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Forensic Investigations of Failures in Rocks: Review and Assessment of Methodologies

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Abstract. Failures in rock masses are one of the leading causes of recurrent disasters like landslides, rock falls, instability during tunneling, dam foundation failures, etc. As the frequency of such catastrophic events increases, thorough forensic investigations of such failure events are essential to obtain representative information of the failure regions and improve the understanding of the factors controlling the stability of rock masses.

This paper reviews reported case studies on forensic investigations of rock failures to assess the various tools and techniques employed to inspect the different types of failures. The importance of detailed forensic investigations to developing a better understanding of the factors responsible for the instability of rock masses is also highlighted in this paper. The review of these failure observations can also aid as a guide for selection of appropriate mitigation measures to avoid such disasters that cause significant socio-economic losses.

Keywords: Forensic investigation, Stability of rock masses, Rock failures, Review

1 Introduction

Failure of rock is one of the top causes which leads to recurrent disasters that have been encountered by mankind today, be it in the form of landslides, rockfalls, toppling of rocks, or dip slope failures, among others. Factors that play an important role in rock failures are divided into two main categories: natural and anthropogenic. Natural factors like topography, structure, stratigraphy ground water flow, the geology of the slopes and rock weathering [1, 2] are the major factors which lead to failure. Triggering factors like water pressure and gas outburst in a magmatic rock can induce damage and bed separation, resulting in the breakup of the parent rocks. Glacial lake outburst flood (GLOF), rock bursting, squeezing of tunnels, and landslides are all disastrous events which are resulted due to rock mass failure [3 – 5]. In some cases when these natural factors create a condition of failure, it gets aggravated due to anthropogenic cause like mining and climate change [6, 7]. Activities like the exploration of radioactive minerals, seismicity, coupling water, hydraulic fracture development, and joint propagation are also reported to destroy assembled rocks or rock structures [8]. These activities also produce weak zones, which can act as an initiator for the particular hazard. Even slope excavation for opencut roads in mountainous regions now is seen as a key factor for slope failure [9].

As the frequency of such catastrophic events increases, it becomes essential to study them to understand the cause of failure and update our knowledge. To attain this objective, a summary of forensic investigation-based analyses of such reported events in the past decades is presented in this paper. In addition, an attempt is also made to list and categorize numerous forensic techniques; thus, this paper provides a detailed review of how such techniques can be used to investigate the causes of failure in various scenarios. This paper combines case studies and observations that can be used as a step toward developing a better understanding of these rock failures.

2 Forensic Investigation Techniques and their applications

The word forensic mainly deals with the branch of science in which scientific methods are employed to study the area under consideration [10]. When this branch of science is used to study various rock mass failure events, the existing designs of such structures can be improved to save the lives and cut down economic losses. The understanding developed from the forensic investigations can also help in predicting failure, which further helps to develop the prediction philosophy of various disastrous events like landslides, rockfalls, slope failures, etc. The forensic investigation techniques can be used to investigate rock mass failures irrespective of the time at which it is employed, i.e., the failure can be monitored or studied at any point of time after a complete collapse has happened [11].

Forensic techniques mainly comprise of four basic factors: (a) ensuring the stability of the existing structure, (b) protecting the overall safety, (c) measuring the extent of the failure, and (d) remedial steps to recover the failure portion. For a safe and thorough forensic investigation, it is essential that each step is followed precisely and in right order. The procedure that ensures these objectives has been devised by Rao [11]. The tasks of the engineer are divided into mandatory tasks, voluntary tasks, scrutiny of data, and report submission. Each task contains a number of sub-tasks that need to be performed by the engineer to complete the investigation. The order of these tasks and their subcategories are shown in Fig. 1. Fig. 1 also provides useful information about the procedure that ensures that maximum data can be acquired from the site in minimum number of visits. It not only reduces the time for the investigation but also helps in reducing the cost.

There are multiple forensic investigation techniques that can be used to study the pre- and post- failure behaviour of the geological material that has undergone failure [11, 12, 24, 29]. Such tools can be categorized into three broad categories based on (a) applicability, (b) time of application, and (c) the failure modes, as shown in Fig. 2. This categorization is further illustrated when various case studies pertaining to each of these categories are referred, as shown in Table 1. Table 1 further summarizes the type of failure/collapse, triggering factors, forensic investigation techniques employed, and the significant observations for each of the referenced case study.

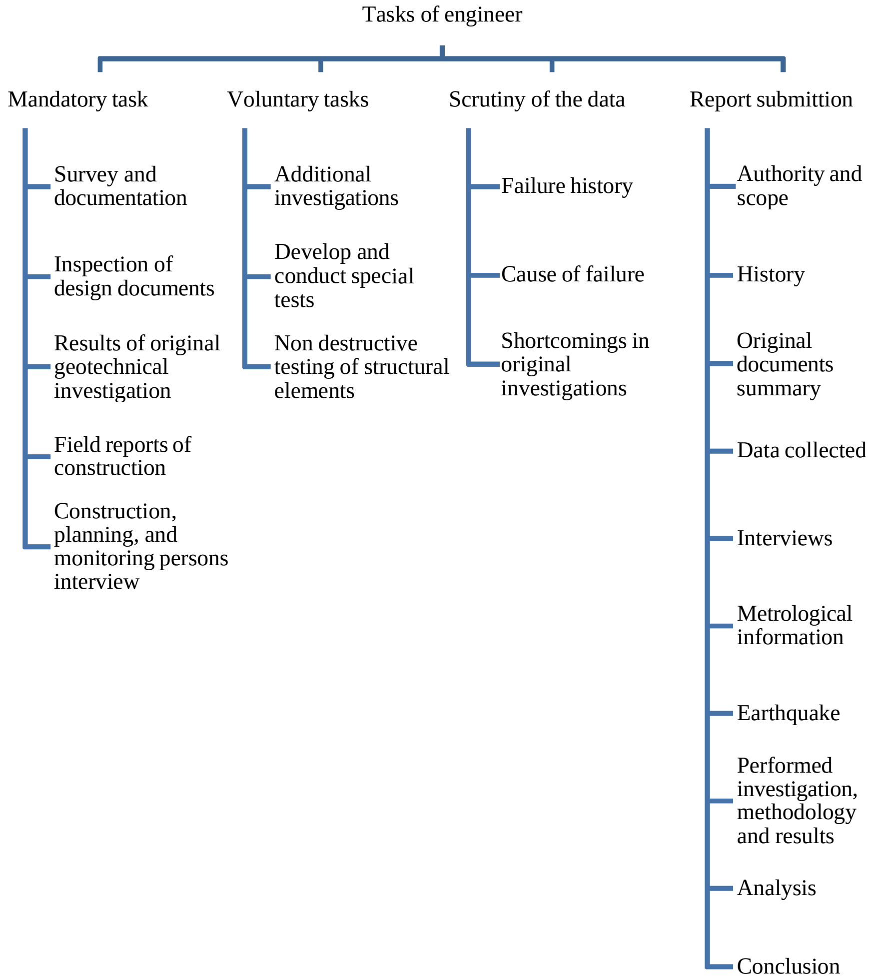

Fig. 1. Categorization of task performed during investigation (Rao 2016)

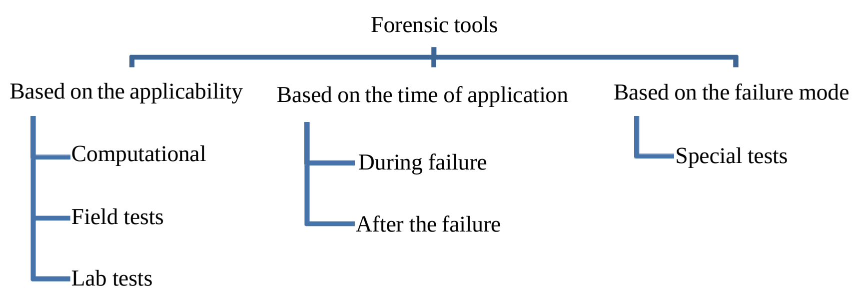

Fig. 2. Different categories of forensic tools

Table 1. List of reviewed case studies

Failure type	**Author/ Year**	**Location description**	**Investigation Techniques/ Methods**	**Categorization of forensic technique**	**Triggering factors**	**Conclusions/Mitigation Measures**
Landslide	Basharat et al. [12]	Northern Pakistan	• Digital elevation models • Global Positioning System • Laser distance meter	• After failure • Computational	• 2005 Kashmir Earthquake of magnitude 7.6 • Highly fractured zone	• Rock avalanche followed the pre-existing synclinal morphology of the Danna and Dandbeh synclines
Slope failure	Lee et al. [9]	Taiwan	• 2D limited equilibrium analysis • FDM analysis (FLAC-3D)	• After failure • Computational	• Weathering and deterioration • Corrosion of ground anchors • Conjugated fissures and joint cracks	• Preventive corrosion measures • Proper sub-surface drainage system • Health inspection and monitoring programs
Landslide	Spreafico et al. [24]	Northern Italy	• Geomorphic and geological data • Runout simulation by DAN3D, and SHALTOP	• Field tests • Computational	• Reverse and transpressive faults • Glacier deposition	• Landslide attain max. velocity of 70m/s, and durations of 70–80s, indicate rapid rock avalanche
Discontinuity persistence	Shang et al. [29]	Blackhill Quarry and Dry Rigg Quarry in Yorkshire, UK	• Non explosive splitting by Dexpan chemical splitter • Schmidt hammer rebound test	• Field tests • During failure	• Near-planar rock discontinuities • Weathering • Geological features	• Schmidt hammer rebound values of persistent stained areas smaller and shows high degree of chemical and physical weathering
Tunnel foundation failure	Prendes-Gero et al. [33]	Lugo province, Spain	• Displacement sensors • Borehole drilling test • Penetration test • Numerical analysis (FLAC-2D, 3D)	• Special tests • During failure • Field tests • C20omputational	• Water filtration, • Ground movement, • Visible signs of displacement and rotation	• Inaccurate geometric design • Geological investigation is underestimated in design • Factor of safety is not sufficiently considered in design of foundation
Tunnel failure	Dhang [34]	Jammu and Kashmir, India	• Topography • Geological investigation	• During failure	• Overstressed rock • Faults and tension fractures zones • Shear zones • and foliation shear zones	• NATM with drilling -blasting/ chipping is the most appropriate method of tunneling due to higher unpredictability

Tunnel failure	Zhang et al. [1]	Ta-warayama Tunnel, Kuma-moto Pre-fecture, Japan	• Lining crack mapping • Photo recording • Geological investigation	• During failure • Field tests	• 2016 Kumamoto earthquake of magnitude 7.3 • Geological conditions • Lining conditions	• Avoid tunnel near the slope faces • Avoid tunnel running across active fault zones • Concern more about longitudinal displacements
Tunnel collapse	Zhang et al. [30]	Zinzhi tunnel, Hangzhou city, China	• Site reconnaissance • Vane shear test	• Field tests	• Ground water seepage • Poor ground conditions • Excavation methodology adopted	Remediation: • Crater filling • Reinforcement • Grouting and dewatering • Debris removal

Various computational techniques were used in order to understand and investigate the mechanism behind the failure of rocks [4, 13–15]. The computational analysis can be done by various numerical methods such as discrete element [16, 17], finite element [18, 19], finite difference [13, 20] and combined finite element [21, 22] and digital elevation methods [23], etc. Simple runout simulations were implemented using DAN3D and SHALTOP codes to understand the landslides dynamics, and validated using laboratory experiments [24]. Xu et al. [13] implemented a time-dependent model to understand the deformations and damage with respect to time in heterogeneous brittle rocks. He and Yang [4] used the Johnson-Holmquist (JH) model to study the dynamic crack propagation in Granite using AUTODYN hydrocode with respect to decoupling coefficients. The AUTODYN code was also used by Zhu et al. [25] to study blast failure in cylindrical rocks. Gu and Ozbay [26] developed a universal 2D Discrete Element Code to investigate the fractures and stresses in discontinuous mass such as jointed rocks. These codes were reported to have advantage over other numerical modeling tools (such as Finite Element, Finite Difference, and Boundary Element methods) due to their simplistic approach in modelling multiple intersecting interfaces, large displacements, and rock rotation. Xue et al. [27] used the analytic hierarchy procedure and the entropy weight approach to determine the weight of the indexes to study the risk of rock failure.

Forensic investigations of rock failures can be best understood by field and laboratory tests. Direct shear tests were conducted on rock sample and deduced that failure of rock included multiple fusion kinds of rock bridges [28]. Since the dynamic characteristics of a rock plays a great role in examining the failure in rocks, He and Yang [4] used a Split Hopkinson pressure bar to analyse the dynamic compressive and tensile strengths of rock sample. A non-explosive technique was proposed namely, Forensic Excavation of Rock Masses (FERM) to investigate the discontinuity present in the rocks by using Dexpan chemical [29]. Field tests were conducted to study the strength characteristics of the debris that flooded the entire tunnel [30]. The crack width and the length of the crack were measured, which got induced due to the earthquake to assess the degree of tunnel damage [31].

3 Forensic Investigations for Various Types of Failures in Rocks

3.1 Landslides

Forensic investigation of a landslide can significantly reduce the chances of further landslides. The primary purpose of post-failure slope and stability analysis is to contribute to safe and cost-effective planning for disaster mitigation.

The forensic investigation for landslides (rock avalanche) occurred in the northern Pakistan resulted due to the earthquake of 7.6 magnitude in 2005 uses digital elevation models and a global positioning system [12]. Investigation revealed that approximately 2 m of displacement has been observed from its original position before the avalanche by laser distance meter. It has been found that this rock avalanche was on an old rockslide [32] which got triggered by the earthquake after many years. Similarly a forensic investigation was performed using numerical modelling for the slope failure which occurred at Da-Pu section of National freeway No. 3 in northern Taiwan [9]. In this, 2D limited-equilibrium slope-stability analysis was used to check the initial slope condition, and the 3D finite-difference method was used to simulate the behavior of the studied anchored slope from the initial to failure stages. The investigation results showed that failure occurred due to certain factors such as weathering of slopes, corrosion of ground anchors, and deterioration due to groundwater submergence. These factors together proved to be fatal for the dip slopes. The geomorphic and geological field data for Cima salt landslide situated at north of lake Garda in the Trentino region of Italy was used to investigate to investigate the landslide dynamics and the volume of the landslide with the help of simple runout simulation codes [24]. The results of the investigation gave the idea of landslide volume and debris deposition depth. Also, the significance of ice and snow entrainment in landslides led to a low shear resistance and long runout distances.

These forensic investigations also revealed that sliding slopes made up of stones like claystone, mudstone, and sandstone are much more prone to fracture, although the orientation of these present in the layers plays a vital role in slope failure.

3.2 Discontinuity Persistence

The characteristics of discontinuities play an important role in the deformation and destruction of rock masses. True persistence of rock discontinuities (regions of negligible tensile strength) is an important factor controlling the engineering behavior of fractured rock masses, but it is very challenging to determine the rock discontinuity persistence using current geological survey methodologies, even where there is good rock exposure. Shang et al. [29] used FERM (forensic excavation of rock masses), a novel approach for examining the discontinuities present in rock both in the field and laboratory. Non-eruptive splitting across the planar or near-planar initial rock discontinuity is used in this approach. It involves non-explosive excavation of rock masses by injecting a Dexpan chemical splitter along incipient discontinuities. Results revealed that the visible trace length of a discontinuity can be a poor indicator of true persistence. This investigation led to the observation that newly failed surfaces through pre-existing rock bridges were relatively rough compared to sections of pre-existing weaker areas of geologically developed discontinuities.

The results conclude that the FERM technique can be used effectively for the forensic investigation of rocks, which can be further useful in characterizing the rocks, understanding the reasons for rock's weathering, and measuring persistence, which ultimately gives us an idea of the cause of rocks failure and many other advantages.

3.3 Failures in Tunnels

Tunneling through the rock is a difficult task, and proper prediction of the ground prior to excavation is very much required. The strength and deformation characteristics of rock masses play a major role in determining stability and support requirements in the tunnel. For this reason, forensic investigation is essential for a tunnel. Forensic investigation applies engineering principles and methodologies to determine the cause of a tunnel performance deficiency and often a tunnel collapse.

A forensic investigation has been performed to find the cause of the tunnel foundation failure in Lugo province [33]. For investigation, displacement sensors were used to observe the maximum displacements. Also, numerical modeling was performed to simulate the effect of the foundation's penetration and settlement within the surrounding ground, and the failure mechanism of the tunnel can be understood. It was found that the failure was due to the inaccurate geometric design of the tunnel. The results showed that deformation was underestimated in the design, and the ground on which the foundation of the tunnel rests was a highly fractured rock. Dhang [34] performed the geomorphologic, geological field data study, and geotechnical investigation to get the required data for understanding and predicting the ground behaviour prior to the excavation in the tunnel extending from Dharam to Sumbar (T-48) with two audits (A1 & 2) are part of USBRL project. Zhang et al. [1] investigated the distribution and characteristics of seismic damages in the Tawarayama Tunnel in Kumamoto Prefecture, Japan (Fig. 3) and summarized it to assess potential influencing factors. Influencing factors for each pattern of seismic damages involve characteristics of seismic waves, concrete lining conditions, and geological conditions, including engineering properties of surrounding rock mass, fault zone, etc.

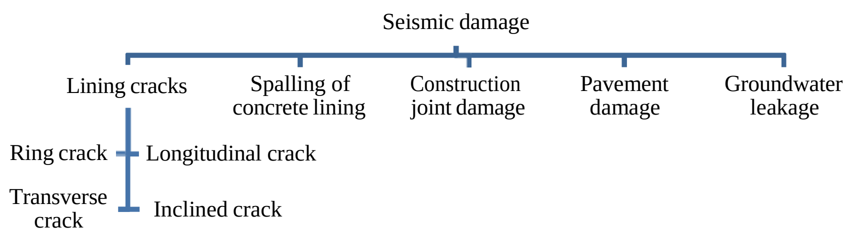

Fig. 3. Different types of seismic damage in tunnel

Zhang et al. [30] performed a site reconnaissance survey to investigate the possible causes for the tunnel collapse under a water channel in Hangzhou city and then evaluated the soil failure mechanisms. In the forensic investigation, it has been found that the soil above the tunnel was of low strength, and groundwater seepage was also present at the site. These were the two major causes that caused tunnel failure.

The results from forensic investigation provides some recommendations for future tunnel planning a) Tunnels should be placed as far away from slope faces if possible. If not, it is important to simultaneously take into account the slope stability assessment [1]. b) Tunnels should not pass-through active fault zones or regions of the weak surrounding rocks. If crossing fault zones, reinforced countermeasures should be taken into account for the concrete lining [34]. c) Some of the quick mitigation technique proposed for the tunnel collapse considers the repair procedures included filling the collapsed crater, strengthening debris in the tunnel by reinforcement, stabilizing the ground by dewatering and grouting, and removing debris from the site and resuming tunnel construction [33].

4 Summary

The present study reviews the various failures and their mechanism in such a way that the characteristic properties of the rock which played a major role in the failure of the rock will be understood in detail so that the predictive theory can be proposed for various disasters. In this study a reverse engineering technique is used as a methodology to develop a knowledge about the behaviour of the rocks which can result in above mentioned events. The detailed review highlighted that even the small events need to be monitored and investigated in detail as these small events can lead to devastating disasters. Further, the rock properties like persistence deformation characteristics and the behavioral nature under different loading need to be studied in detail to understand the role of fracture and its propagation under the loading along with the continuous detrimental effects like weathering, which continuously weakens the rock mass. There is a reduction in the strength of the rock during the weathering cycle especially due to the presence of the water. As increase in the moisture content of the rock mass will result in the decrease of the strength. Forensic studies help in understanding the short-comings in the existing knowledge, which helps in protecting not only new structures but also the existing structure so that the losses can be minimized. There is a pressing need for present-day engineering designs to understand the behavior of the material and how it reacts in various situations and eliminate various assumptions taken in the design. This can be achieved by studying various failure patterns as discussed in the present paper. This branch of science will also aid in developing more sustainable design and construction methodology, along with the economy in the design of various structures.

References

[1] X. Zhang, Y. Jiang, and S. Sugimoto, "Seismic damage assessment of mountain tunnel: A case study on the Tawarayama tunnel due to the 2016 Kumamoto Earthquake," *Tunn. Undergr. Sp. Technol.*, vol. 71, no. April 2017, pp. 138–148, 2018, doi: 10.1016/j.tust.2017.07.019.

[2] P. B. Durgin, "Landslides and the weathering of granitic rocks," *GSA Rev. Eng. Geol.*, vol. 3, 1977, doi: 10.1130/REG3-p125.

[3] M. Amini, A. Majdi, and M. A. Veshadi, "Stability analysis of rock slopes against block-flexure toppling failure," *Rock Mech. Rock Eng.*, vol. 45, no. 4, 2012, doi: 10.1007/s00603-012-0220-7.

[4] C. He and J. Yang, "Experimental and numerical investigations of dynamic failure process in rock under blast loading," *Tunn. Undergr. Sp. Technol.*, vol. 83, 2019, doi: 10.1016/j.tust.2018.08.047.

[5] Y. Zhao *et al.*, "Study of the Rock Mass Failure Process and Mechanisms During the Transformation from Open-Pit to Underground Mining Based on Microseismic Monitoring," *Rock Mech. Rock Eng.*, vol. 51, no. 5, 2018, doi: 10.1007/s00603-018-1413-5.

[6] D. E. Dunn, L. J. LaFountain, and R. E. Jackson, "Porosity dependence and mechanism of brittle fracture in sandstones," *J. Geophys. Res.*, vol. 78, no. 14, 1973, doi: 10.1029/jb078i014p02403.

[7] D. A. Lockner, "Rock Failure," in *Rock Physics & Phase Relations: A Handbook of Physical Constants*, 2013.

[8] K. F. Zhou and S. S. Wang, "Spectral properties of weathered and fresh rock surfaces in the Xiemisitai metallogenic belt, NW Xinjiang, China," *Open Geosci.*, vol. 9, no. 1, 2017, doi: 10.1515/geo-2017-0027.

[9] W. F. Lee, H. J. Liao, M. H. Chang, C. W. Wang, S. Y. Chi, and C. C. Lin, "Failure

Analysis of a Highway Dip Slope Slide," *J. Perform. Constr. Facil.*, vol. 27, no. 1, pp. 116–131, 2013, doi: 10.1061/(asce)cf.1943-5509.0000345.

[10] W. G. Eckert, *Introduction to Forensic Sciences*. CRC Press, 1996.

[11] V. V. S. Rao, "Guidelines for Forensic Investigation of Geotechnical Failures," 2016.

[12] M. Basharat, J. Rohn, D. Ehret, and M. S. Baig, "Lithological and structural control of Hattian Bala rock avalanche triggered by the Kashmir earthquake 2005, sub-Himalayas, northern Pakistan," *J. Earth Sci.*, vol. 23, no. 2, pp. 213–224, 2012, doi: 10.1007/s12583-012-0248-3.

[13] T. Xu, Q. Xu, C. an Tang, and P. G. Ranjith, "The evolution of rock failure with discontinuities due to shear creep," *Acta Geotech.*, vol. 8, no. 6, 2013, doi: 10.1007/s11440-013-0244-5.

[14] W. C. Zhu, C. A. Tang, Z. P. Huang, and M. Z. Pang, "Numerical simulation on splitting failure mode of rock under static and dynamic loadings," *Yanshilixue Yu Gongcheng Xuebao/Chinese J. Rock Mech. Eng.*, vol. 24, no. 1, 2005.

[15] Y. C. Wang, X. C. Yin, F. J. Ke, M. F. Xia, and K. Y. Peng, "Numerical simulation of rock failure and earthquake process on mesoscopic scale," *Pure Appl. Geophys.*, vol. 157, no. 11–12, 2000, doi: 10.1007/PL00001067.

[16] L. A. M. Camones, E. do A. Vargas, R. P. de Figueiredo, and R. Q. Velloso, "Application of the discrete element method for modeling of rock crack propagation and coalescence in the step-path failure mechanism," *Eng. Geol.*, vol. 153, 2013, doi: 10.1016/j.enggeo.2012.11.013.

[17] Y. Lu, Y. Tan, and X. Li, "Stability analyses on slopes of clay-rock mixtures using discrete element method," *Eng. Geol.*, vol. 244, 2018, doi: 10.1016/j.enggeo.2018.07.021.

[18] R. E. Hammah, T. Yacoub, B. Corkum, and J. H. Curran, "The practical modelling of discontinuous rock masses with finite element analysis," 2008.

[19] L. F. Wang and X. P. Zhou, "A field-enriched finite element method for simulating the failure process of rocks with different defects," *Comput. Struct.*, vol. 250, 2021, doi: 10.1016/j.compstruc.2021.106539.

[20] J. Tu, Y. Zhang, G. Mei, and N. Xu, "Numerical investigation of progressive slope failure induced by sublevel caving mining using the finite difference method and adaptive local remeshing," *Appl. Sci.*, vol. 11, no. 9, 2021, doi: 10.3390/app11093812.

[21] D. Fukuda *et al.*, "Development of a 3D Hybrid Finite-Discrete Element Simulator Based on GPGPU-Parallelized Computation for Modelling Rock Fracturing Under Quasi-Static and Dynamic Loading Conditions," *Rock Mech. Rock Eng.*, vol. 53, no. 3, 2020, doi: 10.1007/s00603-019-01960-z.

[22] R. E. Hammah, J. H. Curran, T. Yacoub, and B. Corkum, "Stability Analysis of Rock Slopes using the Finite Element Method," 2004.

[23] R. W. Jibson, E. L. Harp, and J. A. Michael, "A method for producing digital probabilistic seismic landslide hazard maps," *Eng. Geol.*, vol. 58, no. 3–4, 2000, doi: 10.1016/S0013-7952(00)00039-9.

[24] M. C. Spreafico, A. Wolter, V. Picotti, L. Borgatti, A. Mangeney, and M. Ghirotti, "Forensic investigations of the Cima Salti Landslide, northern Italy, using runout simulations," *Geomorphology*, vol. 318, no. 2017, pp. 172–186, 2018, doi: 10.1016/j.geomorph.2018.04.013.

[25] Z. Zhu, H. Xie, and B. Mohanty, "Numerical investigation of blasting-induced damage in cylindrical rocks," *Int. J. Rock Mech. Min. Sci.*, vol. 45, no. 2, 2008, doi: 10.1016/j.ijrmms.2007.04.012.

[26] R. Gu and U. Ozbay, "Numerical investigation of unstable rock failure in underground mining condition," *Comput. Geotech.*, vol. 63, 2015, doi: 10.1016/j.compgeo.2014.08.013.

[27] Y. Xue, X. Li, G. Li, D. Qiu, H. Gong, and F. Kong, "An analytical model for assessing

soft rock tunnel collapse risk and its engineering application," *Geomech. Eng.*, vol. 23, no. 5, 2020, doi: 10.12989/gae.2020.23.5.441.

[28] Y. Zhang, Y. Jiang, D. Asahina, and C. Wang, "Experimental and Numerical Investigation on Shear Failure Behavior of Rock-like Samples Containing Multiple Non-Persistent Joints," *Rock Mech. Rock Eng.*, vol. 53, no. 10, 2020, doi: 10.1007/s00603-020-02186-0.

[29] J. Shang, S. R. Hencher, L. J. West, and K. Handley, "Forensic Excavation of Rock Masses: A Technique to Investigate Discontinuity Persistence," *Rock Mech. Rock Eng.*, vol. 50, no. 11, pp. 2911–2928, 2017, doi: 10.1007/s00603-017-1290-3.

[30] N. Zhang, J. S. Shen, C. Lin, A. Arulrajah, and J. C. Chai, "Investigation of a large ground collapse and countermeasures during mountain tunnelling in Hangzhou: a case study," *Bull. Eng. Geol. Environ.*, vol. 78, no. 2, pp. 991–1003, 2019, doi: 10.1007/s10064-017-1098-0.

[31] Y. Shen, B. Gao, X. Yang, and S. Tao, "Seismic damage mechanism and dynamic deformation characteristic analysis of mountain tunnel after Wenchuan earthquake," *Eng. Geol.*, vol. 180, 2014, doi: 10.1016/j.enggeo.2014.07.017.

[32] S. A. Dunning, W. A. Mitchell, N. J. Rosser, and D. N. Petley, "The Hattian Bala rock avalanche and associated landslides triggered by the Kashmir Earthquake of 8 October 2005," *Eng. Geol.*, vol. 93, no. 3–4, 2007, doi: 10.1016/j.enggeo.2007.07.003.

[33] M. B. Prendes-Gero, F. Lopez-Gayarre, C. Menendez-Fernandez, and M. Rodriguez-Avial Llardent, "Forensic analysis of the failure of the foundations of a tunnel built to channel the course of a river," *Eng. Fail. Anal.*, vol. 32, 2013, doi: 10.1016/j.engfailanal.2013.01.004.

[34] P. C. Dhang, "Tunneling in overstressed rock: Example from the Lesser Himalaya of Jammu and Kashmir, India," 2017.