

## *Selected Slope Model Publications*

### Journals:

1. Havaej, M. and D. Stead. (2016) "Investigating the Role of Kinematics and Damage in the Failure of Rock Slopes," *Computers and Geotechnics*, **78**, pp. 181-193.

ABSTRACT: Recent developments in numerical codes provide an important tool for modeling brittle fracture associated with the failure of rock slopes. This is particularly important in simulation of rock slopes that may initially appear kinematically stable but if brittle fracture is considered within the model, stress-induced release surfaces may cause slope failure. This paper investigates the inter-relation between kinematics, failure surface geometry and damage leading to the failure of high rock slopes using a three dimensional lattice-spring code. Two new methods are introduced to quantify damage in our numerical simulations. In the first method, an "ellipsoid of damage" is defined to encompass newly created cracks within a given rock Slope Model. Geometrical characteristics of the ellipsoid including volume, length and orientation of its axes allow quantification of damage within a model. In the second method, damage is quantified using "damage intensity" parameters, D21 and D32. In this method damage is defined as the ratio of total length/area of the newly created cracks within the model to the sampling area/volume. The combined use of these two approaches allows a quantitative description of the intensity and extent of damage development within the rock Slope Models. Our numerical simulation results highlight a strong relationship between kinematics, failure surface geometry and damage in the failure of high rock slopes.

2. Havaej, M., A. Wolter and D. Stead. (2015) "The possible role of brittle rock fracture in the 1963 Vajont Slide, Italy," *Int. J. of Rock Mechanics & Mining Sciences*, **78**, pp. 319-330.

ABSTRACT: We use a state-of-the-art numerical simulation approach to investigate the Vajont slope failure, a large catastrophic landslide that resulted in the loss of 1910 lives. This study represents the first three-dimensional (3D) brittle fracture simulation of the Vajont Slide that includes the effect of groundwater on the failure process. A realistic representation of the Vajont slope geometry, failure surface and discontinuities in a 3D lattice spring code allowed us to study the kinematics of the landslide. Using a lattice-spring block model approach, the relations among the number of blocks, slope damage, and stability are investigated. The influence of an elevated groundwater table on displacements and cracking within the model is evaluated. The results show a good agreement with the reported microseismic events prior to the failure. Two new techniques, "damage intensity", D32, and the "ellipsoid of damage", are introduced and used to quantify brittle damage within the numerical simulations.

3. Vivas, J., D. Stead, D. Elmo and C. Hunt. (2015) "Simulating the Interaction Between Groundwater and Brittle Failure in Open Pit Slopes," *Int. J. of Environmental, Chemical, Ecological, Geological and Geophysical Engineering*, **9**(12), pp. 1295-1303.

ABSTRACT: This paper presents the results of a study on the influence of varying percentages of rock bridges along a basal surface defining a biplanar failure mode. A pseudo-coupled-

hydromechanical brittle fracture analysis is adopted using the state-of-the-art code Slope Model. Model results show that rock bridge failure is strongly influenced by the incorporation of groundwater pressures. The models show that groundwater pressure can promote total failure of a 5% rock bridge along the basal surface. Once the percentage of the rock bridges increases to 10 and 15%, although, the rock bridges are broken, full interconnection of the surface defining the basal surface of the biplanar mode does not occur. Increased damage is caused when the rock bridge is located at the daylighting end of the basal surface in proximity to the blast damage zone. As expected, some cracking damage is experienced in the blast damage zone, where properties representing a good quality controlled damage blast technique were assumed. Model results indicate the potential increase of permeability towards the blast damage zone.

#### Conference Proceedings:

4. Cundall, P.A., B. Damjanac and Varun. (2016) "Considerations on Slope Stability in a Jointed Rock Mass," ***Proceedings, 50<sup>th</sup> U.S. Rock Mechanics/Geomechanics Symposium (Houston, Texas, June 2016)***. ARMA 16-0339. Alexandria, Virginia: ARMA.

ABSTRACT: We consider a jointed rock mass in which significant brittle fracturing is necessary between discontinuous joint segments for overall failure to occur. Simple methods to determine slope stability in such a rock mass rely on assumptions about the behavior of rock bridges. We use simple examples to show such assumptions — for example, the notion of an equivalent shear strength — to be unjustified. Further, the fracture behavior of a joint segment may be influenced by the proximity of another joint segment, even if there is no fracturing between the segments. The conclusion is that small details of joint geometry may influence the stability of a slope. Since such details cannot be determined for in situ rock masses, it is believed that for the class of rock masses considered slope stability estimates must be assigned great uncertainty, or a large number of realizations must be considered to understand the range of outcomes and to determine the probability of failure.

5. Macciotta, R. and C.D. Martin. (2016) "Influence of Joint Stiffness in Back Analysis of Rock Tensile Strength Using *Slope Model*," in ***Applied Numerical Modeling in Geomechanics – 2016, Proceedings of the 4<sup>th</sup> Itasca Symposium on Applied Numerical Modeling (Lima, Peru, March 2016)***. pp. 111-120. P. Gómez, C. Detournay, R. Hart and M. Nelson, Eds. Minneapolis: Itasca.

ABSTRACT: Slope Model is a discontinuous approach capable of incorporating the geometry and geomechanical properties of discontinuities explicitly within the rock mass. Two objectives for its development are the back analysis of rock slope failures to understand their mechanisms, and investigate the contribution of intact rock bridges in the stability of rock slopes. Variations in discontinuity normal and shear stiffness can impact the back analysis of a slope failure. This paper evaluates the variation in rock tensile strength required to achieve a state of insipient failure with variations of discontinuity stiffness. Variations of discontinuity normal and shear stiffness through three orders of magnitude resulted in variations of the rock tensile strength up to +/- 60% of average results. All models suggested that internal rock breakage was required for sliding to be kinematically feasible.

6. Silva Guzmán, R. and P. Gómez Pérez. (2015) "Towards a Mechanically Based Definition Of the Disturbance Factor Using The "Slope Model" Lattice Code," *Integrating Innovations of Rock Mechanics, Proc. of the 8<sup>th</sup> South American Congress on Rock Mechanics (Buenos Aires, Argentina, November 2015)*. R.J. Rocca et al., Eds. pp. 3-10. doi: 10.3233/978-1-61499-605-7-3. IOS Press.

ABSTRACT: The disturbance factor (D) included in the Hoek-Brown criterion represents a strength reduction parameter associated to the damage induced in large open pit slopes as a result of the blasting process and also as a consequence of the stress relaxation and stress rotations induced by the excavations during the mining process. The spatial distribution of the D factor, as well as its value, remain unresolved issues in the current rock mechanics practice applied to slope stability analysis. While it is reasonable to expect that in the long term, numerical modeling based on lattice formulations or strain softening constitutive models will be able to address this issue properly, the current state-of-the-practice (using both limit equilibrium and numerical modeling approaches) will remain applicable for some time. Current methods would therefore benefit from more robust guidelines to define the extent of the disturbed zone, as well as the distribution of strength degradation of the rock masses within a mined slope. In this study, an empirically-based guideline is proposed for the distribution of disturbance with depth in a slope. Furthermore, a first step is made at providing a mechanical interpretation of the disturbance of large open pit slopes in medium to hard rocks due to loss of confinement and is aimed at defining the extent of disturbance using lattice modeling. As the final purpose of the study is identifying the real effect of the disturbance in the strength properties and its location with respect to the slope surface, some initial attempts are also made to measuring the strength of undisturbed and disturbed rock mass samples using a Synthetic Rock Mass approach.

7. Havaej, M., D. Stead, J. Mayer, and A. Wolter. (2014) "Modelling the relation between failure kinematics and slope damage in high rock slopes using a lattice scheme approach," in *Proceedings, 48<sup>th</sup> US Rock Mechanics/Geomechanics Symposium (Minneapolis, Minnesota, June 2014)*, ARMA-14-7374. Alexandria, Virginia: ARMA.

ABSTRACT: With recent developments in numerical codes, it is now possible to investigate the relation between kinematics and the damage required for the failure of rock slopes. This paper investigates the influence of kinematics and failure surface geometry on damage leading to the failure of rock slopes using a three-dimensional lattice spring code. Two new methods are introduced to quantify damage in the numerical simulations. In the first method, damage is quantified using "damage intensity" parameters,  $D_{21}$  and  $D_{32}$ . In this method damage is defined as the ratio of total length/area of the newly created cracks within the model to the sampling area/volume. In the second method an "ellipsoid of damage" is defined to encompass newly created cracks within a given model. Geometrical characteristics of the ellipsoid including volume, length and orientation of its axes allow quantification of damage within the model. The numerical simulation results highlight the close connection between kinematics and damage in high rock slopes.

8. Macciotta, R., and Martin, C. D. (2015). "Discontinuum model to improve understanding of the behaviour of a slope close to limit equilibrium," in *Slope Stability 2015* (Proceedings, International

Symposium on Slope Stability in Open Pit Mining and Civil Engineering, Cape Town, South Africa, 2015). pp. 329–340. Johannesburg, South Africa: SAIMM/SANIRE.

**ABSTRACT:** The occurrence of some rock slides requires the breakage of intact rock for the formation of a through-going sliding surface. This breakage of intact rock is associated with deformation processes and progressive failure of rock slopes. Numerical approaches incorporating the geometry and geomechanical properties of discontinuities and intact rock in an explicit manner offer a means to model the initiation and propagation of failure along discontinuities and intact rock. This paper presents a case study of a rock slope cut that showed up to 15 cm of deformation during excavation works. The deformations were associated with a wedge sliding on non-daylighting shears. A numerical analysis of the slope was performed that allowed slippage through explicit discontinuities and breakage of intact rock. The model shows that slope displacements are defined by the geometry of the major discontinuities, and that breakage of intact rock along the toe of the slope and throughout the rock mass occurs within the deforming mass. The model illustrates the practical use of a discontinuum approach to understand the progressive failure mechanisms of a slope that was considered to be close to limit equilibrium during excavation but had not failed in a sudden catastrophic manner.

9. Havaej, M., A. Wolter, D. Stead, Z. Tuckey, L. Lorig and E. Eberhardt. (2013) “Incorporating Brittle Fracture into Three-Dimensional Modelling of Rock Slopes,” in ***Slope Stability 2013 (Proceedings, International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering Brisbane, Australia, September 2013)***. pp. 625–638, P. Dight, Ed. Perth: Australian Centre for Geomechanics.

**ABSTRACT:** During the last decade significant advances have been made in the two-dimensional modelling of brittle fracture associated with rock slope failure both in open pit mines and natural mountain slopes. This paper focuses on the application of the three-dimensional lattice code, Slope Model, in modelling brittle fracture and damage evolution involved in three-dimensional kinematically-controlled slope instability mechanisms. Results of simulations of non-daylighting wedge failure and active-passive block slope failures are presented, with an emphasis on characterising brittle damage at varying stages of slope failure development. A new approach to characterising brittle fracture damage is developed based on fracture generation rates and the inverse velocity of the failing rock mass. Brittle fracturing of ‘in-plane’ and ‘out-of-plane’ rock bridges is simulated using a conceptual approach incorporating a simple Discrete Fracture Network (DFN) into simulations. In order to simulate the complex geometry associated with three-dimensional slope failures, pre-processing routines have been developed to incorporate photogrammetric and LiDAR derived Digital Elevation Models (DEMs) within the Slope Model software. Procedures are demonstrated through the use of preliminary Slope Model simulations of the Vajont landslide, a major catastrophic landslide, which resulted in the loss of over 2,000 lives.

10. Damjanac, B., P. A. Cundall and Varun. (2013) “Validation of Lattice Approach for Rock Stability Problems,” in ***Proceedings, 47th US Rock Mechanics/Geomechanics Symposium (San Francisco, California, June 2013)***. ARMA 13-488. Alexandria, Virginia: ARMA.

ABSTRACT: Conventional design methods for rock slopes involve the use of continuum strength criteria for rock mass, such as Hoek-Brown. Alternatively, a numerical approach has been developed based on the distinct element method. Rather than using finite-sized particles, a greater efficiency can be realized with a lattice of point masses connected by springs. This model allows fracture by the breakage of springs and joint slip by using a smooth representation of joint segments. The methodology of a new 3D lattice program, Slope Model, is described in this paper. Slope Model allows a general geometry of a rock slope to be simulated. The rock mass contains joint segments derived from a user-specified Discrete Fracture Network (DFN). The code and the lattice approach are verified and validated for rock mass stability analysis by comparing the model predictions with analytical solutions and experimental data. The results of the validation of the lattice approach by comparison with solution and test data for bending of a beam, propagation of a wing crack, shearing of a rock bridge and flexural toppling are presented in this paper.

11. Havaej, M., D. Stead, L. Lorig and J. Vivas. (2012) "Modelling rock bridge failure and brittle fracturing in large open pit rock slopes," in ***Proceedings, 46<sup>th</sup> US Rock Mechanics/Geomechanics Symposium, (Chicago, Illinois, June 2012)***. Paper No. 12-248. Alexandria, Virginia: ARMA.

ABSTRACT: As large open pit slopes increase in depth, it is becoming increasingly necessary to investigate nonconventional slope failure mechanisms. The existence of rock bridges can have a significant effect on rock slope stability therefore, it is necessary to further our understanding of the impact of rock bridges and brittle fracture processes. In the first part of this study, the 3D lattice spring code Slope Model allows evaluation of the effect of rock bridges on the stability of a pentahedral or "non-daylighting" wedge. The geometry adopted simulates a 3D equivalent of a conventional 2D bi-planar wedge. As a preliminary analysis, various rock bridge percentages were simulated by the location of intact rock along the basal surface of the wedge. The results demonstrated that 2% rock bridges on the basal surface were required to stabilize the wedge. In the second part of this study, the staged construction of a rock slope containing a pentahedral wedge was modeled to investigate damage at the toe of the slope and the depth at which the wedge would fail. Significant damage at the toe was noted prior to daylighting of the basal surface of the wedge.

12. Tuckey, Z., D. Stead, M. Havaej, F. Gao, and M. Sturzenegger. (2012) "Towards an Integrated Field Mapping-Numerical Modelling Approach for Characterising Discontinuity Persistence and Intact Rock Bridges in Large Open Pits," in ***GeoManitoba, Building on the Past (Proceedings, 65th Canadian Geotechnical Conference, Winnipeg, September 30-October 3, 2012)***, Paper 182. Toronto: Canadian Geotechnical Society.

ABSTRACT: Four major rock slopes were investigated using modified geotechnical survey methods to help improve characterisation of discontinuity persistence and intact rock bridges. Field observations and digital mapping results form the basis for a conceptual numerical modelling study, where distinct element and lattice-spring codes were used to investigate the influence of intact rock bridge content on slope behaviour. Preliminary results suggest that in addition to increasing shear strength along potential failure surfaces, intact rock bridge content can also influence the internal strength and deformability of potential slide volumes. Based on field observations and modelling results, the authors make preliminary recommendations for improving characterisation of discontinuity persistence and intact rock bridges in rock slopes. The

authors emphasize the need for a flexible methodology, which can be adapted according to site-specific factors including geology, slope size, blast-induced damage, and the mapping tools available to the practitioner.

13. Lorig, L., P. A. Cundall, B. Damjanac and S. Emam. (2010) "A Three-Dimensional Model for Rock Slopes Based on Micromechanics," in ***Proceedings, 44th U.S. Rock Mechanics Symposium/5th U.S.-Canada Rock Mechanics Symposium (Salt Lake City, June 2010)***, Paper No. 10-163. Alexandria, Virginia: ARMA.

ABSTRACT. Conventional analysis methods for rock slopes typically involve the use of empirical methods to estimate continuum strength criteria for the rock mass, ignoring important mechanical aspects such as size effect or the complex propagation of localized failure. A numerical approach based on the distinct element method (DEM) and called the Synthetic Rock Mass (SRM) has recently been developed, which allows both fractures to develop in the intact material and joint slip. A new 3D program, Slope Model, based on the SRM and on a "lattice" representation of brittle rock that accepts an overlaid general Discrete Fracture Network is described. Non-steady fluid flow is modeled throughout the jointing network, with full mechanical coupling, including strain-induced aperture variation, evolution of the pressure and flow fields due to mechanical and fluid perturbations, and the influence of changing effective pressures on slope stability.

14. Cundall, P. A., and B. Damjanac. (2009) "A Comprehensive 3D Model for Rock Slopes Based on Micromechanics," in ***Slope Stability 2009 (Proceedings, International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Santiago, Chile, November 2009)***. Perth: Australian Centre for Geomechanics.

ABSTRACT: Conventional design methods for rock slopes involve the use of continuum strength criteria (such as Hoek Brown) for the rock mass, in which yield of both intact material and discontinuities (joints) must occur for overall failure to take place. Empirical methods often are used to estimate parameters for the rock mass because of the impossibility of testing directly (to failure) a large extent of rock. Alternatively, a numerical approach, called the synthetic rock mass (SRM), has been developed, based on the distinct element method. Rather than using finite-sized particles, greater efficiency can be realized with a "lattice" of point masses connected by springs. This model allows fracture, by breakage of springs, and joint slip, using a smooth representation of joint segments. The methodology of a new 3D lattice program, Slope Model, is described, which accepts a general DFN (discrete fracture network). Fluid flow throughout the jointing network also is modeled, with the resulting pressures being used to compute effective stresses on each joint element. Pressure changes also arise through mechanical coupling. Examples are presented of the use of Slope Model to determine the stability, flow regime and transient coupled response of 3D jointed rock slopes due to mining activities.

Theses:

15. Havaej, M. (2015) ***Characterisation of High Rock Slopes using an Integrated Numerical Modelling - Remote Sensing Approach***. Ph.D. Thesis, Simon Fraser University.

ABSTRACT: During the last decade significant advances have been made in geomechanical modelling and remote sensing data acquisition techniques. These developments have allowed for improved rock slope stability analysis through consideration of the role of brittle fracture, kinematics and spatial variability in discontinuities within numerical models. This thesis investigates the role of several key parameters including damage, failure surface geometry and kinematics in rock slope failure using both conceptual slope geometries and natural and engineered rock slopes. Investigation of bi-planar and ploughing failure mechanisms in footwall slopes using the hybrid FDEM code, ELFEN, highlights the role of both brittle fracture in the development of secondary release surfaces and rock mass dilation in facilitating the slope failure. The bi-planar models show development of a highly damaged transition zone between the active and passive blocks. This failure mechanism is also observed in pseudo-two-dimensional bi-planar simulations using Slope Model. Three-dimensional simulation of non-daylighting wedges using Slope Model shows that this type of wedge, although apparently kinematically stable may in practice fail through stress concentration at the slope toe leading to failure of rock bridges, toe-breakout and slope collapse. Long-range terrestrial photogrammetry was conducted of the north-east slope of the Delabole Quarry, Cornwall, UK. The photogrammetry model was used to characterize rock discontinuities and to develop a realistic 3D geometry for subsequent distinct element analysis using 3DEC. The effect of selected input parameters (discontinuity friction angle, spacing and persistence) on the stability of the quarry slope was investigated using a deterministic approach. A stochastic approach using discrete fracture networks (DFN) was also employed to investigate the role of discontinuity uncertainty and spatial variability on the failure mechanism of the quarry slope. The deterministic and stochastic 3DEC-DFN models highlighted the role of kinematics and spatial variability of discontinuity characteristics on the slope failure mechanism, size and shape of the failed blocks. Lattice spring 3D simulations (using Slope Model) of the 1963 Vajont Slide, a catastrophic landslide that resulted in the loss of 1910 lives, clearly emphasized the role of brittle fracture, kinematics, block size and raised groundwater level on the failure mechanism. The Slope Model simulations conducted represent the first 3D brittle fracture simulation of the landslide considering the effect of groundwater on the failure. Innovative data post processing techniques are introduced throughout the thesis and used to gain a better understanding of the failure mechanisms of the modeled rock slopes. Damage extent parameters (ellipse of damage in 2D and ellipsoid of damage in 3D) are introduced and used to characterize the extent of the damaged zone within the numerical simulations. Inverse numerical velocity is also adopted within this dissertation to determine the numerical onset-of-failure and to better understand the regressive and progressive failure stages within the model simulations.

16. Becerra, J.V. (2014) ***Groundwater Characterization and Modelling in Natural and Open Pit Rock Slopes***. MS Thesis, Simon Fraser University.

ABSTRACT: The stability of rock slopes is often compromised by the presence of groundwater in the discontinuities within the rock mass. Discontinuities form the major pathways for groundwater flow and result in seepage zones along slopes. The hydrogeological characterization of fractures is, hence, an important task in rock slope investigations. Nevertheless, most current techniques require direct access to the rock slope, which can often be severely limited due to access, safety and the limited coverage of survey methods. In an attempt to both complement and overcome existing limitations of current methods, the present research makes use of remote sensing techniques to implement a window mapping approach to allow for the collection of

structural and seepage information over a wide spatial area. Photogrammetry, ground based LiDAR and Infrared Thermography (IRT) are discussed.

Research is also undertaken investigating continuum, discontinuum (distinct element model) and lattice-spring scheme modelling applied to assess the effect of groundwater on large open pit rock slope stability. Fluid flow within a fractured rock mass occurs as a coupled process where the flow field is influenced by the stress field and changes in stress resulting in changes in pore water pressures within the rock mass. Understanding coupled and uncoupled groundwater and mechanical processes in complex fractured rocks is essential for slope-stability engineering. Application of Discrete Fracture Network Engineering (DFNE) methods in the interpretation of seepage zones and simulated damage within rock slopes (due to both mechanical and pore water pressure induced brittle fracture) are demonstrated.

The key findings gathered through this research highlight the importance of considering the use of coupled field and state-of-the-art remote sensing techniques in the characterization of seepage areas on high engineered and natural rock slopes. Discontinuity persistence is shown to be a parameter that is highly dependent on the sampling domain area and therefore, results suggest that further considerations should be given to the selection of an appropriate mapping window size. Similarly, numerical codes provided meaningful ways to account for the effect of incorporating groundwater in slope stability analysis. The continuum code, Phase 2, is shown to be suitable for simulating non-fracture controlled slope analysis. Nevertheless, limitations exist when groundwater flow is mainly affected and controlled by the fractures defining the rock mass. Under these conditions discontinuum codes may be more appropriate. The conventional UDEC code is shown to be useful at providing information on the effect of the inclusion of pore water pressures. UDEC-Voronoi/Trigon is demonstrated to be an innovative and meaningful technique to account for the development of stress-induced brittle fracturing. The newly developed lattice-spring Slope Model is proven to be a useful means to assess the role of groundwater conditions on slope instability. Additionally, the use of DFN engineering principles are demonstrated to be very important in the interpretation of both mapped and simulated damage within rock slopes, especially, due to mechanical and pore water induced brittle fracture.

17. Tuckey, Z. (2012) ***An Integrated Field Mapping-Numerical Modelling Approach to Characterising Discontinuity Persistence and Intact Rock Bridges in Large Open Pit Slopes***. MS Thesis, Simon Fraser University.

ABSTRACT: Field investigations were undertaken at three open pit mines and one major natural rock slope. Modified geotechnical field mapping techniques and remote sensing methods including LiDAR and photogrammetry were adapted for each site, in an effort to improve characterisation of discontinuity persistence and intact rock bridges. A fracture network engineering approach is proposed for trace mapping, with intensity factors to describe intact rock bridge trace intensity, R21, and blast-induced fracture intensity, B21. Results from the field investigations form the basis for a conceptual numerical modelling trial, where finite element, distinct element, and lattice-spring codes are used to investigate the role of persistence and rock bridges in large open pit slopes. A damage intensity approach is introduced to characterise the fracturing induced within a slope, D21. The results are used to make preliminary recommendations for improving field characterization and post-processing methods to assess discontinuity persistence and rock bridges in large open pits.