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A REVIEW OF METHODS USED TO INVESTIGATE STRUCTURAL CONTROL ON SLOPE INSTABILITY.

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ABSTRACT: Many features and phenomena, such as slope morphology, climate, hydrogeological and hydrological conditions, and material strength, contribute to slope instability. One of the most important preconditioning factors, particularly in rock slopes, is structural control. Structural control includes any tectonic processes or features that may influence landslide initiation, movement, or termination, including *in situ* stress conditions, discontinuities, faults, folds, and foliation. Structures affect not only the failure geometry, such as headscarp shape, but also deposit volume, morphology, block size, damage, and emplacement behaviour. Structural features and processes thus influence all aspects of landslide behaviour, from the development of unstable conditions to deposition. Interestingly, mass movement studies can also highlight structures, and contribute to detailed mapping of previously unrecognised faults, folds, and other features. Methods such as regional lineament mapping, traditional fieldwork, photography and photogrammetry, LiDAR surveys, InSAR interpretation, and numerical modelling are used to analyse structural features and processes related to slope instability. This short paper presents an overview of these methods and highlight their applications in a case study.

Keywords: structural control, slope instability, methods, Vajont Landslide.

1. INTRODUCTION

Structural geological features and processes, such as discontinuities, folds, faults, foliation, and *in situ* stresses, are recognised as important controls on slope instability, particularly in rock slopes (Agliardi et al., 2001; Stead and Wolter, 2015) (Fig. 1). In this context, discontinuities include pre-existing lineaments that may influence failure geometry and behaviour, whereas faults are lineaments that typically produce damage or shear zones of weaker material surrounded by more competent material (Loew et al., 2012; Milmo et al., 2014; Bonilla-Sierra et al., 2015). Fold axes are commonly weak zones, and fold geometry may influence failure geometry (Badger, 2002; Jaboyedoff et al., 2011; Humair et al., 2013). Foliation may affect sliding zone development (Braathen et al., 2004; Adhikary and Dyskin, 2007; Vick et al., 2020). The tectonic inheritance and *in situ* stress conditions of a given slope influence slope stability, and rock mass behaviour and damage (Hoek et al., 2009; Ambrosi and Crosta, 2011; Agliardi et al., 2013; Stead and Eberhardt, 2013; Elmo et al., 2018).

Inclusion of structural control analysis when studying mass movements contributes to improved understanding of failure preconditioning, initiation and behaviour at various scales, and ultimately to landslide hazard and risk reduction. For example, Glastonbury and Fell (2000) and Stead et al. (2006) illustrated how structures affect failure mechanisms, from translational to complex multi-mechanism failure. Recent analysis of structural control within the creeping Moosfluh slope adjacent to the Aletsch glacier in Switzerland examines the application of sophisticated monitoring to determine the role of structural control in developing failure mechanisms and in slope stability evolution (Glueer et al, 2019a, b; Manconi et al., 2019). In Troms, Norway, Vick et al. (2020) focus on Rock Slope Deformations (RSDs), highlighting the role of foliation, discontinuities, and faults in RSD formation and evolution and presenting a new geotechnical model for these failures.

Aside from recognising the importance of structural control as in the above examples, incorporating techniques traditionally used in structural geology into geotechnical assessments of slopes facilitates analysis and improves slope characterisation. For example, Havaej and Stead (2016) applied the concept of the strain ellipsoid to brittle fracture and damage in open pit mines and natural slopes, determining an “ellipsoid of damage”.

The aim of this short paper is to provide a review of methods used to investigate the influence of structural geological features and processes on slope instability. Methods are described in the next section, followed by a case study highlighting the application of several of these methods to the famous Vajont Landslide and a discussion of the methods.

2. METHODS

Analysis of slope stability has incorporated numerous techniques to improve understanding of failure mechanisms, including site investigations, drilling, groundwater, displacement and climate monitoring, geo-

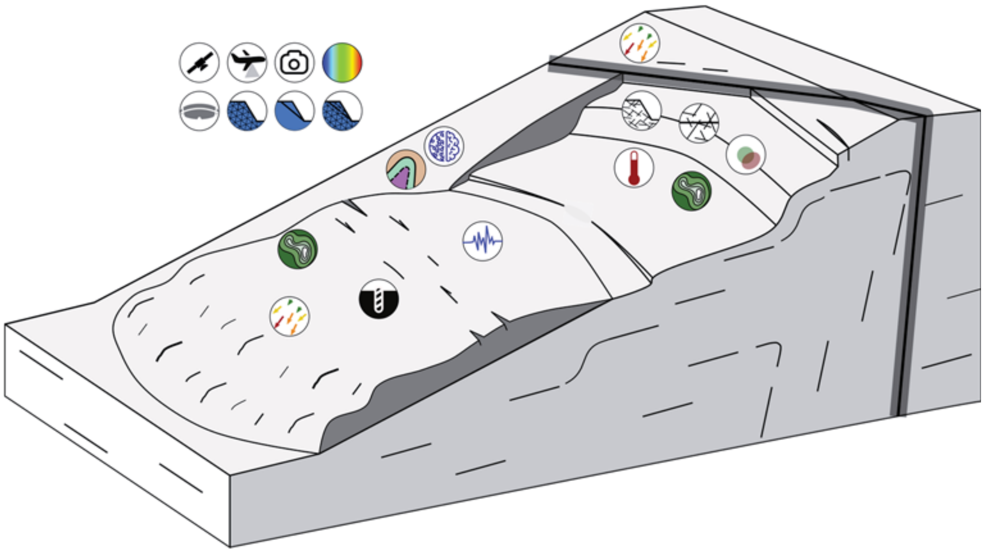

Fig. 1 - Structural features and controls (such as folds, fault zones, rock bridges, crown cracks, transverse cracks and ridges, and radial cracks) on landslides, with methods used to investigate them represented by icons. See Tab. 1 for legend of icons.

Method	Description	Examples
Field Methods		
Rock Mass Analysis	Collect data such as material strength, block shape and size, weathering grade, rock bridge properties using *in situ* and laboratory testing, GSI, survey lines/windows, etc.	Agliardi et al. (2017) Yuskar et al. (2017)
Discontinuity Analysis	Collect data such as orientation, persistence, spacing, aperture, infill, roughness using compass or app, survey lines/windows, JRC profiler, etc.	Singeisen et al. (2020)
Geological Mapping	Describe lithological units, properties of structures such as faults and folds using outcrop mapping, strain indicator analysis, compass, etc.	Humair et al. (2013)
Morphological Mapping	Map and describe morphology of deposits (ridges, tension cracks, etc.) to determine failure behaviour and stresses within failure mass.	Shea & van Wyk de Vries (2008) Dufresne & Davies (2009) Wolter et al. (2015)
Displacement Monitoring	Monitor landslide displacement using GPS, total station, crackmeters, etc.; can indicate new gravitational structures or characterise known ones within the deposit.	Glueer et al. (2019a, b) Manconi et al. (2019)
Borehole Investigations	Obtain subsurface data such as rock mass characteristics, locations of structures, deformation using core logging, geotechnical testing, inclinometers, acoustic televiewer logs, etc.	Ganerød et al. (2008) Loew et al. (2012)
Geophysical Methods	Obtain subsurface data such as rock mass characteristics using electromagnetic, gravity, seismic, etc. techniques.	Perrone et al. (2014) Cody et al. (2020) Guo et al. (2020)
Remote Sensing		
LiDAR Analysis	May include morphometric analysis, lineament mapping, change detection and monitoring; may be limited by resolution, repeat survey gaps.	Gillon et al. (2009) Kromer et al. (2015)
InSAR Analysis	Determine areas of movement and evolution of structures and mass movements; several factors such as LOS and coherence may limit applicability.	Henderson et al. (2011) Wasowski & Pisano (2019)
Photogrammetry	Analyse processed data for discontinuity analysis, change detection, morphology, etc.; may be affected by orientation bias, occlusion.	Sturzenegger & Stead (2012)
Infrared Thermography	Detect and characterise discontinuities, analyse rock masses and damage; consider atmospheric effects, temperature resolution.	Mineo et al. (2015) Guerin et al. (2019)
Hyperspectral Imagery	Detect lithological variations and contacts, weathering/alteration; limited by resolution, user knowledge.	Stead et al. (2019)
Simulations		
Kinematic Analysis	Analyse planar, wedge, and toppling failure; does not typically consider discontinuity persistence or spacing.	Gschwind et al. (2019)
Continuum Modelling	May be used to investigate stress and strain distributions at the slope scale; treats materials as continua; does not allow for fracturing/large displacements.	Chávez et al. (2017) Alfaro et al. (2019)
Discontinuum Modelling	May be used to investigate fracture, large displacements along structures; scale and modelling properties of rock masses and discontinuities challenging to determine.	Corkum & Martin (2004) Brideau & Stead (2010) Wolter et al. (2013)
Hybrid Simulations	May be used to investigate fracture through continua and discontinua, large displacements along structures; computationally expensive.	Havaej & Stead (2016) Donati et al. (2019)
Other		
Virtual/Mixed/ Augmented Reality	May be used to visualise structures and controls on landslides and develop 3D models of sites; limited by input data quality.	Mathiesen et al. (2012) Mysiorek et al. (2019)
Artificial Intelligence	Analyse large datasets. Applications to slope instability currently mainly limited to machine learning.	Dickson & Perry (2016) Đurić et al. (2019)

Tab. 1 - Summary of methods used to investigate structural features and processes affecting slope stability. Note that field methods here include laboratory methods for simplicity. GSI = Geological Strength Index; JRC = Joint Roughness Coefficient; LOS = Line-of-Sight.

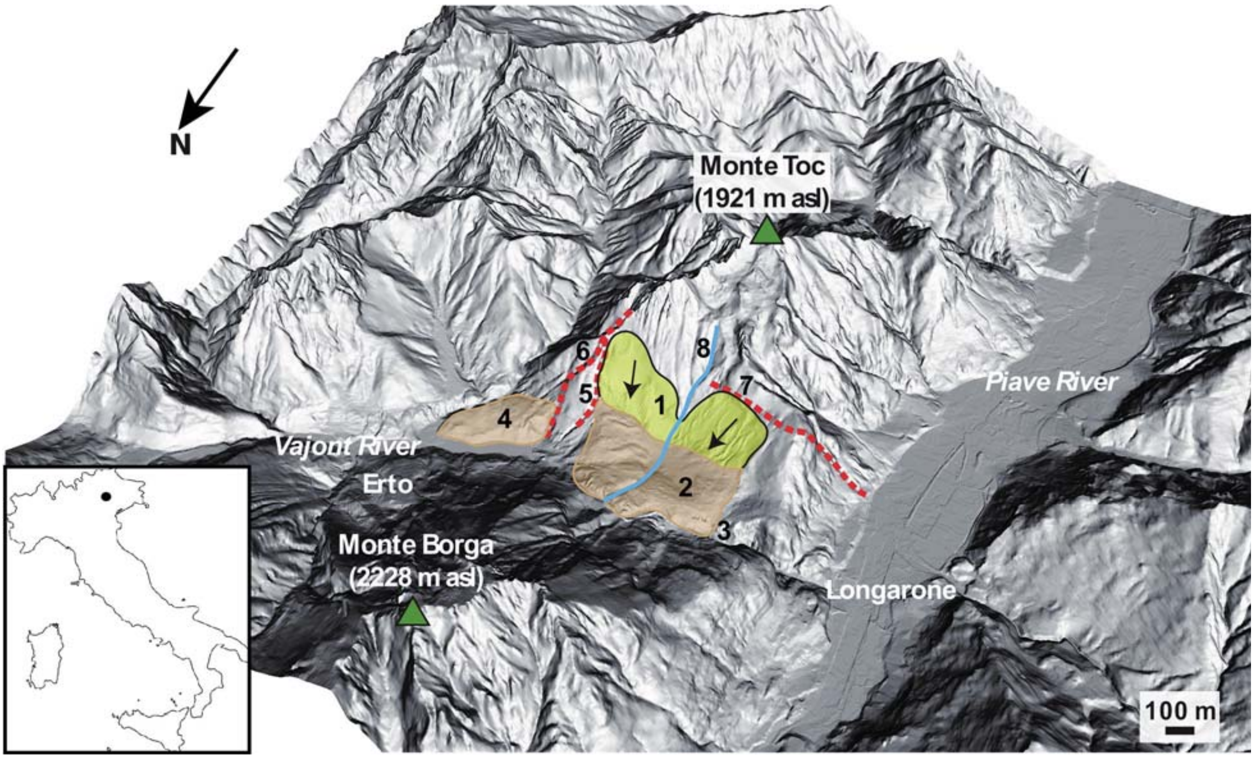

Fig. 2 - Location and context of the Vajont Landslide. 1 - Vajont Landslide failure scar, 2 - Vajont Landslide deposit, 3 - Vajont Dam, 4 - Pineda Landslide deposit (prehistoric failure), 5 - Col Tramontin Fault, 6 - Croda Bianca Fault, 7 - Col delle Erghene Fault, 8 - Massalezza Stream. (Modified after: Wolter et al., 2014.)

physical methods, remote sensing, and physical and numerical simulations. Figure 1 and Tab. 1 summarise the traditional and novel methods applied to the analysis of slope instabilities and their features, focussing on structural control and features, and separated into field methods, remote sensing and visualisation, and simulation and modelling.

3. CASE STUDY

3.1. Background

The Vajont Landslide is a well-known ~270 million m^3 event that failed catastrophically on October 9th, 1963 in the Dolomites of northern Italy, approximately 100 km north of Venice (Fig. 2). The failure initiated on the southern valley wall of the Vajont Valley on the flank of Mt. Toc (peak at 1921 m asl), above the Vajont Dam, which was the highest double-arch dam in the world at the time of the disaster. The sudden failure caused a displacement wave of the Vajont Reservoir that spread upvalley and downvalley, overtopped the dam, and flooded the main Piave Valley below. Resulting in just under 2000 deaths, the Vajont catastrophe is cited as one of the worst engineering and natural disasters in history. The landslide is among the most researched slope failures in the world, with over 200 studies on its geological, hydrogeological, geotechnical, and social aspects (cf. Genevois and Ghirotti, 2005; Superchi et al., 2010; Paronuzzi and Bolla, 2012; Genevois and Tecca, 2013). Several critical aspects, such as the significance of changing hydrological and hydrogeological conditions and centimetre-scale clay beds, and the existence of a "paleoslide", have been discussed for decades (cf. Hendron and Patton, 1985; Semenza, 2010). Only recently have geomorphological and structural preconditions and regional evolution been investigated in relation to the Vajont Landslide.

Several compressional deformation events shaped the Dolomites before and during the Late Miocene Alpine orogeny, including the Neoalpine and Dinaric deformations. The E-W oriented Vajont Valley follows the Erto Syncline, an E-ESE plunging recumbent fold that formed during the Neoalpine event and was affected by the Belluno Thrust to the South and the Monte Borgá and Spesse thrusts to the North. The Vajont Landslide is located on the southern refolded limb of the Erto Syncline (Ravagnan, 2011; Massironi et al., 2013).

The recently recognised open Massalezza Syncline (Massironi et al., 2013), with a fold hinge oriented N-S and located in the centre of the Vajont Landslide along the Massalezza Stream (Fig. 2), is associated with the Dinaric deformation event and creates the bowl shape observed in the landslide failure scar. Interference patterns between the Neoalpine and Dinaric fold generations contribute to the complex morphology of the failure scar (Bistacchi et al., 2015).

Two faults bound the Vajont Landslide. The Col Tramontin Fault, a sub-vertical splay of the Croda Bianca reverse fault, acts as the eastern lateral release. The Col delle Erghene normal fault forms part of the western lateral and rear release of the landslide. Other faults surrounding the landslide include the Col delle Tosatte

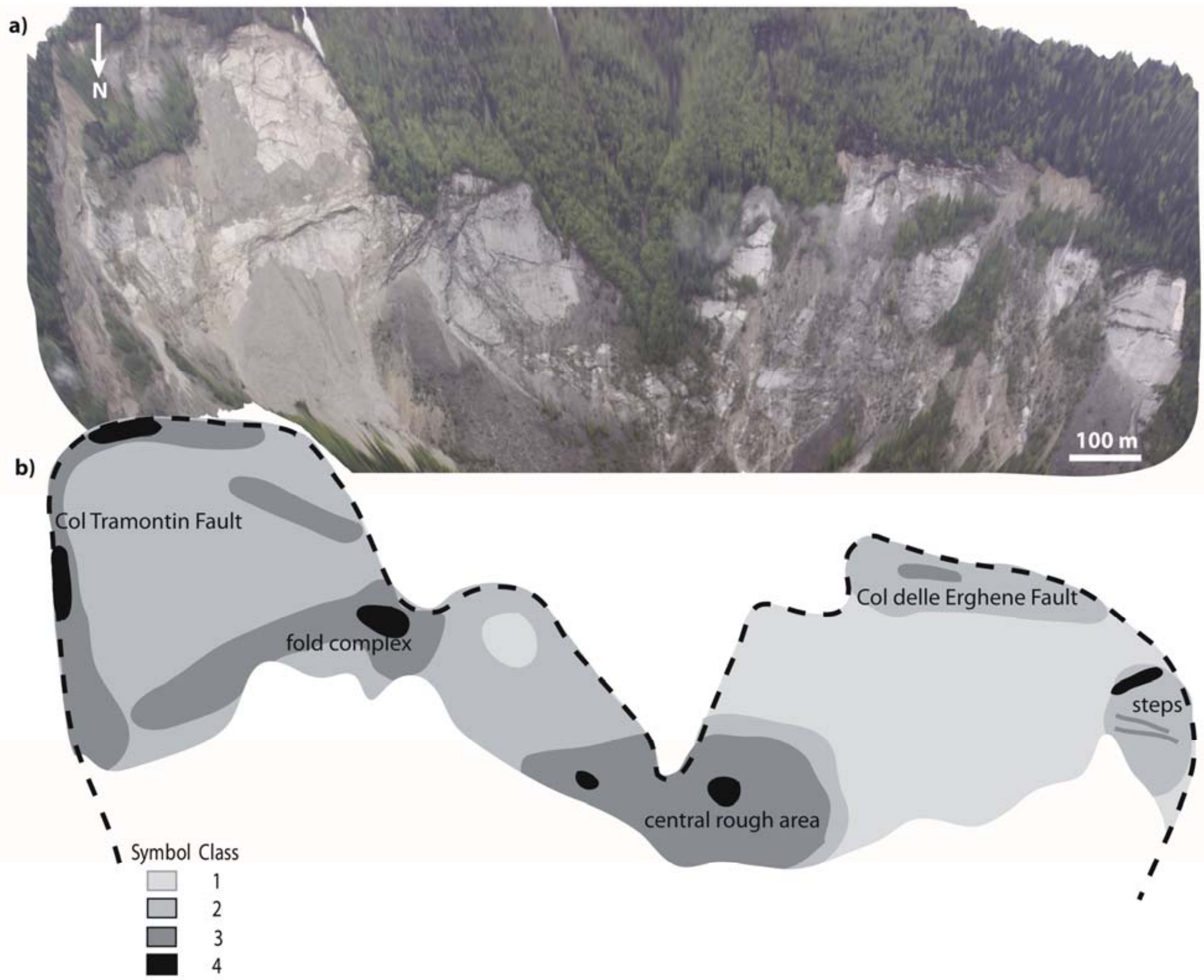

Fig. 3 - Roughness classes on the Vajont Landslide scar, based on block statistics. Class 1 represents areas that are largely planar and smooth, with roughness increasing to Class 4. Rougher areas are more likely to have caused dilation of the failure mass over asperities and/or rock bridge failure through asperities, with implications for movement behaviour. (Source: Wolter et al., 2014.)

reverse fault and the regionally significant Belluno flat-ramp-flat thrust system (Massironi et al., 2013).

3.2. Investigations on Structural Features and Control at Vajont

To study the effects of the tectonic setting on failure kinematics and dynamics, engineering geological, structural geological, geophysical and geotechnical methods have been applied to the Vajont Landslide. For example, Bistacchi et al. (2015) constructed a 3D geological model incorporating borehole, morphological, and geological data to characterise damage within the deposit as well as tectonic structures influencing the failure, and Petronio et al. (2016) used P-wave, SH-wave, and surface wave analysis to characterise the rock masses involved in the Vajont Landslide. Paronuzzi and Bolla (2015) investigated the interaction of pre-existing tectonic discontinuities with discontinuities formed due to gravitational stresses within the Vajont Landslide area, based on discontinuity orientation. Wolter et al. (2014, 2015) used terrestrial photogrammetry, engineering geomorphological analysis and mapping, and engineering geological field investigations to characterise the Vajont Landslide scar and deposit.

Through these studies focussed on structural control, several insights have been gained. Detailed morphological and structural investigations of the failure scar - influenced mainly by interference patterns between the two fold generations mentioned above - using methods such as photogrammetry, roughness characterisation, and block statistics, indicated smooth and rough areas of the scar, with implications for where rock bridges and concentrated damage could have formed within the sliding zone (Fig. 3) (Massironi et al., 2013; Wolter et al., 2014). Lineament mapping shows the influence of tectonic discontinuities on the geometry of the failure. The roughness of the failure scar and the locations of the Col Tramontin Fault and Massalezza Syncline also explain the separation of the landslide deposit into several blocks (e.g., Wolter et al., 2015). Continued

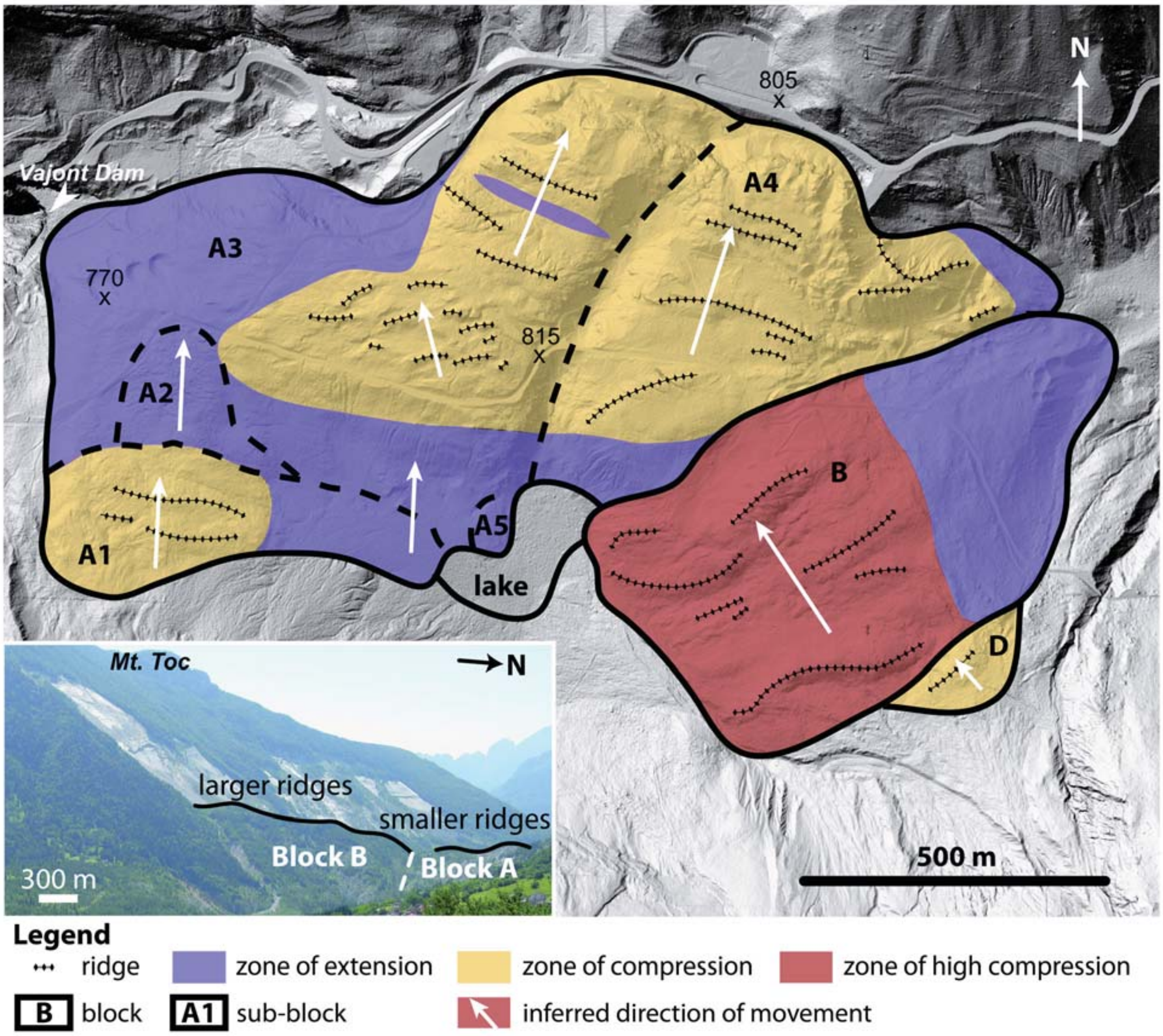

Fig. 4 - Morphostructural features of the Vajont Landslide deposits, showing zones of extension and compression, as well as blocks within the deposit. (Source: Wolter et al., 2015.)

evolution of the failure scar post-1963 has focussed in a particularly active area under a fold visible in the failure scar (Wolter et al., 2014).

The Vajont Landslide deposits include areas of compression and extension, as indicated by morphological features such as transverse ridges and internal shear zones on engineering geomorphological maps (Fig. 4) (Wolter et al., 2015). These deformed zones suggest further separation of the landslide mass into individual blocks, and they aid in determining the movement behaviour of the catastrophic landslide.

Numerical modelling of the Vajont Landslide, including continuum, discontinuum, and hybrid simulations, has suggested that internal damage developed prior to catastrophic failure at critical locations within the rock mass, as also observed in morphological and structural geological field investigations. Modelling suggests that strain concentrated within an ellipsoid of damage, and certain pre-existing discontinuities likely separated the failure mass into several blocks (Wolter et al., 2013; Havaej et al., 2015).

4. DISCUSSION AND CONCLUSION

Numerous methods have been developed to analyse structural control on slope failures. The following discusses some of the caveats and limitations of methods mentioned in this paper.

Any data collection method must be employed with care and expert judgement, as subsequent analysis is only as good as the dataset input. For example, particularly when investigating structural features, structural domains within the study area should be considered. Scale of observation is also an important consideration. Structural geologists commonly examine features either at the regional or microscopic scale to determine tectonic history. Although these scales of analysis provide context for slope-scale investigations, meso-scale features are often more significant to slope stability. In fact, slope investigations can identify previously unknown structures such as local folds and faults, as seen in the Vajont Landslide case above.

Field (and laboratory) methods remain essential in assessing rock masses and discontinuities, as well as their role in failure kinematics and dynamics. It is only through these methods that properties such as material strength can be quantified. In recent years, using smartphone applications to measure discontinuity, fold, and foliation orientation, as well as collecting other geological data, has started to displace the use of a compass. Apps allow much more efficient collection of data and can reduce time spent in precarious field environments. However, their precision and accuracy have been debated (Vanderlip, 2016; Allmendinger et al., 2017; Lee et al., 2018; Nováková & Pavlis, 2019), and it is still highly recommended to check the accuracy of the app chosen and to calibrate apps using a compass frequently (up to one in every 10 app measurements). Understanding the theory behind the data being collected is also important to avoid poor quality or erroneous data.

Remote sensing applications allow data to be gathered in otherwise inaccessible areas and over large areas and have become widely used to investigate and monitor slopes. These methods require specialised knowledge and awareness of their limitations, some of which are listed in Tab. 1. Scaioni et al. (2014), Francioni et al. (2017) and Stead et al. (2019) provide further review of remote sensing as applied to unstable slopes.

Augmented and virtual reality techniques are relatively new to structural geology and slope investigations. They have proven to be useful tools in visualising the often multi-layered and complex datasets gathered using other methods. Although not used to map or model phenomena directly yet, there are some promising developments (e.g., Mysiorek et al., 2019).

Numerical modelling, powerful when used appropriately, should be seen as a conceptual tool to aid in understanding physical processes. Like remote sensing methods, numerical methods require highly specialised knowledge. With the increased development of user-friendly interfaces, it is particularly important to have well-defined research goals, and to know the limitations of the approach used as well as the fundamental science underlying each study. Stead and Wolter (2015) discuss numerical modelling as applied to structural control in slopes in more detail.

The incorporation of Artificial Intelligence (AI), particularly machine learning, into slope stability analysis is a relatively new development, and has allowed for more efficient processing of large datasets. Landslide susceptibility assessment currently applies AI most frequently. Studies such as Dickson & Perry (2016), who identify controls on coastal cliff stability using machine learning, and Đurić et al. (2019), using machine learning to classify slopes as stable, dormant or active in Belgrade, nonetheless show broader applications to slope stability. For a review of machine learning methods applied to structural geology, see Gunderson et al. (2019).

This paper has highlighted methods applied to slope investigations, focussed on the characterisation of structural features and processes that may control slope instability. Although each of the methods presented provides data and can be used to gain insight into failure mechanisms and behaviour related to structural control, studies benefit greatly from using an integrated approach, combining multiple methods. This combined approach deepens understanding and reduces uncertainty. After all, each method is simply one tool in the endeavour to comprehend complex natural processes.

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REFERENCES

Adhikary D.P., Dyskin A.V. (2007) - Modelling of progressive and instantaneous failures of foliated rock slopes. Rock Mechanics and Rock Engineering, 40 (4), 349-362.

Alfaro P., Delgado J., Esposito C., Tortosa F.J., Marmoni G.M., Martino S.D. (2019) - Time-dependent modelling of a mountain front retreat due to a fold-to-fault controlled lateral spreading. Tectonophysics, 773, 228233. Doi: 10.1016/j.tecto.2019.228233

Agliardi F., Crosta G., Zanchi A. (2001) - Structural constraints on deep-seated slope deformation kinematics. Engineering Geology, 59(1-2), 83-102.

Agliardi F., Crosta G.B., Meloni F., Valle C., Rivolta C. (2013) - Structurally-controlled instability, damage and slope failure in a porphyry rock mass. Tectonophysics, 605, 34-47.

Agliardi F., Dobbs M.R., Zanchetta S., Vinciguerra S. (2017) - Folded fabric tunes rock deformation and failure mode in the upper crust. Scientific reports, 7 (1), 1-9.

Allmendinger R.W., Siron C.R., Scott C.P. (2017) - Structural data collection with mobile devices: Accuracy, redundancy, and best practices. Journal of Structural Geology, 102, 98-112.

Ambrosi C., Crosta G.B. (2011) - Valley slope influence on deformation mechanisms of rock slopes. In: Jaboyedoff, M. (Ed.), Slope Tectonics. Geological Society of London, London, UK, 215-233.

Badger T.C. (2002) - Fracturing within anticlines and its kinematic control on slope stability. Environmental and Engineering Geoscience, 8(1), 19-33.

Bistacchi A., Massironi M., Francese R., Giorgi M., Taller C. (2015) - The 3D geological model of the 1963 Vajont rockslide, reconstructed with implicit surface methods. Geophysical Research Abstracts, Vol. 17, EGU2015-15743.

Bonilla-Sierra V., Scholtès L., Donzé F.V., Elmouttie M. (2015) - DEM analysis of rock bridges and the contribution to rock slope stability in the case of translational sliding failures. International Journal of Rock Mechanics and Mining Sciences, 80, 67-78.

Braathen A., Blikra L.H., Berg S.S., Karlsen F. (2004) - Rock-slope failures in Norway; type, geometry, deformation mechanisms and stability. Norwegian Journal of Geology/Norsk Geologisk Forening, 84 (1), 67-88.

Brideau M.A., Stead D. (2010) - Controls on block toppling using a three-dimensional distinct element approach. Rock Mechanics and Rock Engineering, 43(3), 241-260.

Chávez C., Equihua L.N., Domínguez F. (2017) - Stability fem analysis of rock masses modeling pattern of joints. In COMPLAS XIV: proceedings of the XIV International Conference on Computational Plasticity: fundamentals and applications - CIMNE, 646-655.

Cody E., Draebing D., McColl S., Cook S., Brideau M. A. (2019) - Geomorphology and geological controls of an active paraglacial rockslide in the New Zealand Southern Alps. Landslides, 1-22.

Corkum A.G., Martin C.D. (2004) - Analysis of a rock slide stabilized with a toe-berm: a case study in British Columbia, Canada. International Journal of Rock Mechanics and Mining Sciences, 41(7), 1109 -1121.

Dickson M.E., Perry G.L. (2016) - Identifying the controls on coastal cliff landslides using machine-learning approaches. Environmental Modelling and Software, 76, 117-127.

Donati D., Stead D., Elmo D., Borgatti L. (2019) - A Preliminary Investigation on the Role of Brittle Fracture in the Kinematics of the 2014 San Leo Landslide. Geosciences, 9, 256, pp. 31.

Dufresne A., Davies T.R. (2009) - Longitudinal ridges in mass movement deposits. Geomorphology, 105(3-4), 171-181.

Đurić U., Marjanovic M., Radić Z., Abolmasov B. (2019) - Machine learning based landslide assessment of the Belgrade metropolitan area: Pixel resolution effects and a cross-scaling concept. Engineering Geology, 256, 23-38.

Elmo D., Donati D., Stead D. (2018) - Challenges in the characterisation of intact rock bridges in rock slopes. Engineering Geology, 245, 81-96.

Francioni M., Salvini R.L., Stead D., Coggan J. (2017) - Improvements in the integration of remote sensing and rock slope modelling. Natural Hazards, 90, 975 -1004.

Ganerød G.V., Grøneng G., Rønning J.S., Dalsegg E., Elvebakk H., Tønnesen J.F., Kveldsvik V., Eiken T., Blikra L.H., Braathen A. (2008) - Geological model of the Åknes rockslide, western Norway. Engineering Geology, 102, 1-18.

Genevois R., Ghirotti M. (2005) - The 1963 Vaiont landslide. Giornale di Geologia Applicata 1, 41-52.

Genevois R., Tecca P.R. (2013) - The Vajont Landslide: State-of-the-art. Italian Journal of Engineering Geology and Environment - Book Series (6), 15-39.

Gillon K.A., Wooten R.M., Latham R.L., Witt A.W., Douglas T.J., Bauer J.B., Fuemmeler S.J. (2009) - Integrating GIS-based geologic mapping, LiDAR-based lineament analysis and site specific rock slope data to delineate a zone of existing and potential rock slope instability located along the Grandfather Mountain Window-Linville Falls shear zone contact, southern Appalachian Mountains, Watauga County, North Carolina. In 43rd US rock mechanics sympo-sium & 4th US-Canada rock mechanics symposium 28 June - 1 July 2009 (p. 13), 181, Asheville.

Glastonbury J., Fell R. (2000) - Report on the Analysis of “Rapid” Natural Rock Slope Failures. University of New South Wales. School of Civil and Environmental Engineering Report No. R390, pp. 154.

Glueer F., Loew S., Manconi A. (2019a) - Paraglacial history and structure of the Moosfluh Landslide (1850-2016), Switzerland. Geomorphology, 355, 106677.
Doi: 10.1016/j.geomorph.2019.02.021

Glueer F., Loew S., Manconi A., Aaron J. (2019b) - From toppling to sliding: progressive evolution of the Moosfluh Landslide, Switzerland. Journal of Geophysical Research: Earth Surface, 124(12), 2899-2919.

Gschwind S., Loew S., Wolter A. (2019) - Multi-stage structural and kinematic analysis of a retrogressive rock slope instability complex (Preonzo, Switzerland) Engineering Geology, 252, 27-42.

Guerin A., Jaboyedoff M., Collins B.D., Derron M.H., Stock G.M., Matasci B., Boesiger M., Lefeuvre C., Podladchikov Y.Y. (2019) - Detection of rock bridges by infrared thermal imaging and modeling. Scientific reports, 9(1), 1-19.

Gunderson K.L., Zhang Z., Cheng S. (2019) - Machine learning applications to structural geology: Philosophy, progress, and pitfalls. Geological Society of America Annual Meeting, Paper No. 143-14, pp. 14.

Guo Q., Pan J., Cai M., Zhang Y. (2020) - Investigating the effect of rock bridge on the stability of locked section slopes by the direct shear test and acoustic emission technique. Sensors (Basel, Switzerland), 20(3), 638.
Doi: 10.3390/s20030638

Havaej M., Wolter A., Stead D. (2015) - The possible role of brittle rock fracture in the 1963 Vajont Slide, Italy. International Journal of Rock Mechanics and Mining Sciences, 78, 319-330.

Havaej M., Stead D. (2016) - Investigating the role of kinematics and damage in the failure of rock slopes. Computers and Geotechnics, 78, 181-193.

Henderson I.H.C., Lauknes T.R., Osmundsen P.T., Dehls J., Larsen Y., Redfield T. F. (2011) - A structural, geomorphological and InSAR study of an active rock slope failure development. Geological Society, London, Special Publications, 351(1), 185-199.

Hendron A.J., Patton F.D. (1985) - The Vaiont Slide: A Geotechnical Analysis Based on the New Geologic Observations of the Failure Surface: Technical Report GL-85-5, pp. 259.

Hoek E., Hutchinson J., Kalenchuk K., Diederichs M. (2009) - Appendix 3: influence of in situ stresses on open pit design. In: Read, J., Stacey, P. (Eds.), Guidelines for Open Pit Slope Design. CSIRO Publishing, Collingwood, Australia, 437-445.

Humair F., Pedrazzini A., Epard J.-L., Froese C.R.,

Jaboyedoff M. (2013) - Structural characterization of Turtle Mountain anticline (Alberta, Canada) and impact on rock slope failure. Tectonophysics 605, 133-148.
Jaboyedoff M., Oppikofer T., Derron M.H., Blikra L.H., Böhme M., Saintot A. (2011) - Complex landslide behaviour and structural control: a three-dimensional conceptual model of Åknes rockslide, Norway. Geological Society, London, Special Publications, 351(1), 147-161.
Kromer R.A., Hutchinson D.J., Lato M.J., Gauthier D., Edwards T. (2015) - Identifying rock slope failure precursors using LiDAR for transportation corridor hazard management. Engineering Geology, 195, 93-103.
Lee S., Suh J., Choi Y. (2018) - Review of smartphone applications for geoscience: current status, limitations, and future perspectives. Earth Science Informatics, 11, 463-486.
Loew S., Gischig V., Willenberg H., Alpiger A., Moore J. R. (2012) - 24 Randa: Kinematics and driving mechanisms of a large complex rockslide. In: Clague J.J., Stead D. (Eds.), Landslides: Types, Mechanisms and Modeling, Cambridge University Press, 297-309.
Manconi A., Loew S., Glueer F. (2019) - Insights on rock mass disintegration at the Moosfluh slope, Switzerland. In Geophysical Research Abstracts (Vol. 21).
Massironi M., Zampieri D., Superchi L., Bistacchi A., Ravagnan R., Bergamo A., Genevois M. (2013) - Geological structures of the Vajont landslide. Italian Journal of Engineering Geology and Environment, 2013(6), 573-582.
Mathiesen D., Myers T., Atkinson I., Trevathan J. (2012) - Geological visualisation with augmented reality. In 2012 15th International Conference on Network-Based Information Systems (172-179) - IEEE. Doi: 10.1109/NBiS.2012.199
Milmo P., Rogers S., Raynor M., Beale G. (2014) - Appendix 3: case study: Diavik North-west wall. In: Read, J., Beale, G. (Eds.), Guidelines for Evaluating Water in Pit Slope Stability. CSIRO Publishing, Collingwood, 436-485.
Mineo S., Calcaterra D., Zampelli S.P., Pappalardo G. (2015) - Application of infrared thermography for the survey of intensely jointed rock slopes. Rendiconti Online Societa Geologica Italiana, 35, 212-215.
Mysiorek J., Onsel I.E., Stead D., Rosser N. (2019) - Engineering Geological characterization of the 2014 Jure Nepal Landslide: An integrated field, remote sensing-Virtual/Mixed Reality approach. In 53rd US Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association, pp. 12.
Nováková L., Pavlis T.L. (2019) - Modern Methods in Structural Geology of Twenty-first Century: Digital Mapping and Digital Devices for the Field Geology. In: Teaching Methodologies in Structural Geology and Tectonics, Springer, Singapore, 43-54.
Paronuzzi P., Bolla A. (2012) - The prehistoric Vajont rockslide: An updated geological model. Geomorphology, 169, 165-191.
Paronuzzi P., Bolla A. (2015) - Gravity-Induced Fracturing in Large Rockslides: Possible Evidence from Vajont. In: Engineering Geology for Society and Territory-Volume 2, Springer, Cham, 213-216.
Perrone A., Lapenna V., Piscitelli S. (2014) - Electrical resistivity tomography technique for landslide investigation: a review. Earth-Science Reviews, 135, 65-82.
Petronio L., Boaga J., Cassiani G. (2016) - Characterization of the Vajont landslide (North-Eastern Italy) by means of reflection and surface wave seismics. Journal of Applied Geophysics, 128, 58-67.
Ravagnan R. (2011) - Evidence of Dinaric Tectonic in the Vajont Area and Consequences on the Local Geological and Hydrogeological Structure. BSc thesis, Universita degli Studi di Padova, Padova, Italy, pp. 117.
Scaioni M., Longoni L., Melillo V., Papini M. (2014) - Remote Sensing for Landslide Investigations: An Overview of Recent Achievements and Perspectives. Remote Sensing, 6, 9600-9652.
Semenza E. (2010) - The story of Vaiont told by the geologist who discovered the landslide. Translation by Carolyn Goodman Masè of Semenza (2001). K-flash, Ferrara, pp. 208.
Shea T., Vries B.V. (2008) - Structural analysis and analogue modeling of the kinematics and dynamics of rockslide avalanches. Geosphere, 4(4), 657-686.
Singeisen C., Ivy-Ochs S., Wolter A., Steinemann O., Akçar N., Yesilyurt S., Vockenhuber C. (2020) - The Kandersteg rock avalanche (Switzerland): integrated analysis of a late Holocene catastrophic event. Landslides, 1-21.
Stead D., Donati D., Wolter A., Sturzenegger M. (2019) - Application of Remote Sensing to the Investigation of Rock Slopes: Experience Gained and Lessons Learned. ISPRS International Journal of Geo-Information, 8(7), 296, pp. 24.
Stead D., Eberhardt E. (2013) - Understanding the mechanics of large landslides. Invited keynote and paper. Italian Journal of Engineering Geology and Environment, Book Ser. 6, 85-112.
Stead D., Eberhardt E., Coggan J.S. (2006) - Developments in the characterization of complex rock slope deformation and failure using numerical modelling techniques. Engineering Geology, 83, 217-235.
Stead D., Wolter A. (2015) - A critical review of rock slope failure mechanisms: The importance of structural geology. Journal of Structural Geology, 74, 1-23.
Sturzenegger M., Stead D. (2012) - The Palliser Rockslide, Canadian Rocky Mountains: Characterization and modeling of a stepped failure surface. Geomorphology, 138(1), 145-161.
Superchi L., Floris M., Ghirotti M., Genevois R., Jaboyedoff M., Stead D. (2010) - Technical Note: Implementation of a geodatabase of published and unpublished data on the catastrophic Vaiont landslide. Natural Hazards and Earth System Sciences, 10(4), 865-873.
Vanderlip C. (2016) - Structural Geology With A Mobile

Phone?: Testing Smartphone Apps For Strike And Dip. Geological Society of America, South-Central Section: 50th Annual Meeting, Paper No. 15-10.

Vick L.M., Böhme M., Rouyet L., Bergh S.G., Corner G.D., Lauknes T.R. (2020) - Structurally controlled rock slope deformation in northern Norway. Landslides, 1-32.

Wasowski J., Pisano L. (2019) - Long-term InSAR, borehole inclinometer, and rainfall records provide insight into the mechanism and activity patterns of an extremely slow urbanized landslide. Landslides, 17, 445-457.

Wolter A., Havaej M., Zorzi L., Stead D., Clague J.J., Ghirotti M., Genevois R. (2013) - Exploration of the kinematics of the 1963 Vajont slide, Italy, using a numerical modelling toolbox. Italian Journal of Engineering Geology and Environment, 6, 599-612.

Wolter A., Stead D., Clague J.J. (2014) - A morphologic characterisation of the 1963 Vajont Slide, Italy, using long-range terrestrial photogrammetry. Geomorphology, 206, 147-164.

Wolter A., Stead D., Ward B., Clague J.J., Ghirotti M. (2015) - Engineering geomorphological characterisation of the Vajont Slide, Italy, and a new interpretation of the chronology and evolution of the landslide. Landslides, 13, 1067-1081.

Yuskar Y., Putra D.B.E., Suryadi A., Choanji T., Cahyaningsih C. (2017) - Structural Geology Analysis In A Disaster-Prone Of Slope Failure, Merangin Village, Kuok District, Kampar Regency, Riau Province. Journal of Geoscience, Engineering, Environment, and Technology, 2(4), 249-254.

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