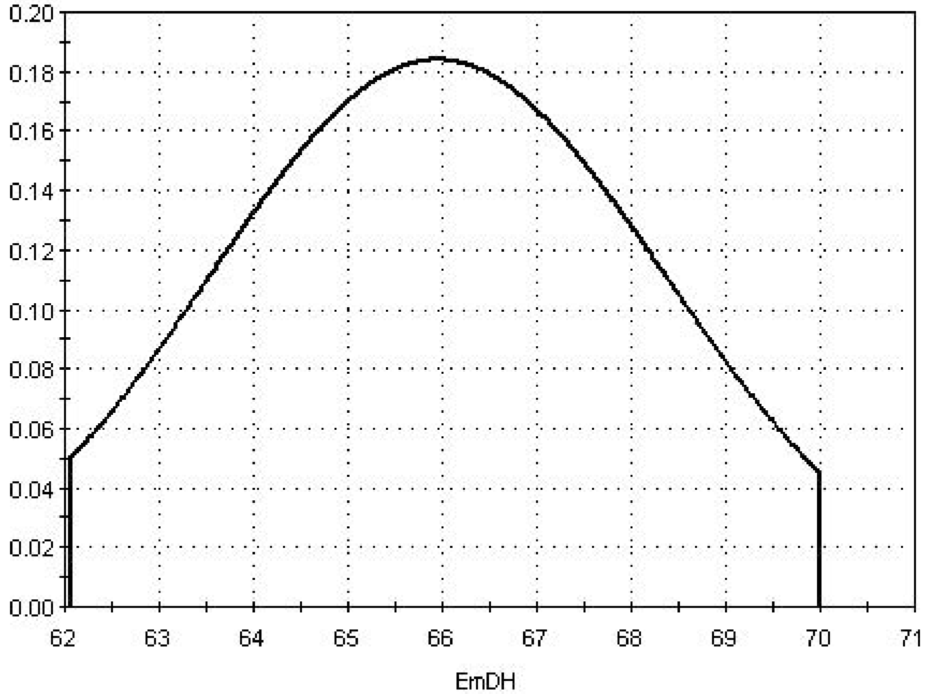

Figure 7-1. *The distribution of the influence of the geometry of the fracture system.*

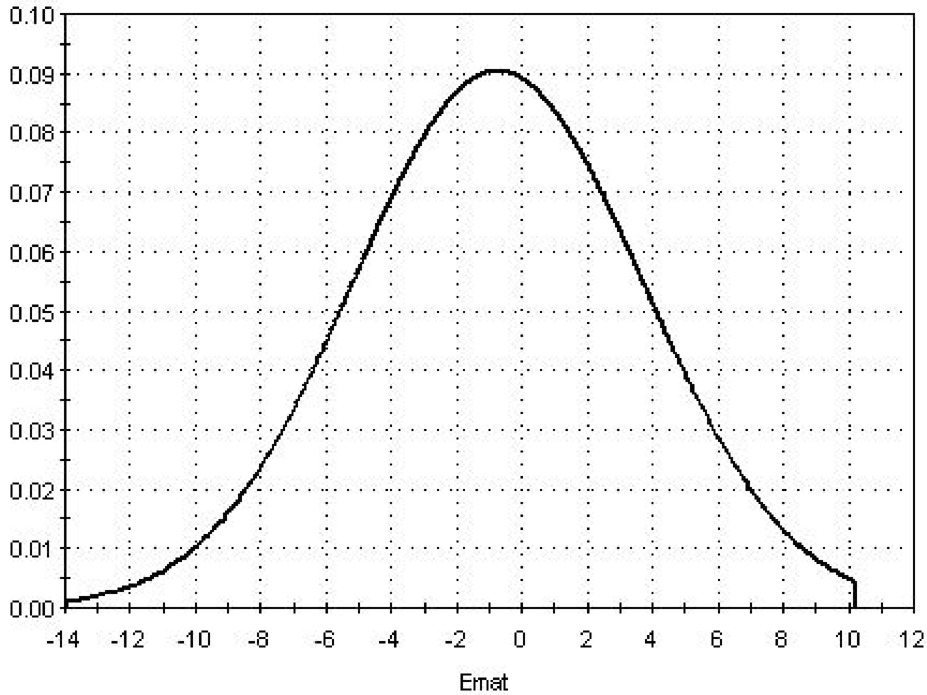

Figure 7-2. *The distribution of the influence of the spatial variability of the material parameters.*

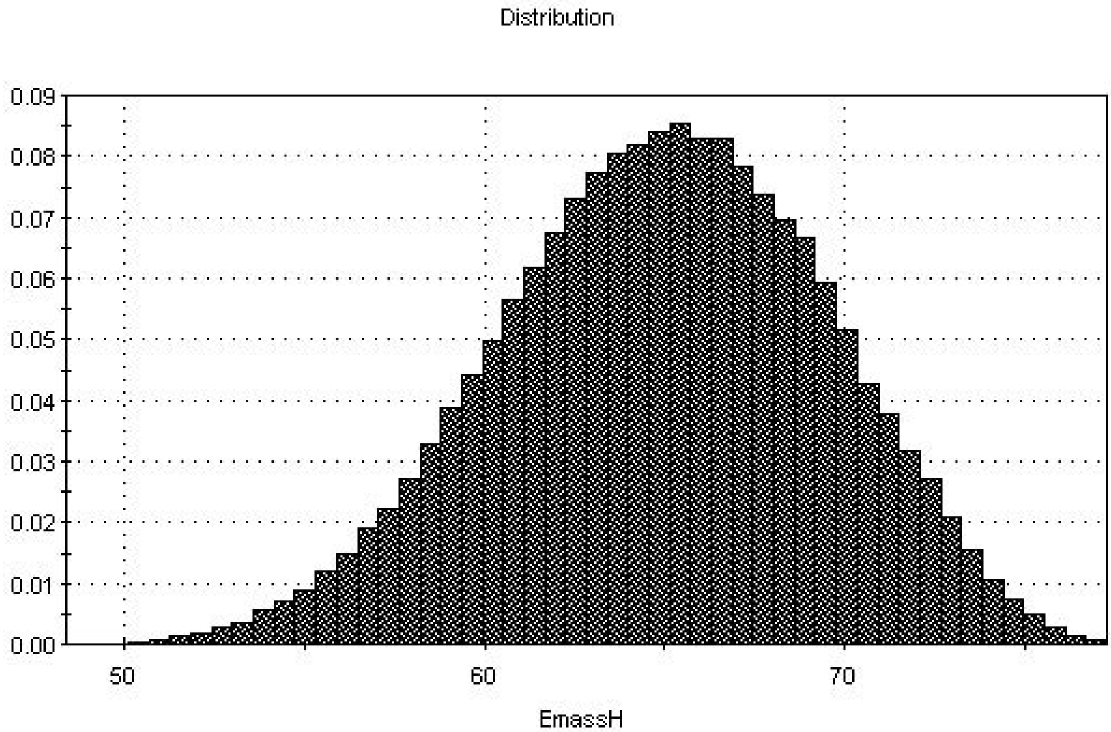

Figure 7-3. *The combined effect of the spatial variability of the geometry of the fracture system and the spatial variability of the material parameters.*

8 Discussion and conclusions

The 3DEC model is an implementation of the UDEC model that has been developed previously. The capacities in 3DEC are such that the generation of fractures is handled in a more optimal way and the assignment of mechanical properties to fractures is also optimized.

Some conclusions can be drawn from the results obtained with 3DEC and UDEC:

- The elastic properties of the rock mass are fairly affected by the methodology used.
- The principal stress at failure is much more sensitive to the methodology applied for the simulations. A possible explanation is that the number of fractures used for generating the rock block model in 3DEC is much more important than in UDEC as no fractures are discarded. This implies a larger amount of blocks in the 3DEC model.

Nevertheless the 3DEC model is not a real 3D model but simulates a "2D" plane strain test. This option has been chosen for the two main following reasons:

- Real 3D numerical simulations with hundreds of fractures are very time-consuming.
- The resulting block geometry in 3D is so complex that the zoning of the blocks is blocked for complex block geometry. These are too significant to allow automatisation of the procedure and a lot of numerical simulations.

Simulations were conducted on a real 3D model in order to validate the assumptions made for the "2D" plane strain model in 3DEC. The main following conclusions can be drawn from the results:

- At present it is not possible to simulate a real 3D loading test on a realistic stochastic fracture network with hundreds of fractures, at least if this should be done sufficiently many times to generate statistically relevant results. The number of fractures input in 3DEC has to be dramatically decreased.
- The rock mass mechanical properties are generally lower for the 3D loading test than for the "2D" plane strain test, which was expected. This discrepancy is reduced if the "2D" model is in the direction of minimal stress.
- The 3D loading test with the model locked in the Z direction presents rock mass mechanical properties quite similar to those obtained with the "2D" plane strain model, and validates the assumptions made for the methodology.

The shortcomings related to the numerical model developed ("2D" plane strain model) can be overcome by rotating the plane extraction of the fractures in order to account for displacements both in the X and Z direction in relation to in situ stresses.

By separating the spatial variability into two parts, one depending on the geometry of the fracture system and one depending on the variation of the material parameters the determination of the rock mass properties are more straightforward compared with the method used in /Staub et al. 2002/.

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