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Application of discrete fracture networks (DFN) in the stability analysis of Delabole Slate Quarry, Cornwall, UK

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ABSTRACT:

The failure mechanism of rock slopes is mainly controlled by the strength and orientation of discontinuities within the rock mass. A realistic representation of the joint network within the rock mass is therefore an essential component of stability analysis of rock structures (e.g. rock slopes, tunnels etc.). Discontinuity persistence and connectivity are significant parameters which control the stability of rock slopes. A small percentage of rock bridges on the discontinuity surface can significantly increase its strength and prevent slope failure. Discontinuities within the rock mass are rarely fully connected. In practice, however, discontinuities are often assumed fully persistent due to the difficulties both in mapping and simulation of non-persistence. Discrete fracture networks (DFN) provide a rigorous and convenient tool for the simulation of joint systems within a rock mass. Utilizing statistical methods, DFNs consider the stochastic nature of some key parameters (e.g. persistence and orientation) within numerical models. Discrete fracture network engineering is increasingly used due to recent developments in discontinuity data acquisition techniques (e.g. ground-based digital photogrammetry and laser scanning). Recent development in geomechanical modelling codes and increased computing power have also allowed to either import DFN's into models or to generate DFN's within the numerical modelling code itself (e.g. 3DEC).

This paper describes the use of photogrammetry at the Delabole slate quarry in Cornwall, UK for remotely acquiring key discontinuity parameter data (orientation, intensity and length) and its subsequent use in developing statistically validated discrete fracture network parameters. The 3D distinct element code, 3DEC, is used for the DFN generation and subsequent stability analysis. Several realizations of the 3DEC-DFN models are run to investigate the stochastic nature of discontinuities within the quarry and their potential influence on the stability of the pit. Finally the simulation results are used to determine the slope instability mechanisms and determine the most likely areas of potential instability.

1. INTRODUCTION

High quality slate has been quarried at Delabole Slate Quarry, located in Cornwall, United Kingdom for more than eight centuries. Structurally the quarry lies in the south-western flank of the Davidstow anticline (Shillitto 2013). Intense tectonic pressure during the American Orogeny formed cleavage normal to the direction of the maximum compressive stress (Riggs 2014). The quarry is approximately elliptical in plan: 700 m in length (north-south direction), 400 m in width (west-east direction) and 150 m in depth. The overall slope angle varies throughout the pit: 28° at north-east, 40° at east and 50° at north (Shillitto 2013). Prominent discontinuities have been given local names by the quarrymen (e.g. Floors, Shortahs and Grain). Evidence of discontinuity-controlled instability on the north-east slope can be seen in Figure 1, which shows an image of a recent 50 m wide and 13 m high planar failure on an upper bench. Crack opening was observed by the quarrymen at the crest of the bench during regular inspection and the unstable section safely removed. The basal surface of the failures is provided by Floors, with lateral release surfaces provided by Shortahs and Grain. The failures highlight the three-dimensional nature of the potential failure due to blocks formed by the discontinuities and the influence of bench-face orientation on the likelihood for instability. Previous geotechnical investigations have also highlighted the controlling influence of discontinuities on both the stability of the quarry and quarrying operations (Clover 1978; Coggan and Pine 1996; Costa et al. 1999).

Terrestrial digital photogrammetry has significantly improved our ability to measure geometrical properties of rock mass discontinuities. This technique provides a promising supplement to the traditional rock engineering scanline or window mapping methods by overcoming some of their constraints such as accessibility and safety (Sturzenegger and Stead 2009). Many authors have demonstrated the application of this method in characterizing rock masses in underground (Preston et al. 2014) and surface applications (Sturzeneger et al. 2011). If properly georeferenced, a photogrammetry model can provide a valuable discontinuity data set which contains the spatial location of individual discontinuities. This data set then can be used to provide key discontinuity information (e.g. length, orientation and fracture intensity) as a discrete fracture network (DFN) to be incorporated into 3D numerical simulation codes such as 3DEC (Itasca 2014).. Discrete fracture networks have been used in a wide range of geomechanical problems (e.g. large open pits, tunneling, block caving, reservoir geomechanics, etc.). Elmo and Stead (2010) incorporated a discrete fracture network within the FDEM code, ELFEN (Rockfield 2009), to realistically simulate the behaviour of fractured rock pillars. Vyazmensky et al. (2010) used a combined FDEM/DFN modelling approach to investigate the pit wall instability triggered by caving operations at Palabora mine, South Africa.

In this paper long-range terrestrial photogrammetry is used to acquire geometrical properties of discontinuities as well as 3D geometry of the North-East wall of Delabole slate quarry. Discontinuity properties are then used to develop a realistic statistical representation of the fracture system using discrete fracture network. Several realizations of the DFN are then incorporated into 3DEC and the stability of the slope comprehensively investigated. In this paper, the process of digital data acquisition and 3DEC model setup is briefly explained, further details are provided in Havaej et al. (2015).

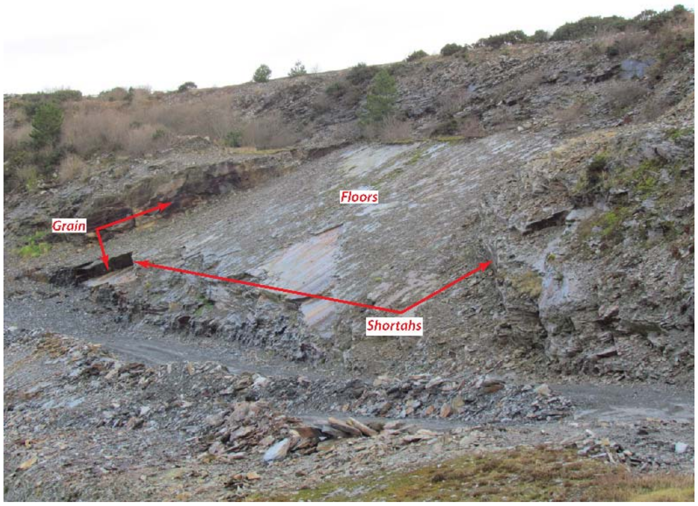


Figure 1. The 2012 planar failure on the upper bench of the north-east Delabole Quarry slope showing the Floors, Grain and Shortahs discontinuity sets that caused the failure; the strike length of upper section of the failure is 50 m

2. METHODOLOGY

Figure 2 shows the methodology used in this study for stability analysis of the NE section of the Delabole Quarry. Terrestrial photogrammetry is used for discontinuity mapping and to obtain a 3D point cloud of the slope geometry. The 3D point cloud is processed to create the 3D slope surface and then converted into a 3D geometry for the subsequent numerical simulations. Discontinuity mapping is also performed using the photogrammetry model, allowing development of a realistic DFN which can be integrated within the 3DEC simulations.

Figure 3 shows the Delabole pit geometry, location of the 2012 slope failure in the north-east section as well as the location of the camera stations within the pit. Terrestrial photogrammetry was performed on the north/north-east slopes using a Canon 7D digital camera with a 200 mm focal length lens. The distance between the slope face and camera stations ranged from 150 to 450 m. The photographs were taken using five camera stations from the bottom of the pit in order to minimize occlusion (Figure 3). The base-distance ratio (the distance between the two camera stations relative to the average distance to the slope face) was set to 1:5 in order to maximize the calculated distance accuracy. All photographs were processed using the Adam Technology 3DM Analyst software suite (ADAM Technology 2014) including 3DM CalibCam, DTM Generator and 3DM Analyst. The point cloud obtained from the photogrammetry model served as an input (to generate the slope geometry) for the subsequent slope stability analysis. The final 3D photogrammetry model and x, y, z, point cloud were then used to map the discontinuities within the pit and to create the 3D slope geometry. Discontinuity surfaces are extracted from the photogrammetry model by fitting a disk to a selected part of the point cloud (Figure 4). The disk is defined by some key information including a vector normal to the plane, origin (x, y, z) and radius. Structural mapping was conducted on the photogrammetry model and all the mapped discontinuities imported into Dips V. 6. 0 (Rocscience 2014a) for discontinuity orientation analysis. Figure 5a shows a lower hemisphere equal angle contoured pole plot of the identified discontinuities. Three discontinuity sets (Floors, Grain and Shortahs) were identified within the slope face. Floors dominate the stability of the north-east slope and are associated with numerous low-angle reverse faults which are also responsible for the thickness of the slate in the quarry (Freshney 1972).

Stability of the north-east wall of the Delabole Quarry is mainly controlled by discontinuities and block kinematics. Therefore a simulation approach which considers the three-dimensional complexity of the rock slope as well as discontinuities provides the most suitable modelling tool. In this study, we use the three-dimensional distinct element code 3DEC V. 5. 0 (Itasca 2014) to investigate the stability of the north/north-east walls of Delabole Quarry. 3DEC has been successfully used to investigate the stability of rock structures in both underground and surface applications. For example, Gao (2013) used 3DEC to study the mechanism of roof failures in underground coal mine roadways. Fekete and Diederichs (2013) used combined laser scaning-3DEC modelling for underground rock mass characterization and stability analysis. Salvini et al. (2014) used a DFN-3DEC approach to investigate the stability of a quarry slope located in the Torano basin, Carrara, Italy. They used a combined terrestrial photogrammetry-laser scanning approach to collect discontinuity data within the quarry. Wolter (2014) used 3DEC to investigate the influence of block geometry and kinematics on failure mechanism of the 1963 Vajont Slide, Italy.

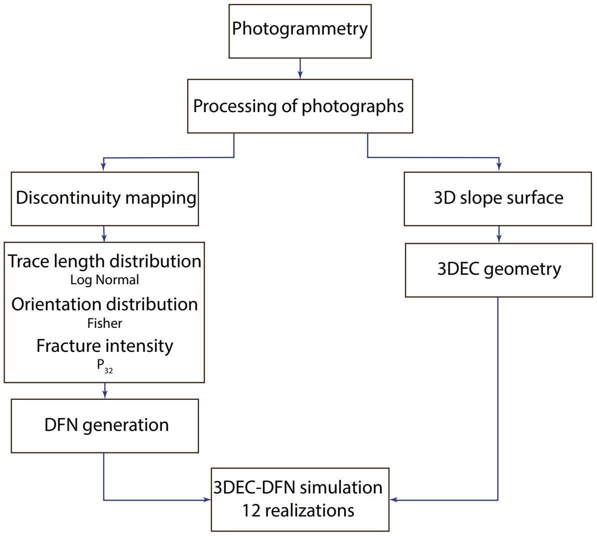


Figure 2. Methodology adopted for rock mass characterization and subsequent numerical simulations

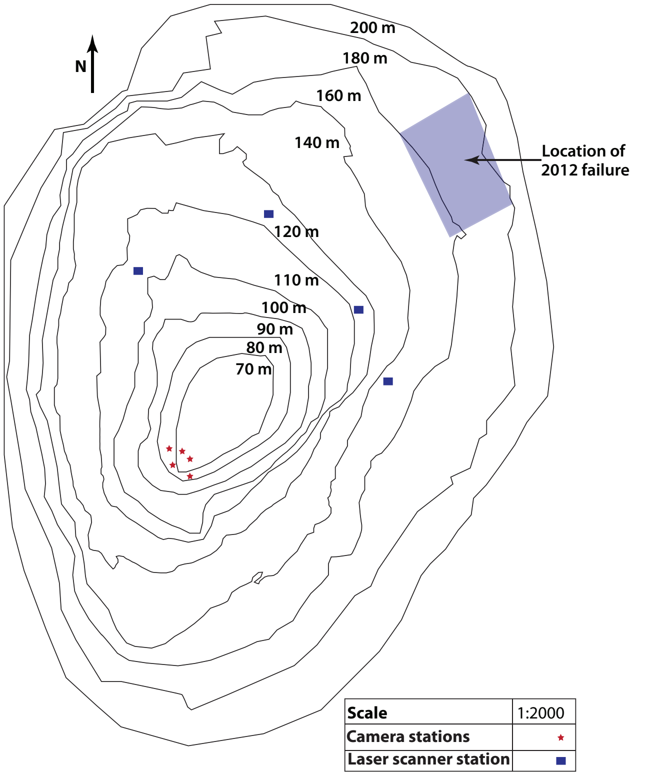


Figure 3. Plan view of Delabole Slate Quarry illustrating the camera and laser scanner stations (after Shillitto 2013)

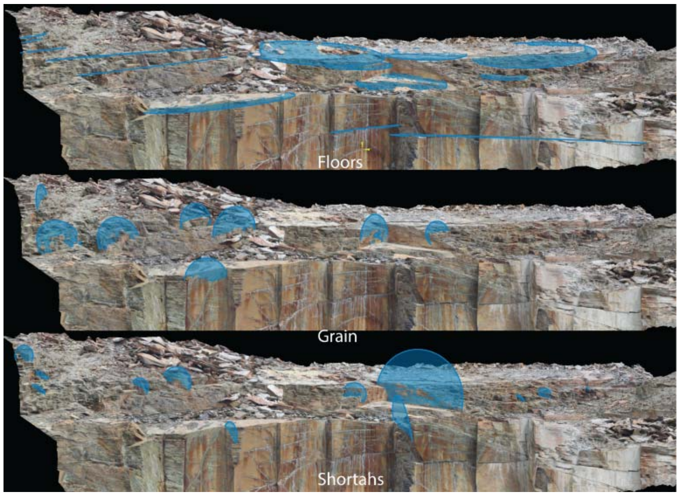


Figure 4. Discontinuity mapping of the North-North East face of Delabole quarry using the photogrammetry model; each disc represents a discontinuity measurement

3. DFN GENERATION AND VALIDATION

The discontinuity data from the photogrammetry model (including orientation, location and fracture intensity) were processed in order to build a representative discrete fracture network. The FracMan code is used to derive the statistical parameters associated with the trace length, orientation as well as the volumetric fracture intensity, P_{32} (area of fractures per unit volume of rock mass).

- Joint set orientation parameters (dip and dip direction) were fitted to a fisher distribution and the output parameters were used to build a representative DFN.
- Values of joint persistence typically display a Negative Exponential, Power Law or Log Normal distribution, whereby the frequency of very persistent discontinuities is much less than that of less persistent discontinuities (Priest and Hudson 1981; Cai 2011). We used a Log Normal distribution to describe fracture size distributions from the mapped discontinuities.
- P_{32} is the preferred measure for fracture intensity for DFN simulation (Rogers et al. 2014). Unlike P_{10} and P_{21} which can be directly derived from field data (using scanline and window mapping), P_{32} cannot be measured in the field. Dershowitz and Herda (1992) proposed a linear correlation between P_{21} (cumulative length of fractures per unit area) and P_{32} (cumulative area of fractures per unit volume) in order to determine P_{32} from P_{21}:

$$P_{32} = C_{21} \times P_{21} \qquad \text{Equation 1}$$

Where, C_{21} is a dimensionless constant (constant of proportionality). The value of C_{21} depends on the orientation and size distributions of the joint set as well as the orientations of the outcrop. It is possible to determine the P_{32} corresponding to the mapped P_{21} in the field by running a series of simulated models and using the fracture size and orientation distributions defined earlier (Staub et al. 2002). A summary of the statistical parameters that describe the fracture network within the north/north-east slopes is provided in Table 1.

Once the statistical characteristics of the representative DFN are determined, they should be validated against the mapped data. In order to do this, orientations and trace length of the synthetic discontinuities are analyzed and compared with the mapped discontinuities. Figure 5 shows lower hemisphere equal angle contoured pole plot of the mapped discontinuities from the photogrammetry model and one DFN realization. The orientations of the stochastically generated discontinuities (Figure 5a) compares favorably with the mapped discontinuities (Figure 5b).

In order to validate the Log Normal distributions assigned to the trace length of the three discontinuity sets, a fracture network associated with each discontinuity set is generated in FracMan (according to the statistical distributions presented in Table 1). The trace lengths of the synthetized discontinuities on the slope face are then analyzed and compared to the trace length analysis for the measured discontinuities. Figure 6 shows the Cumulative Distribution Function for the trace lengths of the mapped discontinuities and a DFN realization. By comparing the range of trace lengths and percentages for the DFN model and the mapped discontinuities, it can be seen that the DFN model favorably reproduces the mapped discontinuities.

Table 1. Summary of the statistical parameters that describe the fracture system within the north, north-east slopes of Delabole Quarry

Discontinuity set	Properties	Distribution	Parameters
Floors	Length(m) Orientation (°) P_{32} (m^{-1})	Log Normal Fisher	µ:0.8 σ: 0.6 D 16, DD 270, κ 18 0.46
Grain	Length(m) Orientation (°) P_{32} (m^{-1})	Log Normal Fisher	µ:0.4 σ: 0.4 D 64, DD 16, κ 8 0.037
Shortahs	Length(m) Orientation (°) P_{32} (m^{-1})	Log Normal Fisher	µ:0.1 σ: 0.6 D70, DD 110, κ 10 0.022

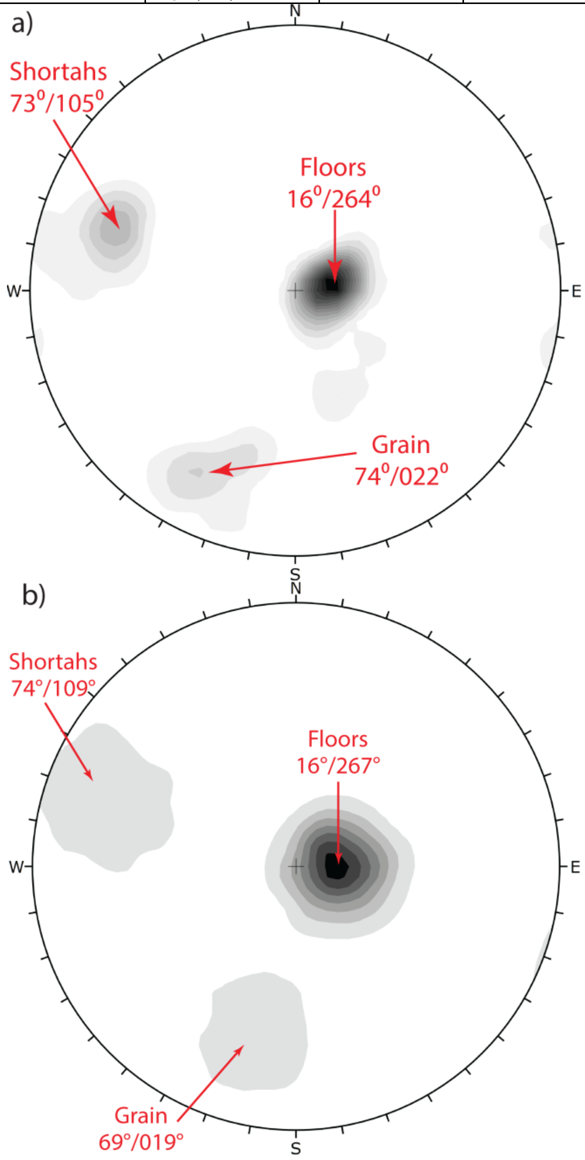


Figure 5. Lower hemisphere equal angle contoured pole plot showing the three discontinuity sets; a) mapped discontinuity sets, b) synthetized discontinuity sets

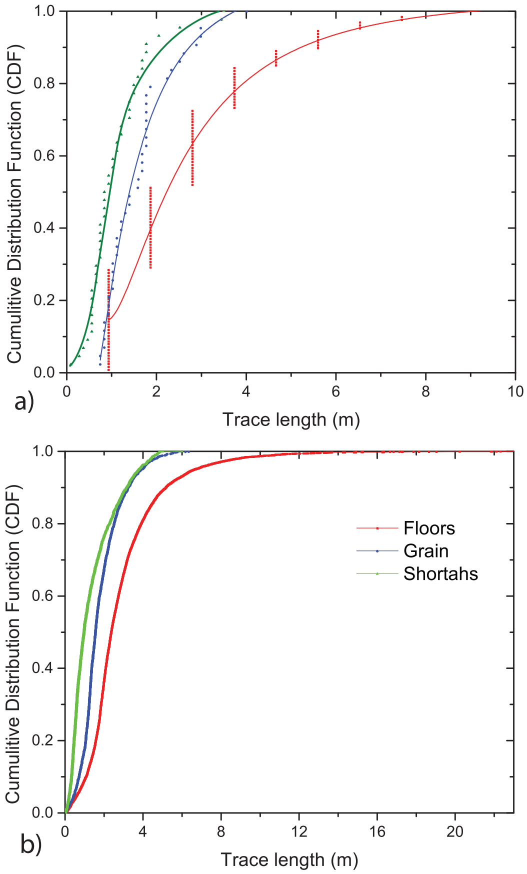


Figure 6. Cumulative Distribution Function of trace lengths for the three discontinuity sets (Floors, Grain and Shortahs) and Log Normal fit assigned to the data a) mapped discontinuity sets, b) synthetized discontinuity sets

4. NUMERICAL MODELLING

The data gained from the terrestrial photogrammetry of the quarry were used to build the geometry of the slope for 3DEC simulations. The georeferenced photogrammetry point cloud was converted into a 3D closed volume for the subsequent distinct element simulations using 3DEC. The model vertical lateral boundaries were fixed in the horizontal direction and the base of the model fixed in both the horizontal and vertical directions. A network of history points comprising five columns and six rows (30 points in total) was located within the model to monitor displacements and velocities throughout the slope simulations (Figure 7). Such an extensive slope monitoring method is designed to better understand the behaviour and stability of different parts of the modelled slope with increasing calculation time steps. This set of history points can help more accurately capture model displacements in each 3DEC-DFN realization. In 3DEC, blocks can behave as either rigid or deformable with an assumed stress–strain constitutive criteria (Cundall 1988). Due to the relatively shallow depth of the quarry (150 m) and the discontinuity controlled nature of the observed instabilities, rigid blocks (with 2600 kg/m^3 density) were assumed in order to focus the investigation on the influence of block kinematics and the strength properties of discontinuities on potential failure mechanisms. Using the statistical parameters associated with the three discontinuity sets (Table 1), discrete fracture networks are developed which were then incorporated within the 3DEC models. Due to the stochastic description of the joint system, each 3DEC model has a unique realization of discontinuities; therefore, each generated DFN is slightly different. In this study 12 DFN realizations are generated and simulated in 3DEC. It should be noted that all models were run for 200000 calculation time steps. Figure 7-9 show block displacement plots for each model. A visual comparison between the results of the DFN models shows that the north-east part of the simulated slope is more unstable than the north section. This is in good agreement with field observations, and emphasizes the controlling influence of discontinuity orientation relative to slope face orientation on potential instability. Since the dip direction of the Floors is within ±20° of the dip direction of the north-east slope, this part of the model is more susceptible to discontinuity-controlled instability. The dip direction of the north part of the model, however, is significantly different from the controlling influence of the Floors, resulting in increased stability within the model. This highlights the detrimental effect of Floors on the stability of the model, particularly within the north-east part of the quarry.

The results of 3DEC-DFN models are used to determine the areas within the quarry with the highest likelihood of block failure. In order to do this, displacements of the history points in each model are exported and the stability state of the model at each history point determined. By repeating this for all models, the number of times that each of the history points show failure (throughout the 12 realizations) can be determined. Using this method a preliminary hazard map which shows the areas with higher risk of failure (areas with higher number of failed blocks) within the pit is developed. Figure 10 illustrates the number of times that any of the 30 history points shows failure (throughout the 12 3DEC-DFN realizations). The figure is colour-coded (with green representing low number of failure instances and red representing higher number of failure instances). This methodology provides improved visualization of the area of the pit which are more likely to develop failure. The figure shows that history locations number 15, 17, 21, and 24 show the highest number of failure instances (they show failure in 4 models). Since all of these history points are located in the centre and right part of the model (North and North-East walls of the pit), it can be concluded that North and the North-East walls of the pit have the highest hazard and are more susceptible to block instability.

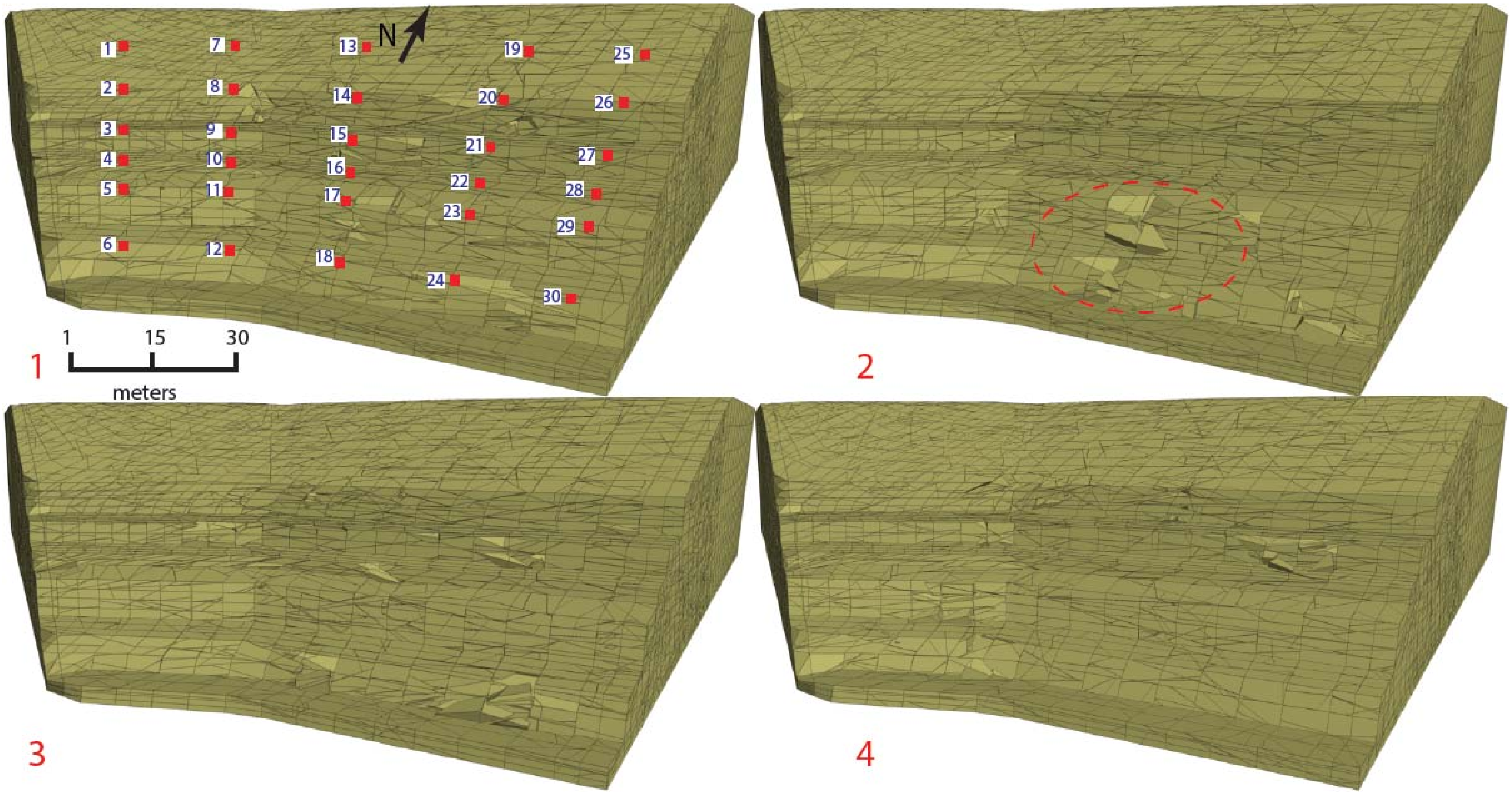


Figure 7. Block displacement plots for the four different 3DEC-DFN model realizations (realizations 1-4)

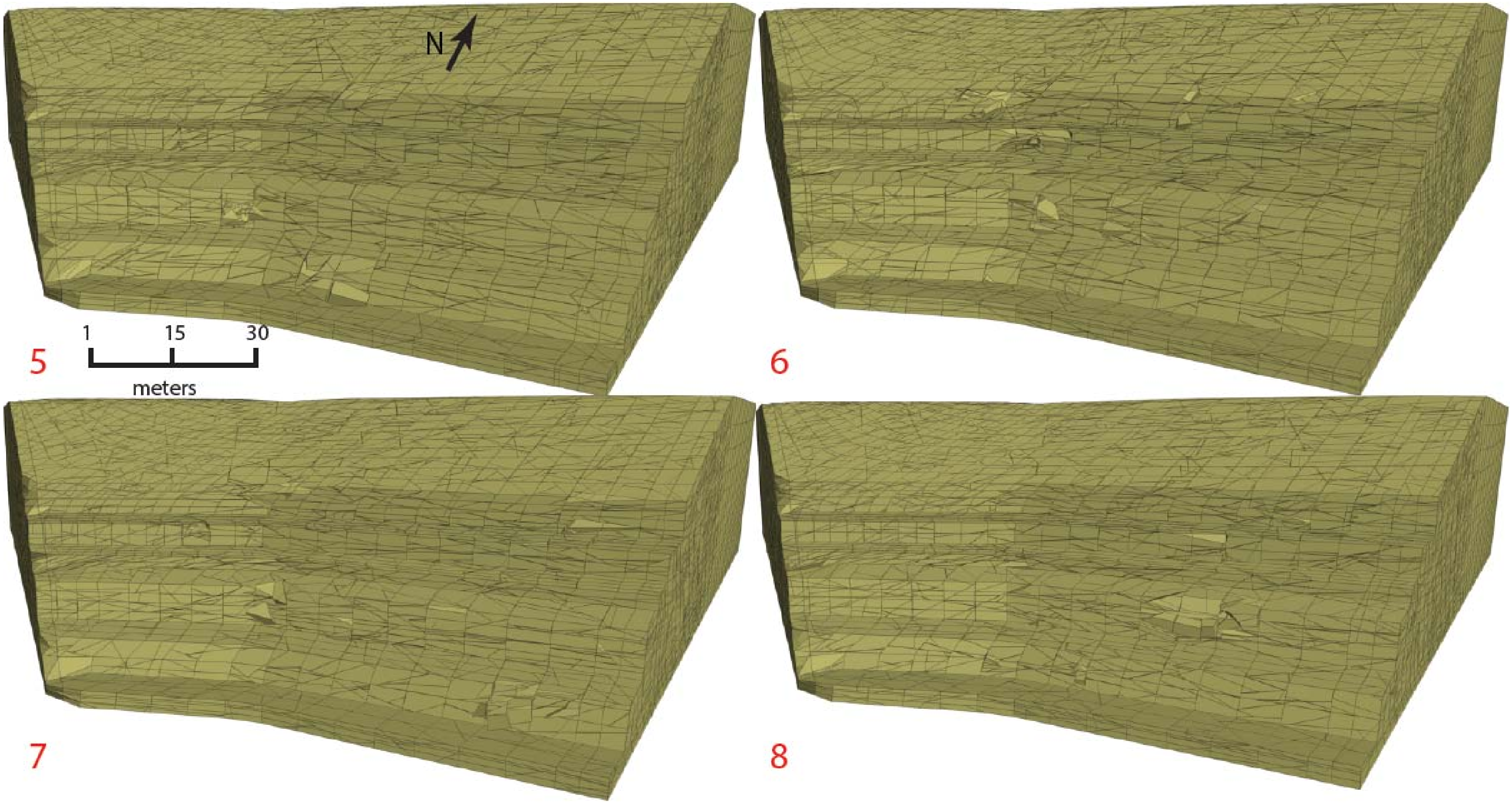


Figure 8. Block displacement plots for the four different 3DEC-DFN model realizations (realizations 5-8)

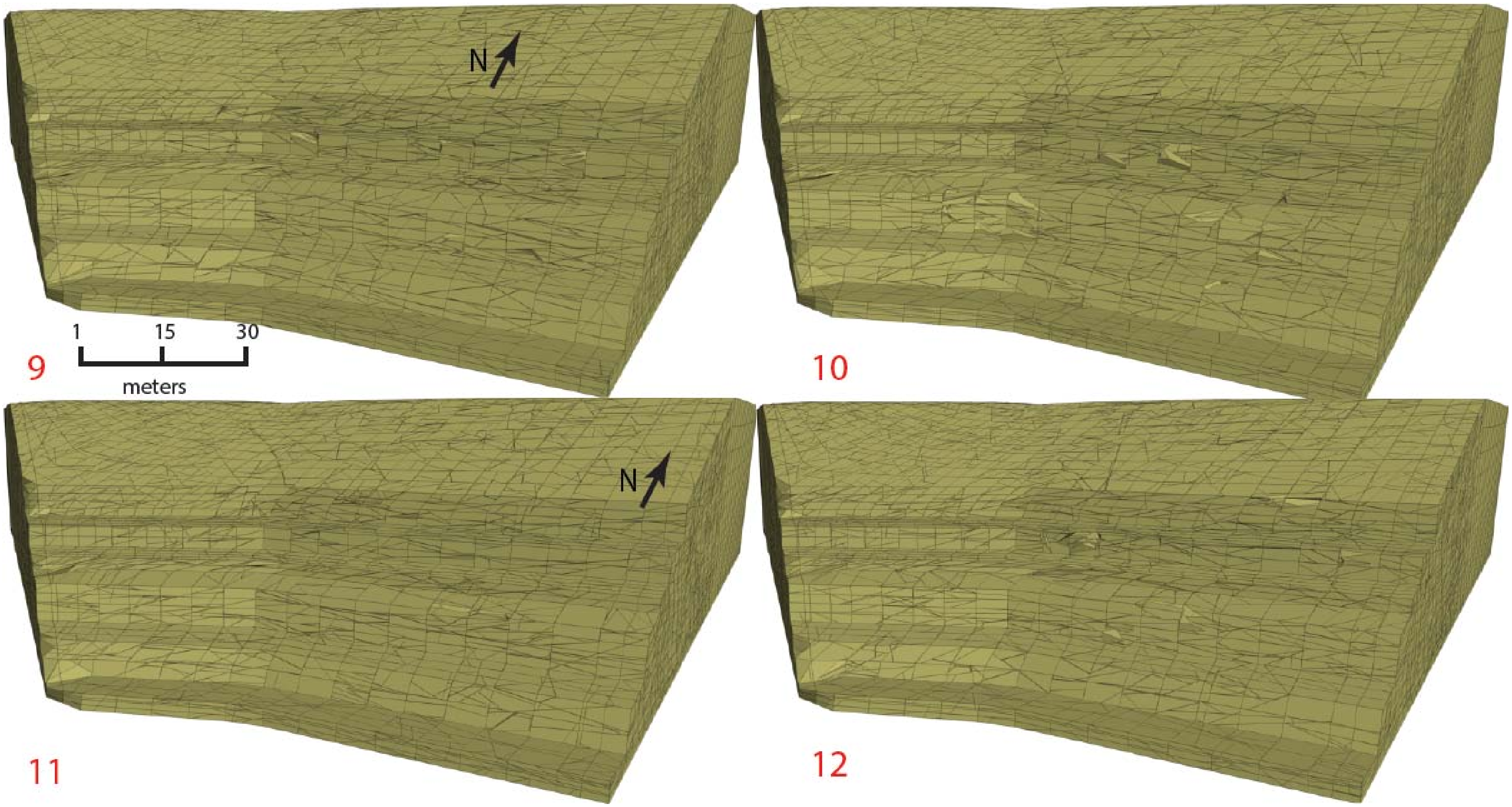
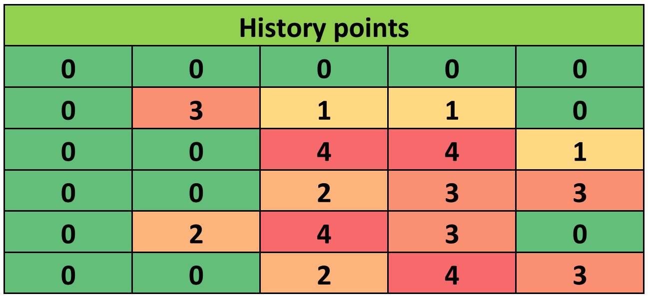


Figure 9. Block displacement plots for the four different 3DEC-DFN model realizations (realizations 9-12)



History points				
0	0	0	0	0
0	3	1	1	0
0	0	4	4	1
0	0	2	3	3
0	2	4	3	0
0	0	2	4	3

Figure 10. Quarry slope hazard matrix; colour-coding illustrates the number of times that each history point has failed in the 12 3DEC-DFN realization undertaken

5. CONCLUSIONS

Digital data acquisition has been successfully used to collect discontinuity characteristics for the north-east slope of Delabole Slate Quarry. Using this technique an accurate data set which includes key discontinuity properties such as orientation, trace length and the location of each discontinuity measurement was produced. This extensive data set was then used to statistically describe the variability of discontinuity orientation, length and intensity through development of discrete fracture networks. Incorporation of these DFNs into realistic 3D slope geometry of the Delabole Quarry developed from the photogrammetry point cloud, helped to better understand the influence of discontinuity variability, kinematics and slope orientation on the potential failure mechanism of the rock slope.

Twelve stochastic simulations, using a combined 3DEC-DFN approach were conducted (Figure 7-9). The simulation results successfully captured the observed block failures within the north-east slope of the Delabole Quarry. Application of the DFN method provided several stochastically generated simulations which were used to develop a preliminary hazard matrix/map of the quarry pit. The hazard map showed that the North and North-East walls of the quarry pit are more likely to develop block related instabilities.

6. REFERENCES

1. ADAM Technology. 2014. 3DM Analyst Mine Mapping Suite. Belmont, Australia: ADAM Technology.
2. Cai, M. 2011. “Rock Mass Characterization and Rock Property Variability Considerations for Tunnel and Cavern Design.” Rock Mechanics and Rock Engineering 44 (4): 379–99. doi:10.1007/s00603-011-0138-5.
3. Clover, A. W. 1978. “Some Aspects of the Rock Excavations on the Western Face at Delabole Slate Quarry, Cornwall.” MSc Thesis, London, UK: Imperial College, University of London.
4. Coggan, J. S., and R. J. Pine. 1996. “Application of Distinct-Element Modelling to Assess Slope Stability at Delabole Slate Quarry, Cornwall, England.” In , A22–30. Transactions of the Institution of Mining and Metallurgy. Section A. Mining Industry 105.
5. Costa, M., J.S. Coggan, and J.M. Eyre. 1999. “Numerical Modelling of Slope Behaviour of Delabole Slate Quarry (Cornwall, UK).” International Journal of Surface Mining, Reclamation and Environment 13 (1): 11–18. doi:10.1080/09208119908944196.
6. Cundall, P. A. 1988. “Formulation of a Three-Dimensional Distinct Element model—Part I. A Scheme to Detect and Represent Contacts in a System Composed of Many Polyhedral Blocks.” International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 25 (3): 107–16. doi:10.1016/0148-9062(88)92293-0.
7. Dershowitz, W. S., and H. Herda. 1992. “Interpretation of Fracture Spacing and Intensity.” In 42nd U.S. Rock Mechanics/Geomechanics Symposium, 8 pages. Santa Fe, New Mexico: American Rock Mechanics Association. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=ARMA-2012-248&societyCode=ARMA.
8. Fekete, S., and M. Diederichs. 2013. “Integration of Three-Dimensional Laser Scanning with Discontinuum Modelling for Stability Analysis of Tunnels in Blocky Rock masses.” International Journal of Rock Mechanics and Mining Sciences 57 (January): 11–23. doi:10.1016/j.ijrmms.2012.08.003.
9. Freshney, E. C. 1972. Geology of the Coast between Tintagel and Bude: (Explanation of Part of One-Inch Geological Sheet 322, New Series). London: Her Majesty’s Stationery Office. https://catalyst.library.jhu.edu/catalog/bib_821412.
10. Gao, F. 2013. “Simulation of Failure Mechanisms around Underground Coal Mine Openings Using Discrete Element Modelling.” PhD Thesis, Burnaby, Canada: Simon Fraser University.
11. Havaej, M., J. Coggan, D. Stead, and D. Elmo. 2015. “A Combined Remote Sensing–Numerical Modelling Approach to the Stability Analysis of Delabole Slate Quarry, Cornwall, UK.” Rock Mechanics and Rock Engineering, August, 1–19. doi:10.1007/s00603-015-0805-z.
12. Itasca. 2014. 3DEC-3 Dimensional Distinct Element Code User’s Guide (version 5.0.). Minneapolis, United States.: Itasca Consulting Group Inc.
13. Preston, R., D. Roberts, H. McIntire, and D. Stead. 2014. “Use of Photogrammetry and Discrete Fracture Networks to Characterize Pillar Damage and Rock Mass Characteristics.” In International Discrete Fracture Network Engineering Conference, 11 – pages. Vancouver, Canada.
14. Priest, S.D., and J.A. Hudson. 1981. “Estimation of Discontinuity Spacing and Trace Length Using Scanline Surveys.” International Journal of Rock Mechanics and Mining Sciences & Geomechanics

Abstracts 18 (3): 183–97. doi:10.1016/0148-9062(81)90973-6.

15. Riggs, W. H. H. 2014. “Applications of Thermal Imaging in Mining and Coastal Slope Stability Analysis.” MSc Thesis, Penryn, UK: The University of Exeter.

16. Rockfield. 2009. ELFEN Manual Version 4.4. (version 4.4.). Swansea, UK: Rockfield Software Limited.

17. Rocscience. 2014. Dips 6.0, Graphical and Statistical Analysis of Orientation Data (version 6.0.). Toronto, Canada: Rocscince Inc.

18. Rogers, S., D. Elmo, G. Webb, and A. Catalan. 2014. “Volumetric Fracture Intensity Measurement for Improved Rock Mass Characterisation and Fragmentation Assessment in Block Caving Operations.” Rock Mechanics and Rock Engineering, April, 1–17. doi:10.1007/s00603-014-0592-y.

19. Salvini, R., R. Giovannini, C. Vanneschi, S. Riccucci, M. Francioni, and D. Stead. 2014. “The Use of Remote Sensing for Iscontinuity Mapping and Analysis in a Large Marble Quarry, Carrara, Italy.” In International Discrete Fracture Network Engineering Conference, 11 pages. Vancouver, Canada.

20. Shillitto, D. A. 2013. “Delabole Quarry - Geotechnical Assessment and Pit Design of the North East Sector.” MSc Thesis, Penryn, UK: The University of Exeter.

21. Staub, I., A. Fredriksson, and O. Outters. 2002. “Strategy for a Rock Mechanics Site Descriptive Model Development and Testing of the Theoretical Approach.” SKB Rapport R-02-02. Stockholm Sweden: Swedish Nuclear Fuel and Waste Management Co.

22. Sturzenegger, M., and D. Stead. 2009. “Quantifying Discontinuity Orientation and Persistence on High Mountain Rock Slopes and Large Landslides Using Terrestrial Remote Sensing Techniques.” Nat. Hazards Earth Syst. Sci. 9 (2): 267–87. doi:10.5194/nhess-9-267-2009.

23. Sturzenegger, M., D. Stead, and D. Elmo. 2011. “Terrestrial Remote Sensing-Based Estimation of Mean Trace Length, Trace Intensity and Block Size/shape.” Engineering Geology 119 (3–4): 96–111. doi:10.1016/j.enggeo.2011.02.005.

24. Vyazmensky, Alexander, D. Stead, D. Elmo, and A. Moss. 2010. “Numerical Analysis of Block Caving-Induced Instability in Large Open Pit Slopes: A Finite Element/discrete Element Approach.” Rock Mechanics and Rock Engineering 43 (1): 21–39. doi:10.1007/s00603-009-0035-3.

25. Wolter, A. 2014. “Characterisation of Large Catastrophic Landslides Using an Integrated Field, Remote Sensing and Numerical Modelling Approach.” PhD Thesis, Burnaby, Canada: Simon Fraser University.