Influence of Shear Surface Geometry on Deformation Processes in Massive Landslides

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ABSTRACT: Massive landslides display complex deformation processes. For instance, slope movements of the Downie Slide, monitored using borehole inclinometers, extensometers, and survey monuments, show considerable spatial and temporal inconsistencies in the displacement rates. This study assesses the influence that inferred shear surface geometry, as a key factor contributing to variable slope movements, has on resolving spatially discriminated slope deformations in three-dimensions. Borehole data defines the shear surface location at discrete points within the slide and therefore, the shear surface geometry for the extent of the slide must be largely inferred. A series of three-dimensional numerical simulations have been run to assess the effect of different interpretations of the shear surface geometry. This investigation illustrates the importance of rigorous geospatial definition of slip surface geometry and the value of three-dimensional modelling.

1 INTRODUCTION

Slope deformations of slow moving, massive landslides are often spatially variable where different regions of the landslide mass do not move at the same rate and do not follow a common down-slope sliding vector. Irregular displacements, indicative of compound or complex landslide processes, are influenced by a number of factors including; topography, ground water, heterogeneous rockmass characteristics, and non–uniform shear surfaces. Commonly used two-dimensional plain strain and simplified spherical or bowl-shaped three-dimensional analyses have inherent geometric limitations. The irregular nature of displacements in large landslides is an indication that the geometry of landslide shear surfaces is more complex in three-dimensions than such simplified models represent (Hutchinson et al. 2006, Agliardi et al. 2001). This paper focuses on the influence of shear surface geometry on spatially variable slope deformations. Advances in three-dimensional numerical modelling techniques allow for complex and, in most cases, more geologically realistic shear surface geometries to be used for simulating slope behaviour. Using the Downie Slide as a case history, the sensitivity of slope behavior to various interpretations of three-dimensional shear surface geometry is explored.

2 DOWNIE SLIDE

Downie Slide, described in accordance with the Cruden and Varnes (1996) suggested sequence for landslide names, is a massive, active, composite, extremely slow moving rockslide located on the west bank of the Columbia River Valley approximately 64 km north of Revelstoke, British Columbia, Canada. This 1.5 x 10^9 m^3 rockslide measures 3300 m from toe to headscarp, reaches a maximum thickness of 245 m and extends 2400 m along the river valley (Enegren and Imrie, 1996). The highly fractured rockmass is composed of interlayered schists, gneisses and quartzites (Imrie et al. 1992). Slope movements are primarily translational, the principal shear zone follows micaceous layers within a weak pelitic horizon; mica foliation dips down-slope towards the east roughly parallel to the topographic surface. Rotational failure occurs at the toe of the slide where the shear surface cuts across the foliation to daylight at the base of the river valley.

The toe of Downie Slide is inundated by the Revelstoke reservoir, operated by the British Columbia Hydro and Power Authority. Reservoir management involves slope monitoring of Downie Slide; the collection of data pertaining to slope deformations and ground water levels, which has been ongoing since 1973. Review of slope deformation data from survey monuments and borehole inclinometers reveals spatial variance in the direction and rate of slide displacements. Figures 1 and 2 illustrate slope movements measured by survey monuments over a 10 year period (1990-1999). Displacement vectors (Fig. 1) show that different regions of the slide are moving in different directions. Movement vectors are scaled according to cumulative displacements over the 10 year period, where larger vectors indicate regions which have moved further. Figure 2 illustrates contours of the average deformation rates; it is evident that higher rates of movement occur near the headscarp and the toe of the slide, while the central portion of the slope is characterized by lower velocities. These spatially discriminated deformation rates are apparent in observations of slope morphology; for instance, the upper portion of the slide features numerous internal scarps (light regions visible in the aerial photograph in Figure 1) indicating an extensional regime in this portion of the slide.

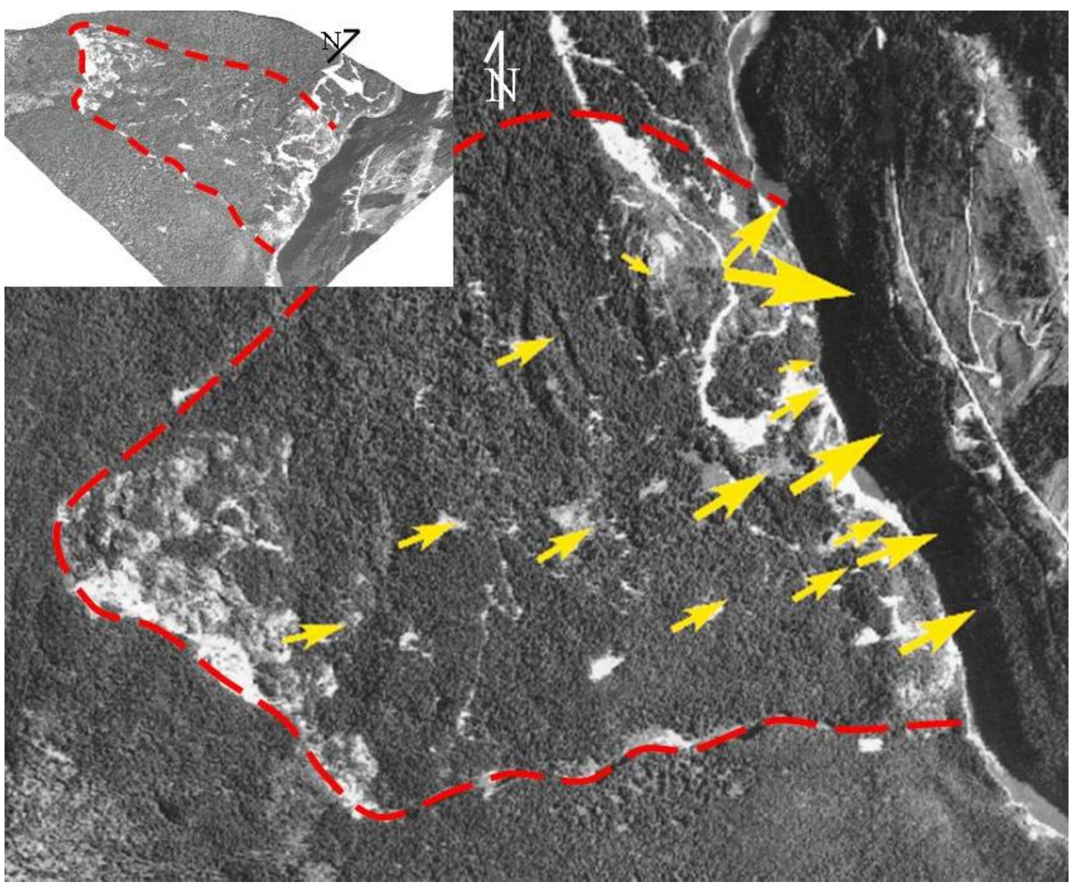

Figure 1: Aerial photograph of Downie Slide; data from survey monuments (maximum sized vector corresponds to 0.3 m/yr displacement) illustrates that different areas of the slope are moving in different di-

rections, hatched line indicates landslide boundary, (inset) oblique view of the landslide looking north-west.

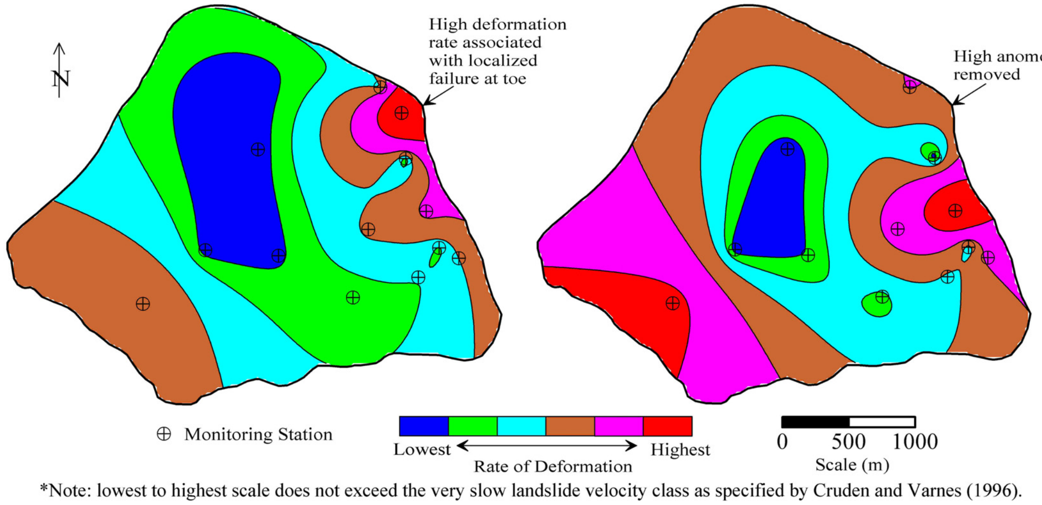

Figure 2: Contoured rates of movement averaged over a 10 year period (1990-1999). High rates are apparent in the upper portions of the slope (near the headscarp), and also near the toe of the landslide. The central portion of the slope is characterized by lower velocities.

3 INTERPRETATIONS OF 3-DIMENSIONAL SHEAR SURFACE GEOMETRY

Three-dimensional shear surface geometry can be interpreted from data obtained during surface and sub-surface site investigation programs. Morphological features and the landslide boundary are resolved from geological mapping, aerial photographs and a digital elevation model, while sub-surface shear zone location can be defined by drilling campaigns (borehole and core logging, and inclinometer installations). With this data, spatial prediction algorithms can be used to interpret fully three-dimensional shear surface geometries. As demonstrated by Kalenchuk et al. (2009), there are many spatial prediction techniques available, including; krigging, radial basis functions, minimum curvature algorithms, and best fit polynomials, to name a few. The selection of a spatial prediction technique requires statistical analysis and expert judgment in order to define which algorithm best suits the available data set and produces the most realistic representation of the geological setting.

Geometric analysis by Kalenchuk et al. (2009) has resolved four geologically reasonable interpretations of the basal slip surface, or principal shear zone, at Downie Slide. Figure 3 illustrates these geometric interpretations; geometries a, b and c assume a continuous shear surface between the landslide boundary and borehole intercepts. Geometry d, defines a stepped surface where the scarp observed along the west and south slide boundaries is extended to depth below the topographic surface. Geometry e is a simplified interpretation defined by a best fit elliptical parabola. These interpreted shear surfaces demonstrate large- and small-scale geometric variations that result from different interpolation algorithms. There are large-scale geometric discrepancies between the continuous (geometries a, b and c), stepped (geometry d), and simplified (geometry e), while small-scale geometric variations distinguish each of the continuous geometries. Numerical simulation of slope behavior for each of these geometries explores the influence of large- and small-scale geometric variations in order to assess how much detail is required to adequately simulate true slope behaviour and to explore if rigorous geometric interpretations are necessary in the geomechanical analysis of large-scale landslide behavior.

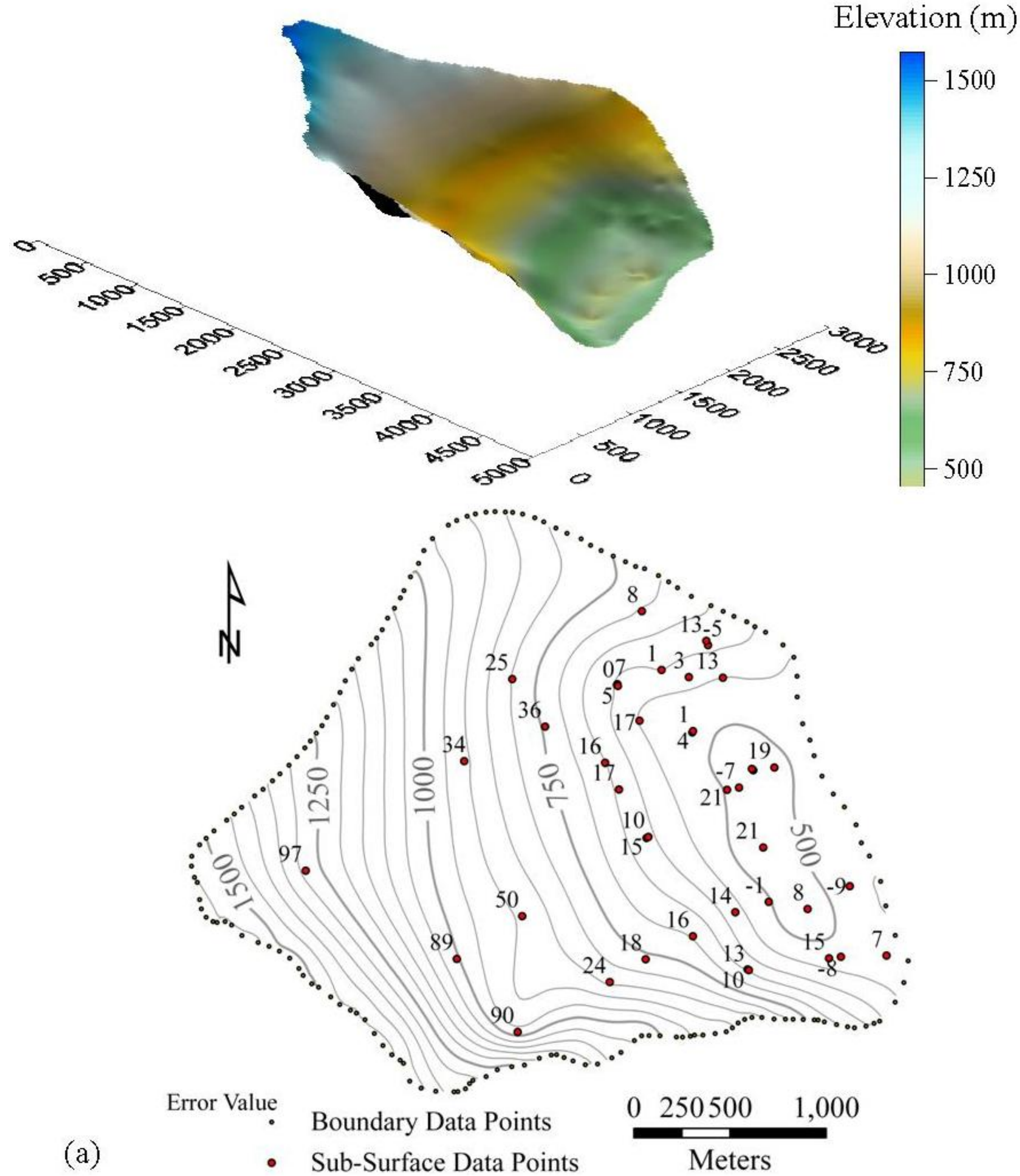

Figure 3: Geometries (looking northwest) and contour plots of the interpolated principal shear at Downie Slide illustrating the error values at sub-surface data points returned from cross-validation for (1) continuous (a. continuous minimum curvature (smooth))

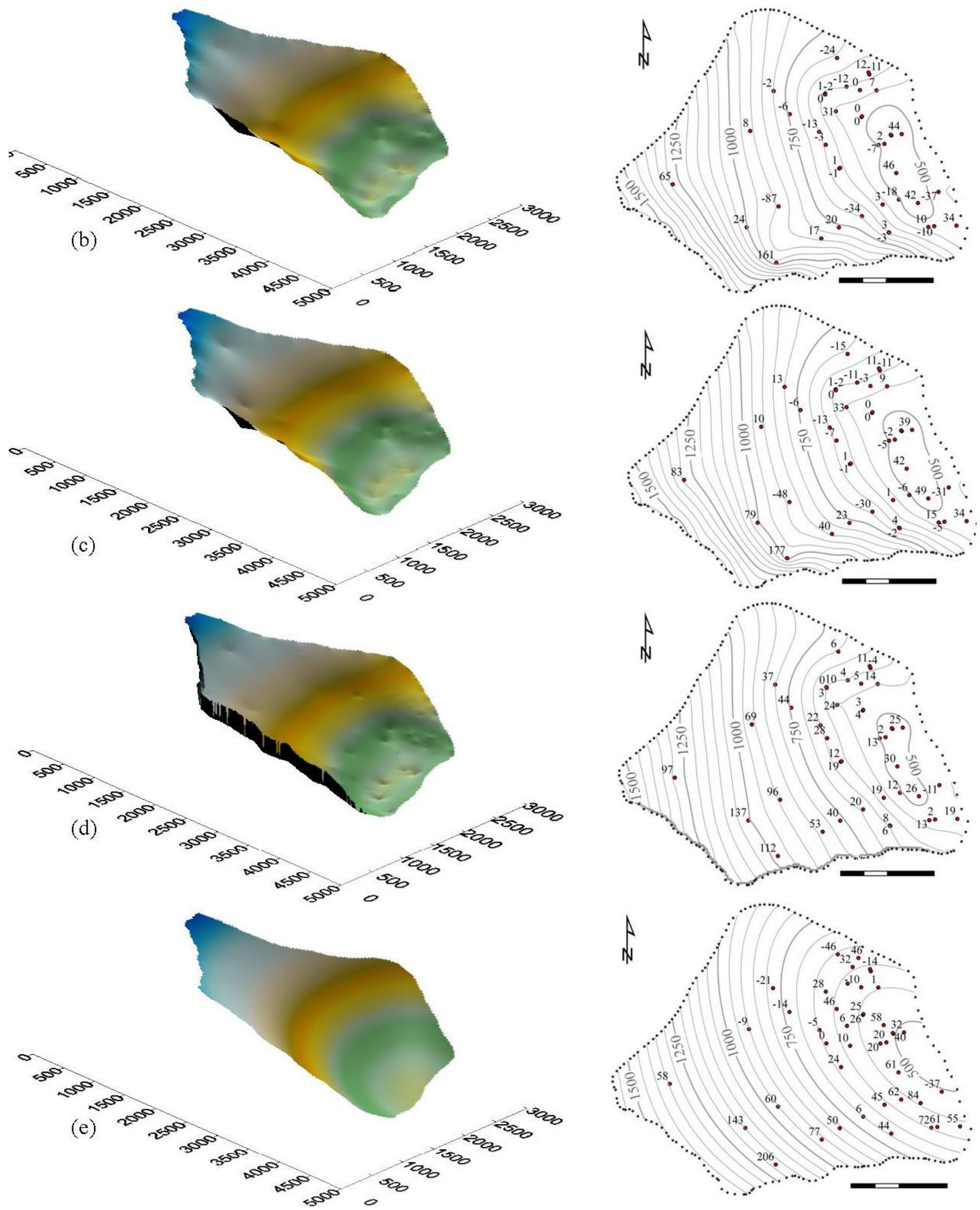

Figure 3 (continued): (b. kriging of a variogram model and c. the multiquadratic radial basis function), (2) stepped (d. minimum curvature (discontinuous)), and (3) simplified (e. the elliptical parabola) geometries (modified from Kalenchuk et al., 2009).

4 MODELLING

Numerical models have been developed to compare slope behavior for each interpretation of shear zone geometry using 3DEC (3-Dimensional Distinct Element Code) (Itasca Consulting Group, Inc. Minneapolis, Minnesota, 2003). Consideration has been given to the use of continuum and discontinuum methods (Cundall and Hart 1993, Jing and Hudson 2002) for the simulation of massive landslides. Modelling with a pure continuum code was ruled out, because when large strains occur, there is excessive stretching of mesh elements, leading to numerical instability. A pure discontinuum model also has inherent challenges, for instance unrealistic high stress points at any non-smooth or irregularly shaped landslide boundary will cause blocks to hang-up, rather than incur small deformations. As such, both continuum and discontinuum modelling methods are incorporated to model the rockmass matrix and shear surface, respectively (Figs 4-5).

Deformable blocks are utilized to simulate the landslide mass and in situ material below the slide. These discrete units are made deformable by discretizing individual blocks into constant strain-rate elements of tetrahedral shape (Itasca, 2003). When displacements in massive landslides occur along a complex, curved surface of rupture, internal deformation occurs within the displaced material, forming internal scarps and grabens in zones of depletion, and bulges at zones of accumulation. To accommodate these deformations, the fractured landslide material is considered to behave as a rockmass with relatively low elastic modulus. A landslide may alternatively be simulated using a fractured model; however it would be very difficult to define the location, orientation, frequency and strength parameters of fractures throughout the rockmass. Furthermore, given the scale of this massive landslide, creating a fractured landslide model would significantly increase numerical runtime. The blocks representing landslide and in situ material interact along a discrete discontinuity defining the principal shear surface. The Coulomb-slip constitutive model considers shear and tensile failure, and dilation (Itasca, 2003). Elastic behavior is governed by normal stiffness (K_n), shear stiffness (K_S), displacements and acceleration.

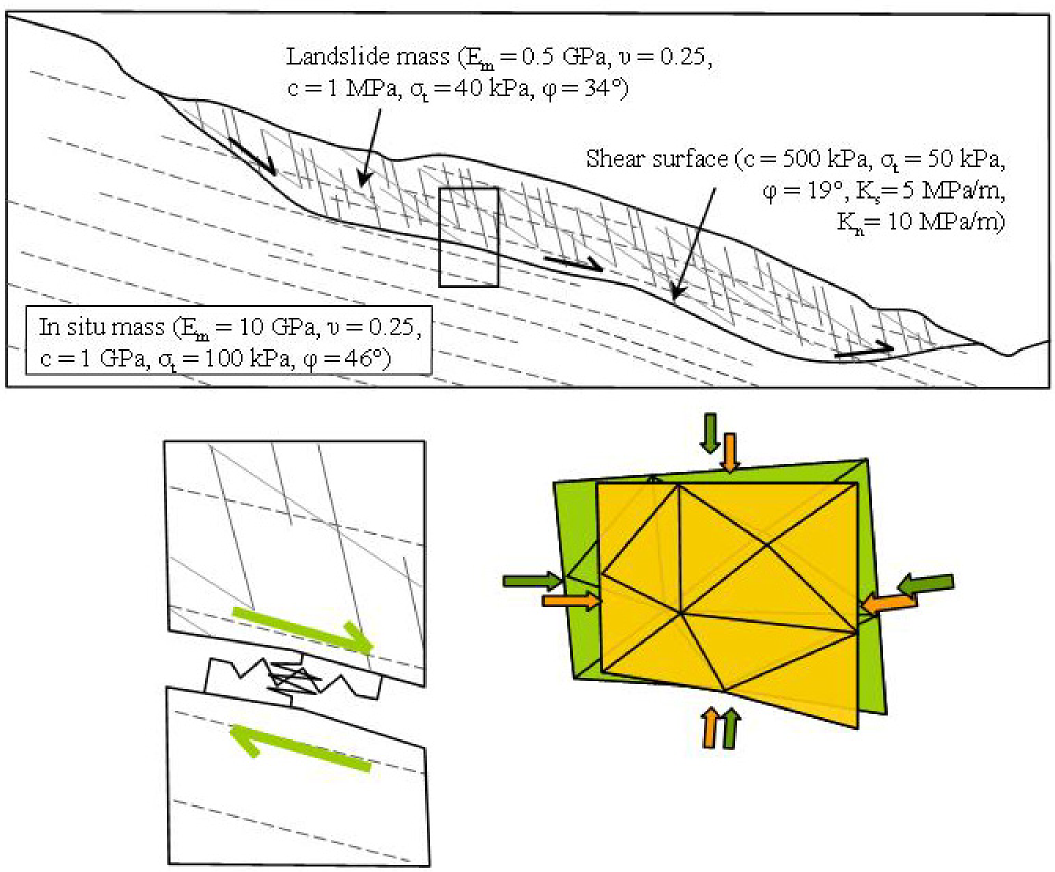

Figure 4: Conceptual schematic of the hybrid continuum-discontinuum landslide modelling.

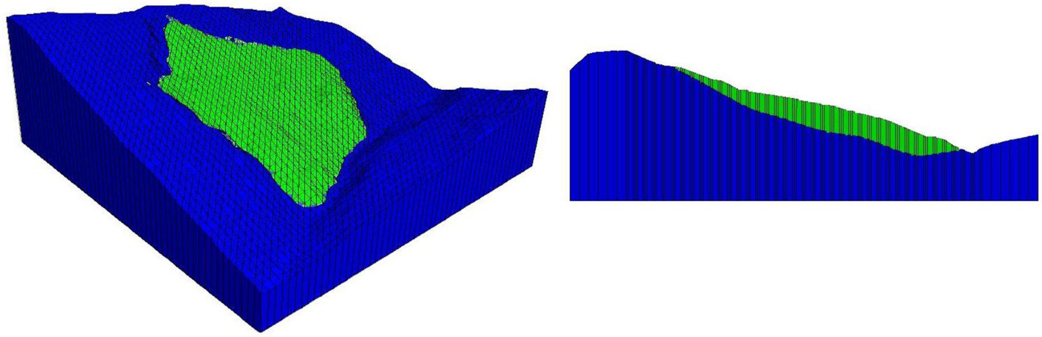

Figure 5: 3DEC model of Downie Slide (left) oblique looking northwest, (right) cross-section looking north.

5 RESULTS

Numerical simulations of the Downie Slide using each of the five shear surface geometries, resolves that the assumed shear surface geometry does influence slope behavior. All models demonstrate a common trend, that is, larger displacements occur near the headscarp and toe of the rockslide as compared to the central portion of the slope. In the upper regions of the slope, where translational failure is occurring, the magnitude of deformations correlate to the slope of the shear surface, where steeper regions exhibit higher rates and larger displacements. The headscarp provides an important release feature and tensile failure occurs through intact material in the upper portions of the slope, a phenomenon also observed in slope morphological features as described in Section 2. Increased deformations near the toe of the slide are due to the lack of confinement where the shear surface outcrops in the valley floor. These higher toe displacements are also observed in the field and likely contribute to the localized toe slumps. A compressional zone occurs through the central portion of the slope where there are relatively lower magnitude deformations and the faster moving upslope material accumulates near the heel of the slide. While this trend is common to all interpreted geometries, a more detailed look at the results shows localized variations in slope behavior between the continuous, stepped and simplified geometries, indicating that variations in the interpreted shear surface geometry do influence numerically simulated slope behavior. Small-scale discrepancies between geometric interpretations show less significant variation in numerical results, as all of the continuous geometries produce very similar results.

Figure 6 compares the total displacements achieved for each of the interpreted geometries. The stepped surface is less steep than the continuous surfaces along the south slide boundary, and shows smaller deformations in this region. The simplified geometry has more consistent shear surface slope along strike of the shear surface, showing very little discrepancy in displacement magnitude from north to south, whereas the more complex geometries of the continuous and stepped surfaces contribute to more detailed discrepancies in total displacements.

Figure 7 compares the contoured displacement rates for numerical models tracked on the topographic surface at the same location as field survey monuments. When compared to the contoured field data in Figure 2 it is evident that some geometries simulated the observed slope behavior better than others. The contoured rates of the continuous surfaces, particularly the geometries produced using the minimum curvature algorithm and krigging of a variogram model, produce contours similar to field data. The stepped geometry does perform well near the toe of the slide; however this surface appears to move too slowly in the southwest portion of the slope. The simplified geometry does reproduce the higher rates observed near the headscarp and toe, with a compressional zone through the central portion of the slope; however this simplified geometry lacks the strike-parallel (north-south) spatial variability.

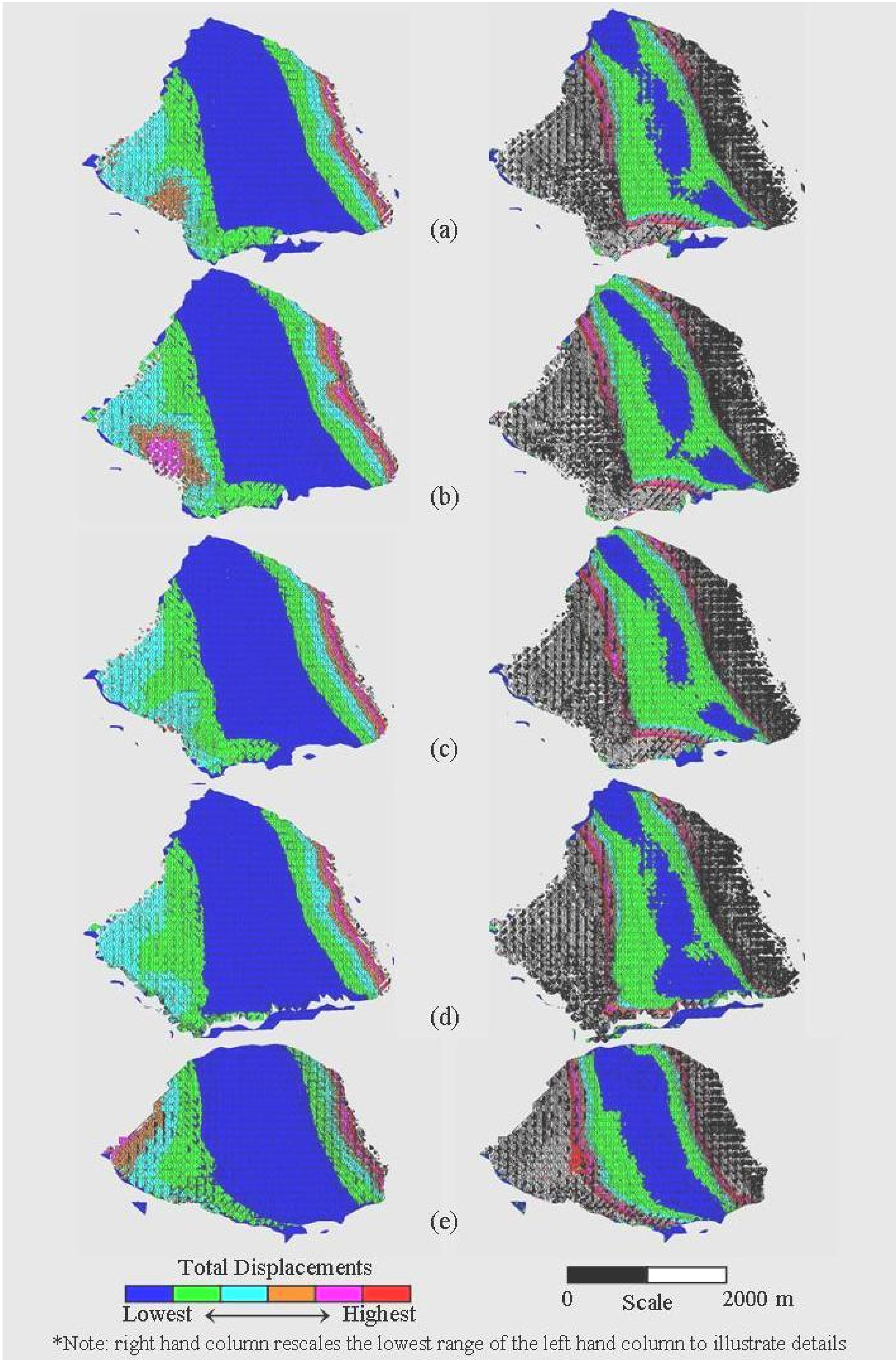

Figure 6: Total displacements achieved (in a prescribed number of numerical time steps) by continuous (a. continuous minimum curvature (smooth), b. kriging of a variogram model and c. the multiquadratic radial basis function), stepped (d. minimum curvature (discontinuous)), and simplified (e. the elliptical parabola) geometries.

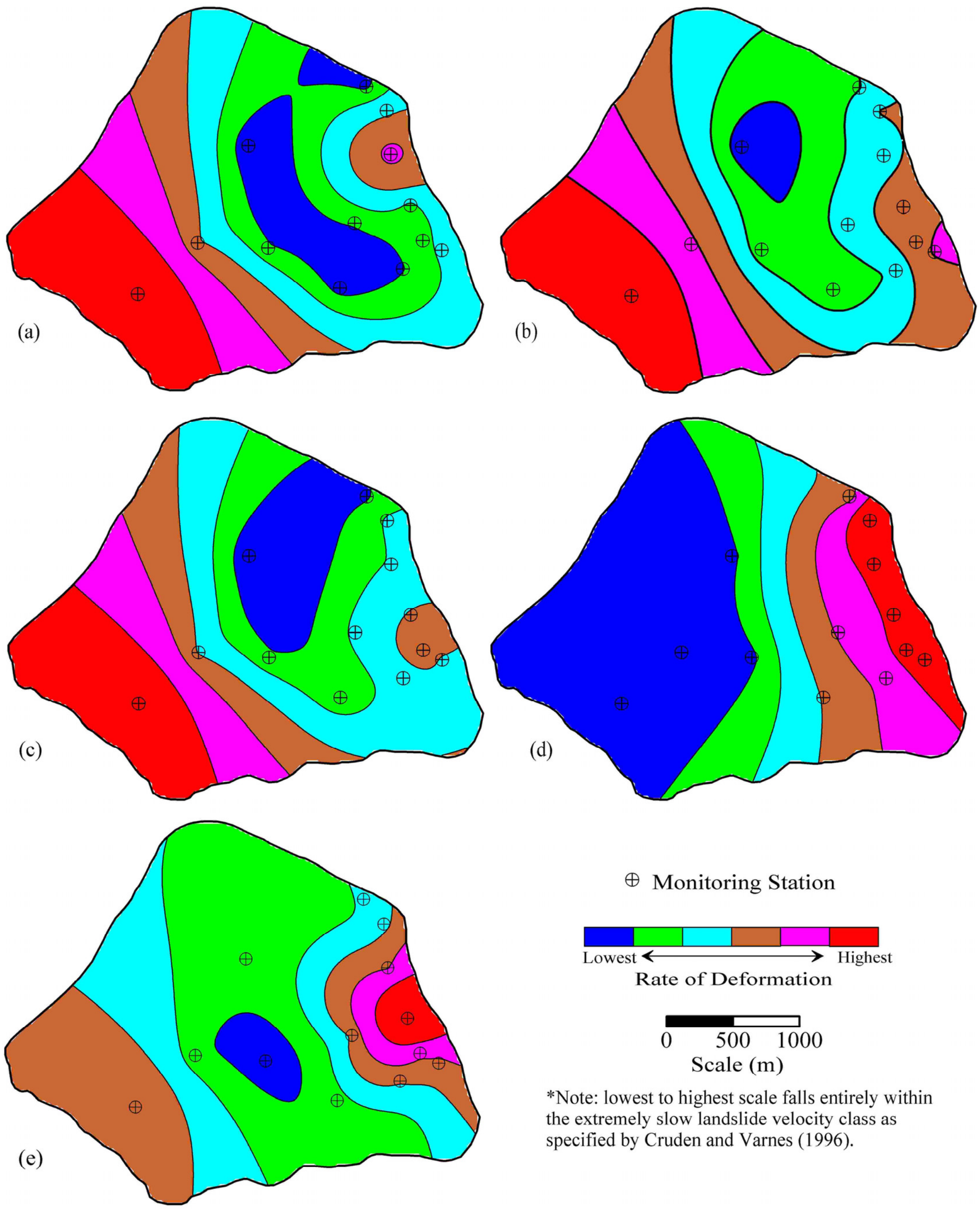

Figure 7: Contoured deformation rates measured in numerical models at the location of field survey monuments. (1) Continuous (a. continuous minimum curvature (smooth), b. kriging of a variogram model and c. the multiquadratic radial basis function), (2) stepped (d. minimum curvature (discontinuous)), and (3) simplified (e. the elliptical parabola) geometries.

6 CONCLUSIONS

Numerical simulations of varying shear surface geometries demonstrate that the three-dimensional shape of shear surfaces in massive landslides is a key factor controlling slope deformations. The simulated behavior of Downie Slide proves to be sensitive to large-scale geometric variations, while small-scale discrepancies in slope geometry do not significant change simulated slope behavior. Therefore, when interpreting shear surface geometry it is important to test different geometric interpretations, and when numerical simulations reproduce observed slope behaviors, conclusions can be drawn as to the true shear surface geometry. Also, this rigorous approach to numerically testing three-dimensional interpretations of shear surface geometry proves to be important in analyzing massive landslides, as the simplified geometric interpretation did not adequately reproduce the observed deformations at Downie Slide.

7 SUMMARY

Geotechnical analysis of massive landslide behaviour is limited by oversimplified slope geometries in two-dimensional cross sections or three-dimensional spherical or bowl-shaped slip surfaces. To improve the analysis of massive landslide systems, spatial prediction algorithms are used to interpret geologically realistic three-dimensional shear surface geometries. Multiple, and different, surface geometries have been interpreted for the Downie Slide, small- and large-scale geometric discrepancies result from the use of different statistical interpolation methods and geological assumptions of surface continuity respectively. Numerical models have explored how variations in shear surface geometries influence the complex behaviour of this massive landslide, proving that large-scale geometric discrepancies do influence simulated slope behavior, while small-scale discrepancies are less significant.

8 ACKNOWLEDGEMENTS

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