Hydromechanical rock mass characterization using discrete fracture network models – a case study based on terrestrial laser scanning and rock mechanical testing

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Abstract. Understanding the anisotropic hydraulic and mechanical properties of fractured rock masses is of great importance for a safe and optimal utilisation of the subsurface. Two sandstone quarries are utilized to obtain fracture network characteristics by Terrestrial Laser Scanning (TLS) producing 3d point cloud data. Semiautomatic analysis of the point clouds provides the probability density functions for each of the fracture parameters used as stochastic input for a Discrete Fracture Network (DFN) model. Rock mechanical laboratory tests are carried out to determine the mechanical properties of the intact rock and fractures. These parameters are then combined in the DFN model to calculate spatially variable tensors for permeability, Young’s modulus and Poisson’s ratio. Thereby, the spatial resolution of the tensor description is adapted to the grid size which can be used in further hydromechanical models. The approach allows to populate these models with more realistic parameters which incorporate also the effect of fractures on the rock mass behaviour. Obtained results are subsequently compared with conventional engineering rock mass classifications. The applied workflow allows for upscaling of rock properties determined in the laboratory to the anisotropic rock mass properties required for further hydromechanical modelling on larger scales, e.g., the reservoir scale.

1. Introduction

Regardless of their origin, fracture networks significantly contribute to the hydromechanical properties of rock masses, implying that a detailed description of the fracture network is essential for characterization of fractured rock masses [1]. A potential opportunity to determine the hydraulic properties of rock masses are in situ measurements such as water-pressure and slug-tests [2]. Mechanical properties can be obtained by in situ measurements like plate jacking and plate load tests [3] or indirectly by empirical relationships based on empirical classification systems such as Rock Quality Designation (RQD) [4], Rock Mass Rating (RMR) [5], Geological Strength Index (GSI) [6] or the Q-System [7]. A further new approach is the development of a deterministic-stochastic Discrete Fracture Network (DFN) model of a fractured rock mass [8] which allows the calculation of anisotropic and spatially variable hydromechanical rock properties [9], i.e. tensors for Permeability, Young’s modulus and Poisson’s ratio. The input data to set up a DFN model can be gathered from surface outcrops and excavations as well as core and image log data. The present study provides a working example of hydromechanical characterization of rock masses using a DFN modeling approach to derive hydraulic and mechanical parameters. Obtained mechanical properties are further validated by a comparison to conventional rock
mass classification systems. The goal is to present a framework for realistically describing and predicting the hydraulic and mechanical behavior of fractured rock masses incorporating the spatial variability of the predominant fracture network.

2. Methodology

Two different sandstone quarries located in Germany are chosen to test the practical value of the DFN modeling approach. The first outcrop studied is located in northern Germany, associated to the Flechtingen High and consists of an upper Rotliegend (Lower Permian) fluvi-aeolian sandstone with frequent grain size variations and a thickness of 6 m. The second quarry treated is encountered and mined in Remlingen, southern Germany. It is stratigraphically assigned to the upper Buntsandstein (Lower Triassic; 244-243 Ma) and shows massive sandstone beds with a thickness up to 6 m with interbedded deposits of up to three cm thick clay/siltstone. Field work is conducted to assess fracture network properties using Terrestrial Laser Scanning (TLS), to determine input parameters for engineering rock mass classifications and to collect samples for rock mechanical testing in the laboratory. The resulting and adjusted point cloud based on the TLS survey allows the assessment of orientation, size and intensity of the fractures for use as input parameters for DFN modeling. Dip direction and dip angle are automatically generated using the plane-patch filter of RiSCAN Pro software [10]. In order to obtain the fracture size, the received point cloud is analyzed using the RANSAC Shape Detection tool [11] using the CloudCompare software [12]. To investigate the fracture intensity, CloudCompare is used by drawing a certain quantity of scan lines across the point cloud. Using these Scanlines, the P10 value is calculated and converted to its P32 value according to [13]. DFN models are developed using FracMan version 7.9 software [14]. The defined model domain is a cube of 50 m edge length located in the center of each case study. After verifying the geometry of the model using the TLS data, the hydromechanical parameters are assigned to the matrix and fractures. In a base model A1, the hydromechanical rock and fracture properties are upscaled to a grid of 5 x 5 x 5 cells, i.e. each cell has a volume of 10 x 10 x 10 m³, according to [15, 16] using VTI symmetry [17]. Subsequently, the mechanical properties are upscaled to a grid B1 of 1 x 1 x 1 cells (50 x 50 x 50 m³) using VTI- and isotropic symmetry. This single-cell grid is utilized in a sensitivity analysis incorporating 18 additional models to investigate the contribution of input parameters, including matrix Young's modulus, shear stiffness, normal stiffness and fracture intensity to the upscaled modeling results and to enable a validation using the empirical rock mass equations. These equations include characteristic values from rock mass classifications (table 1), which are themselves associated with uncertainties. As DFN models inherently comprise a stochastic component, uncertainties and variability of the parameters utilized in the rock classifications are incorporated using probabilistic methods, i.e., Monte Carlo simulation techniques.

3. Results

Analysis of the adjusted point clouds allows the assessment of orientation, size and intensity of the fractures used as input parameters for the DFN modelling summarized in table 2. These include three vertically oriented fracture sets for Flechtingen (F1-3) as well as two vertical (R1-2) and one horizontal (R3) fracture set for Remlingen based on the fracture network analysis using TLS. These geometrical parameters are subsequently used to generate a stochastic fracture network for both sandstones shown in figure 1.
Table 1. Empirical classification systems used in the Monte Carlo Simulation for the assessment of the empirical evaluation of the rock mass Young’s modulus.

| Publication                        | Classification System          | Equation                                                                 |
|------------------------------------|--------------------------------|--------------------------------------------------------------------------|
| Bieniawski (1978) [5]              | RMR                            | $E_m = 2 \times RMR - 100$                                               |
| Read et al. (1999) [18]            | $E_m = 0.1 \left( \frac{RMR^3}{10} \right)$                                 |
| Nicholson and Bieniawski (1990) [19]| RMR + intact rock              | $E_m = \frac{E_i}{100} \left[ 0.0028 RMR^2 + 0.9 \exp \left( \frac{RMR}{22.82} \right) \right]$ |
| Galera et al. (2005) [20]          | GSI                            | $E_m = E_i e^{0.0654 GSI}$                                               |
| Gokceoglu et al. (2003) [21]       | GSI                            | $E_m = 0.1451 e^{0.0654 GSI}$                                             |
| Sanei et al. (2013) [22]           | GSI + intact rock              | $E_m = 0.0222 GSI^2 - 2.172 GSI + 54.24$                                 |
| Sonmez et al. (2004) [23]          | GSI + intact rock              | $E_m = E_i \left( s^2 \right)^{0.4}$                                  |
| Hoek and Diederichs (2006) [24]    | Q-System                       | $E_m = E_i \left[ 0.02 + \frac{1 - D/2}{1 + e^{(60 + 15 D - GSI)/11}} \right]$ |
| Barton (2002) [25]                 | Q-System                       | $E_m = Q_c^{1/3}$                                                        |
| Ajalloeian and Mohammadi (2014)    | RQD                            | $E_m = -0.016 Q^2 + 1.581 Q + 0.961$                                    |
| Zhang and Einstein (2004) [27]     | RQD                            | $E_m = 10^{0.0186 (RQD - 1.91)} E_i$                                     |
| Gardner (1987) [28]                | RQD                            | $E_m = 0.0231 RQD - 1.32$                                                |

Table 2. Geometrical properties of the fracture sets from the quarry Flechtingen (F1-3) and Remlingen (R1-3) including the associated distribution functions.

| Orientation [°] | Size [m]    | $P_{32}$ [m$^3$] |
|-----------------|-------------|-----------------|
| F1 119/89 ($\kappa = 80$) | 3.44 ± 1.78 (normal) | 0.29 |
| F2 018/89 ($\kappa = 80$) | 4.08 ± 2.29 (normal) | 0.23 |
| F3 175/84 ($\kappa = 80$) | 3.54 ± 1.51 (lognormal) | 0.38 |
| R1 168/90 ($\kappa = 80$) | 7.63 ± 0.56 (lognormal) | 0.28 |
| R2 073/88 ($\kappa = 80$) | 6.97 ± 0.89 (lognormal) | 0.24 |
| R3 175/05 ($\kappa = 80$) | 50.00 ± 5.00 (lognormal) | 0.20 |

Figure 1. (a) Left: Verified DFN model (50 x 50 x 50 m$^3$) of the stochastic fracture network of Flechtingen. Right: Superimposed 5 x 5 x 5 grid A1 leading to a cell size of 10 x 10 x 10 m$^3$. (b) Left: Verified DFN model (50 x 50 x 50 m$^3$) of the stochastic fracture network of Remlingen. Right: Superimposed 1 x 1 x 1 grid B1 leading to a cell size of 50 x 50 x 50 m$^3$. 
Mechanical input parameters required for DFN modeling and partly, for the empirical rock mass classification systems, of rock matrix and fractures are obtained in the laboratory using uniaxial and direct shear tests on samples collected from the outcrop and are provided in table 3. Values for matrix and fracture permeability, matrix porosity as well as fracture aperture are set according to [29, 30]. No samples from the horizontal set (R3) of the Remlingn quarry could be collected, so the input parameters were taken from [31]: a residual cohesion of 0.025 MPa, a residual friction angle of 25 °, a shear stiffness of 0.015 MPa/mm and a normal stiffness of 1 MPa/mm are applied. Aside from this, all remaining parameters applied to the fracture sets in the two outcrops are the same. The corresponding scores for the empirical rock mass classification systems used in the Monte Carlo Simulations are shown in table 4.

As no cores of both outcrops are available, the RQD value was determined according to [32].

### Table 3. Rock mechanical parameters determined in the laboratory for each investigated quarry.

| Parameter                          | Flechtingen       | Remlingen          |
|------------------------------------|-------------------|--------------------|
| Permeability\_matrix \([\text{m}^2]\)| 4.96x10\(^{-17}\) ± 1.01x10\(^{-18}\) | 5.50x10\(^{-17}\) ± 8.24x10\(^{-18}\) |
| Permeability\_fracture \([\text{m}^2]\)| 1.40x10\(^{9}\) ± 2.38x10\(^{-10}\) | 7.00x10\(^{-10}\) ± 1.89x10\(^{-10}\) |
| Aperture\_fracture \([\text{mm}]\)   | 0.13 ± 0.02       | 0.09 ± 0.02        |
| Porosity\_matrix \([\%]\)           | 9.60 ± 0.10       | 12.90 ± 0.30       |
| Uniaxial Compressive Strength \([\text{MPa}]\) | 103.29 ± 8.36    | 98.89 ± 8.03       |
| Young\’s Modulus \([\text{GPa}]\)   | 17.72 ± 4.39      | 15.83 ± 0.78       |
| Poisson\’s ratio \([-]\)            | 0.38 ± 0.05       | 0.30 ± 0.07        |
| Cohesion\_initial \([\text{MPa}]\)  | 13.84             | 12.27              |
| Friction Angle\_initial \([\degree]\)| 43.12             | 34.99              |
| Cohesion\_residual \([\text{MPa}]\) | 0.39              | 0.37               |
| Friction Angle\_residual \([\degree]\)| 39.01             | 37.91              |
| Normal Stiffness \([\text{MPa/mm}]\)| 7.50 ± 2.8        | 7.10 ± 2.3         |
| Shear Stiffness \([\text{MPa/mm}]\) | 0.75 ± 0.28       | 0.71 ± 0.23        |

### Table 4. Results from Monte Carlo simulation of the calculated rock mass classification systems.

|          | RQD       | RMR       | GSI       | Q-System  |
|----------|-----------|-----------|-----------|-----------|
| Flechtingen | 100.00 ± 2.00 | 72.99 ± 2.11 | 77.00 ± 2.25 | 3.66 ± 2.09 |
| Remlingen | 100.00 ± 2.00 | 76.01 ± 2.12 | 76.99 ± 2.01 | 4.88 ± 1.79 |

Computing and upscaling the properties of both rock and fractures using the approach of Oda [16] based on Grid A1 and VTI-symmetry yields a second-order permeability tensor for each grid cell. The permeabilities in the W-E, N-S and vertical directions are denoted as \(K_{xx}\), \(K_{yy}\), and \(K_{zz}\), respectively. Three diagonal spatial directions are also derived, referred as \(K_{xy}\), \(K_{yz}\), and \(K_{zx}\). The calculation of the Poisson ratios in xy (horizontal) and xz (vertical) direction also indicate varying values. Here, considerably higher Poisson ratios can be observed in the horizontal direction compared to the vertical direction. Values for Poisson's ratio above the 0.5 limit may be caused by the VTI-symmetry [34]. The corresponding modeling results for the hydromechanical rock mass properties are shown in table 5.
Table 5. Results obtained from DFN modeling for the rock mass characteristics using Grid A1.

| Parameter                        | Flechtingen          | Remlingen          |
|----------------------------------|----------------------|--------------------|
| Permeability$_{xx}$ [m$^2$]      | $1.15 \times 10^{-13} \pm 2.64 \times 10^{-14}$ | $1.46 \times 10^{-14} \pm 6.73 \times 10^{-15}$ |
| Permeability$_{yy}$ [m$^2$]      | $4.69 \times 10^{-14} \pm 1.66 \times 10^{-14}$ | $1.16 \times 10^{-14} \pm 5.42 \times 10^{-15}$ |
| Permeability$_{zz}$ [m$^2$]      | $1.57 \times 10^{-13} \pm 3.48 \times 10^{-13}$ | $2.48 \times 10^{-14} \pm 9.59 \times 10^{-15}$ |
| Permeability$_{xy}$ [m$^2$]      | $1.56 \times 10^{-14} \pm 1.03 \times 10^{-14}$ | $-2.63 \times 10^{-16} \pm 2 \times 10^{-15}$ |
| Permeability$_{yz}$ [m$^2$]      | $-6.09 \times 10^{-15} \pm 3.37 \times 10^{-15}$ | $2.11 \times 10^{-16} \pm 6.88 \times 10^{-16}$ |
| Permeability$_{zx}$ [m$^2$]      | $1.38 \times 10^{-15} \pm 1.69 \times 10^{-15}$ | $1.19 \times 10^{-16} \pm 5.95 \times 10^{-16}$ |
| Transversal Young’s Modulus [GPa]| $4.30 \pm 0.63$      | $5.73 \pm 0.85$    |
| Longitudinal Young’s Modulus [GPa]| $12.61 \pm 0.79$     | $4.30 \pm 2.46$    |
| Poisson’s ratio$_{xy}$ [-]       | $0.54 \pm 0.02$      | $0.57 \pm 0.03$    |
| Poisson’s ratio$_{xz}$ [-]       | $0.33 \pm 0.01$      | $0.10 \pm 0.06$    |

A comparison of the empirically generated properties using the empirical classification systems to validate the DFN results of Grid B1 indicates that in particular empirical equations incorporating intact rock parameters produce comparable outcomes to the DFN models (figure 2). This applies to both the VTI- and the isotropic symmetries of the DFN models for the Remlingen sandstone. Results for the Flechtingen sandstone exhibit similar findings for the transversal and isotropic elastic modulus of the DFN models. However, the computed longitudinal elastic modulus of the DFN models exhibits increased values but remains in agreement with the results of the empirical equations, being lower than the intact elastic modulus. Nevertheless, it can be observed for both sandstones that the results of the DFN models are in the lower range of the values obtained by the empirical equations. However, the range of potential outcomes is noticeably more restricted relative to the predicted outputs of the empirical rock classifications.

Figure 2. Validation of the DFN Models using grid B1 compared to the results of the Monte Carlo simulation for Flechtingen (left) and Remlingen (right).
4. Discussion
To investigate the geometric characteristics of fracture networks of surface outcrops, contactless techniques such as TLS have been shown to be superior compared to conventional field methods. Of particular importance is the more comprehensive data set, improving the quality of the input required for the probability density functions and thereby increasing the quality of the model itself. In this study, both DFN models are exclusively built from stochastic parameters, since no large-scale deterministic features such as faults are present. The upscaling of permeability to the dimensions of the calculation grid A1 (5 x 5 x 5 m³) already indicates a spatial scatter for the components of the permeability tensor by two orders of magnitude caused by the orientation of the fracture network. Directional differences are especially observed for the Flechtingen sandstone since the three fracture sets of the Remlingen sandstone are almost orthogonal to each other and parallel to the axes of the DFN model. The modelling results for grid A1 with respect to the elastic properties emphasize the weakening effect fractures have on rock mass properties. For the given grid size, calculations reveal a significant reduction of the transversal elastic modulus to approximately 5 GPa caused by the predominant vertical fracture sets for both sandstones. Slightly lower values for the Flechtingen sandstone can be explained by the increased number of vertical fracture sets leading to an increased fracture intensity. However, the Flechtingen sandstone exhibits only a slight decrease in longitudinal elastic modulus resulting from the absence of horizontal fractures causing a discernible anisotropy. Contrary to this, the longitudinal elastic modulus of the Remlingen sandstone indicates a significant decrease, which leads to an approximately isotropic behavior of the rock mass. It is worth mentioning that although the number and intensity of the horizontal fracture sets are lower, the decrease in the elastic rock mass modulus is similar to the longitudinal modulus, resulting in the assumption that the single, mechanically weak fracture set influences the elastic rock mass modulus in a greater way than the two, mechanically stronger vertical fracture sets including a higher intensity. Mean values of the calculated moduli are significantly lower and account for only 25% to 35% of the isotropic Young's modulus of the intact rock which is consistent with values obtained by [35, 36]. In order to establish a proper comparability to empirical classifications for validation, the DFN models generated using grid B1 consisting of a cell of 50 x 50 x 50 m³. By comparing the two sandstones, it can be seen that the empirical equations are capable of providing a reasonable approximation of the elastic rock mass modulus. However, they cannot represent the anisotropy of the rock mass being investigated, as shown with the Flechtingen example. These findings show the advantages of upscaling rock characteristic using the DFN modeling approach. DFN models are scale independent as the size of the upscaled region including the size of the grid cells can be arbitrarily chosen depending on the current application. Moreover, different fracture sets can be assigned with various hydraulic properties such as permeabilities and apertures as well as mechanical properties including fracture stiffnesses depending on fracture fillings or fracture alterations. Those opportunities enable a more complex and detailed hydromechanical anisotropic characterization of rock masses using the DFN modeling approach which is applicable to any type of fractured rock. A validation of the upscaled permeability distribution can be accomplished by comparing the flow simulation results with actual observed hydraulic test data [2]. To further validate the upscaled mechanical characteristics similarly remains challenging however, in-situ tests like plate load or large flat-jack tests offer a possible alternative in limited rock volumes. An additional opportunity is the use of seismic P- and S-wave velocities to analyze larger volumes [37], necessitating a transformation from dynamic to static elastic properties.

5. Conclusion
This study shows that a complex and detailed hydromechanical characterization of anisotropic rock masses can be performed using the DFN modeling approach. It demonstrates that a fractured rock mass exhibits significant spatial variation in hydraulic and mechanical parameters if fracture geometry and characteristics are incorporated utilizing a stochastic DFN model. Modeling results reveal a considerable reduction in the mechanical parameters of a fractured rock mass if fracture geometry and properties are incorporated. Furthermore, DFN models demonstrate that fracture orientation and, more importantly,
their mechanical characteristics significantly affect the mechanical properties of the rock mass. The comparison used for validation of the DFN results utilizing empirically generated properties based on the empirical classification systems reveals that the DFN models provide comparable results especially with empirical equations containing intact rock parameters. However, it should be pointed out that the range of possible results is on the one hand clearly more restricted and the DFN models demonstrate that they are capable of computing and representing anisotropic hydraulic and mechanical properties of rock masses. In conclusion, we propose that the results obtained using the DFN approach will provide a new perspective on the characterization of rock masses, since it integrates the basic concepts of rock characterization, structural geology as well as statistics providing a hydromechanical rock mass characterization.

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References
[1] Wittke W 2014 Rock mechanics based on an Anisotropic Jointed Rock Model (AJRM) (Berlin: Ernst)
[2] Hekel U and Odenwald B Bohrlochversuche zur Bestimmung der Gebirgsdurchlässigkeit von Fels. Johann-Ohde-Kolloquium vol 95 (Karlsruhe) pp 139–50
[3] Palmstrom A and Singh R 2001 The deformation modulus of rock masses - comparisons between in situ tests and indirect estimates Tunn. Undergr. Space Technol. 16 115–31
[4] Deere D U 1964 Technical description of rock cores for Engineering purposes Rock Mech. Eng. Geol. 1
[5] Bieniawski Z T 1989 Engineering rock mass classifications (New York: Wiley)
[6] Hoek E 1994 Strength of rock and rock masses. ISRM News J 4–16
[7] Barton N, Lien R and Lunde J 1974 Engineering classification of rock masses for the design of tunnel support Rock Mech. 6 189–236
[8] Elmo D, Rogers S, Stead D and Eberhardt E 2014 Discrete Fracture Network approach to characterise rock mass fragmentation and implications for geomechanical upscaling Min. Technol. 123 149–61
[9] Sayers C M and den Boer L D 2012 Characterizing production-induced anisotropy of fractured reservoirs having multiple fracture sets: Production induced anisotropy of fractured reservoirs Geophys. Prospect. 60 919–39
[10] RIEGL GmbH 2020 RiScan Pro (2.9) (Horn, Austria)
[11] Schnabel R, Wahl R and Klein R 2007 Efficient RANSAC for Point-Cloud Shape Detection Comput. Graph. Forum 26 214–26
[12] CloudCompare 2020 [GPL software] (version 2.11.3) Retrieved from http://www.cloudcompare.org/
[13] Wang X 2005 Stereological Interpretation of Rock Fracture Traces on Borehole Walls and Other Cylindrical Surfaces (Virginia State University)
[14] Golder Associates Ltd. 2020 FracMan7 Interactive Discrete Feature Data Analysis, Geometric Modeling and Exploration Simulation (Golder Associates Ltd.)
[15] Oda M, Suzuki K and Maeshibu T 1984 Elastic Compliance for rock-like materials with random cracks Soils Found. 24 27–40
[16] Oda M 1985 Permeability tensor for discontinuous rock masses Géotechnique 35 483–95
[17] Browaeys J T and Chevrot S 2004 Decomposition of the elastic tensor and geophysical
applications Geophys. J. Int. 159 667–78

[18] Read S A L, Perrin N D and Richards L R 1999 Applicability of the Hoek–Brown failure criterion to New Zealand greywacke rocks. 9th ISRM Congress. International Society for Rock Mechanics and Rock Engineering (Paris, France) pp 655–60

[19] Nicholson G A and Bieniawski Z T 1990 A nonlinear deformation modulus based on rock mass classification Int. J. Min. Geol. Eng. 8 181–202

[20] Galera J M, Álvarez M and Bieniawski Z T 2005 Evaluation of the deformation modulus of rock masses using RMR: comparison with dilatometer tests. Proceedings ISRM Workshop

[21] Gökceoğlu C, Sonmez H and Kayabasi A 2003 Predicting the deformation moduli of rock masses Int. J. Rock Mech. Min. Sci. 40 701–10

[22] Sanei M, Rahmat A, Faramarzi L, Goli S and Meinrad A 2013 Estimation of rock mass deformation modulus in Bakhtiyari Dam Project in Iran 3rd ISRM SINOROCK Symposium, Rock Characterisation, Modelling and Engineering Design Methods (Shanghai, China)

[23] Sonmez H, Gökceoğlu C and Ulusay R 2004 Indirect determination of the modulus of deformation of rock masses based on the GSI system Int. J. Rock Mech. Min. Sci. 41 849–57

[24] Hoek E and Diederichs M S 2006 Empirical estimation of rock mass modulus Int. J. Rock Mech. Min. Sci. 43 203–15

[25] Barton N 2002 Some new Q-value correlations to assist in site characterisation and tunnel design Int. J. Rock Mech. Min. Sci. 39 185–216

[26] Ajalloeian R and Mohammadi M 2014 Estimation of limestone rock mass deformation modulus using empirical equations Bull. Eng. Geol. Environ. 73 541–50

[27] Zhang L and Einstein H H 2004 Using RQD to estimate the deformation modulus of rock masses Int. J. Rock Mech. Min. Sci. 41 337–41

[28] Gardner W S 1987 Design of drilled piers in the Atlantic Piedmont Found. Excav. Decomposed Rock Piedmont Prov. ASCE 62–86

[29] Frank S, Heinze T and Wohnlich S 2020 Comparison of Surface Roughness and Transport Processes of Sawed, Split and Natural Sandstone Fractures Water 12 2530

[30] Frank S, Heinze T, Ribbers M and Wohnlich S 2020 Experimental Reproducibility and Natural Variability of Hydraulic Transport Properties of Fractured Sandstone Samples Geosciences 10 458

[31] Ernst C, Hecht T and Witt K J 2016 In-situ-Bestimmung von effektiven Scherparametern in rutschgefährdeten Schichten im Oberen Buntsandstein geotechnik 39 110–8

[32] Priest S D and Hudson J A 1976 Discontinuity spacings in rock Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 13 135–48

[33] Ghafrarokhi P K 2017 The structured gridding implications for upscaling model discrete fracture networks (DFN) using corrected Oda’s method J. Pet. Sci. Eng. 153 70–80

[34] Christensen R M 2005 Mechanics of composite materials (Mineola, N.Y: Dover Publications)

[35] Beiki M, Bashari A and Majdi A 2010 Genetic programming approach for estimating the deformation modulus of rock mass using sensitivity analysis by neural network Int. J. Rock Mech. Min. Sci. 47 1091–103

[36] Pollard D D and Fletcher R C 2005 Fundamentals of structural geology (Cambridge, UK; New York: Cambridge University Press)

[37] Guerra C, Fischer K and Henk A 2019 Stress prediction using 1D and 3D geomechanical models of a tight gas reservoir—A case study from the Lower Magdalena Valley Basin, Colombia Geomech. Energy Environ. 19 100113