3CroCEE

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.140

EFFECT OF SEISMIC LOAD ON THE STABILITY OF A DOLOMITE QUARRY IN HUNGARY

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Abstract

The rock slope stability in seismically active regions is a critical aspect for safe and sustainable quarrying. This study investigates the effect of seismic loading on the stability of a dolomite quarry, integrating traditional analytical methods with advanced two-dimensional finite element models. The site, located near a historically active earthquake zone, provides an ideal environment to explore slope stability under both static and dynamic conditions. Site measurements and rock mass data, supplemented by geological data from comparable formations, inform the development of a comprehensive geotechnical model. The methodology the slope design framework emphasizing kinematic analysis and failure mode evaluation, particularly relevant to the structural integrity of strong, jointed rock masses like dolomite. Regulations, including Eurocode 7 partial factors and criteria for safety and failure probability, frame the analytical approach. Slope stability is first assessed through empirical techniques, such as SMR and Q Slope, then through detailed analytical solutions using RocScience software. Through RocScience RS2 could examine the application of seismic load in finite element models and highlight potential failures under earthquake conditions**.** While optimization of mining slopes is outside the scope, this analysis emphasizes model sensitivity to seismic inputs, joint geometry, and mesh size, demonstrating critical conditions under dynamic loading. Limitations in data availability, particularly historical earthquake data, are addressed with approximate time-history data.

Keywords: rock slope stability, seismic loading, dolomite quarry, geotechnical modelling, jointed rock masses, earthquake effects

1. Introduction

Open-pit mining often involves the excavation of rock masses with complex geological structures, requiring detailed slope stability assessments to ensure operational safety and economic viability. Stable slopes are critical to minimizing the risks of rockfalls or large-scale collapses, which can result in fatalities, equipment damage, and operational disruptions. In regions subject to seismic activity, the risk of slope instability is further exacerbated by dynamic forces, necessitating specialized approaches for slope analysis [1, 2]. This study focuses on addressing these challenges in the context of a dolomite quarry in Vilonya, Hungary, where the interplay of geological conditions and seismicity poses significant engineering concerns.

The Vilonya dolomite quarry is situated in an area of moderate seismic activity, as evidenced by the 1985 Berhida earthquake, which had a moment magnitude of Mw = 5.2 and occurred approximately 5 km from the site. This earthquake highlighted the potential for seismic events to impact local infrastructure and geological stability [3]. Given the quarry's proximity to the epicentre, understanding the seismic response of slopes is essential for designing resilient pit walls. The absence of local acceleration time history data necessitated using comparable seismic records, such as those from the 2004 Parkfield earthquake in California, to model the effects of dynamic loading on slope stability [4].

The primary objective of this study is to assess the stability of a slope in the Vilonya dolomite quarry under both static and seismic conditions. This involves:

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1. Utilizing traditional analytical methods, such as Slope Mass Rating (SMR) and kinematic analysis, to identify potential failure mechanisms.
2. Incorporating advanced numerical modelling techniques using finite element methods (FEM) to simulate the effects of seismic loading.
3. Comparing analytical and numerical results to evaluate the reliability and accuracy of different methods in predicting slope behaviour under varying conditions.
4. Providing recommendations for slope design and monitoring strategies to mitigate the risks associated with seismic activity.

2. Geological and Geotechnical Framework

The Vilonya dolomite quarry is located in western Hungary, within Veszprém County, near the village of Vilonya. The area is predominantly composed of the Budaörs Dolomite Formation, a Triassic-era carbonate rock unit with a thickness of up to 1.5 kilometres. The dolomite is overlain by the Dachstein Limestone Formation and underlain by the Veszprém Marl Formation. These formations provide a stable geological foundation but require detailed characterization to assess their engineering behaviour [5].

The rock mass in the quarry consists predominantly of dolomite, a sedimentary carbonate rock with a fractured and blocky structure. The dolomite is characterized by the following features:

Material Properties: Laboratory testing has determined a uniaxial compressive strength (UCS) of approximately 68.8 MPa and a unit weight of 27.69 kN/m³. The dolomite exhibits a residual UCS of 20-30% of its intact strength under high-stress conditions.

Joint Systems: The rock mass contains significant discontinuities, including a primary joint set with a dip/dip direction of 30°/311°. The joints are rough (mean Joint Roughness Coefficient, JRC = 10) and variably spaced, with a typical interjoint distance of 10 m. These features strongly influence the stability and potential failure mechanisms of the slopes.

Geological Strength Index (GSI): The dolomite is classified within a GSI range of 40–60, reflecting its blocky, interlocked structure with moderate surface weathering. Residual GSI values are lower (20–30), corresponding to degraded conditions after failure [6, 7].

The hydrogeological setting of the quarry has a minimal impact on slope stability. The site is located in the catchment area of the Séd River but lacks significant groundwater sources, springs, or surface water bodies within a 1-kilometer radius. Precipitation and infiltration rates are low due to the region's fractured, karstic nature, which promotes rapid drainage. As a result, the effects of groundwater pressure or hydrodynamic forces on slope stability are considered negligible for this analysis.

3. Seismic Activity and Loading Considerations

The Vilonya dolomite quarry is situated in a region of moderate seismic activity. One of Hungary's largest recorded earthquakes occurred in 1985 near Berhida, just 5 kilometres from the quarry. This earthquake, with a moment magnitude of Mw = 5.2, was caused by strike-slip faulting at a focal depth of approximately 10–12 kilometres [8]. The event generated a peak ground acceleration (PGA) of 0.15g and a peak ground velocity (PGV) of 7 cm/s, which resulted in localized structural damage and heightened awareness of seismic risks in the area. The proximity of the quarry to this epicentre underscores the need for detailed seismic stability assessments on its slopes [9].

A key challenge in the analysis was the absence of detailed acceleration time-history data from the 1985 Berhida earthquake. To address this, comparable seismic events were identified using global earthquake databases. The 2004 Parkfield earthquake in California, which had a moment magnitude of Mw = 6.0, was selected as a reference due to its similar geological setting (strike-slip faulting) and focal depth (7.9 km). The acceleration data from the Turkey Flat #1 Rock South station provided a reliable basis for the analysis, with a peak horizontal ground acceleration of 0.25g, closely matching the design acceleration for the quarry. This selection ensured that the seismic input accurately represented the dynamic forces that might act on the slope during an earthquake.

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Two seismic loading approaches were employed to assess slope stability under earthquake conditions: Pseudo-Static Analysis: A horizontal seismic coefficient (kH) of 0.15g was applied as the design acceleration, representing the region's typical seismic activity. Additionally, a higher kH value of 0.25g, corresponding to the peak acceleration observed in the Parkfield earthquake, was used to simulate extreme conditions. These values were applied in a static framework using analytical methods such as RocPlane and Swedge . Dynamic Analysis: To capture the transient effects of seismic loading, the acceleration time history from the Parkfield earthquake was integrated into the finite element model (FEM) using RocScience RS2 software. This dynamic approach accounted for the progressive buildup and dissipation of seismic forces, providing insights into displacement patterns, joint yielding, and potential failure mechanisms.

4. Methodology

The methodology for assessing the effect of seismic loading on the stability of a dolomite quarry slope near Vilonya, Hungary, integrates field investigations, analytical techniques, and numerical modelling [10] to provide a comprehensive analysis. Field investigations began with data collection on-site, including the measurement of joint properties using geological compasses and Barton comb profilometers to determine key parameters such as the Joint Roughness Coefficient (JRC) and joint stiffness values. The geometry and structure of the slope were recorded, and a photogrammetry-based 3D model of the quarry was developed, incorporating reference points measured on-site to ensure dimensional accuracy Fig. 1. Laboratory tests from a comparable dolomite quarry provided values for the uniaxial compressive strength (UCS), density, and elastic modulus of the rock, which were used alongside field observations to establish Geological Strength Index (GSI) ranges for the generalized Hoek-Brown failure criterion.

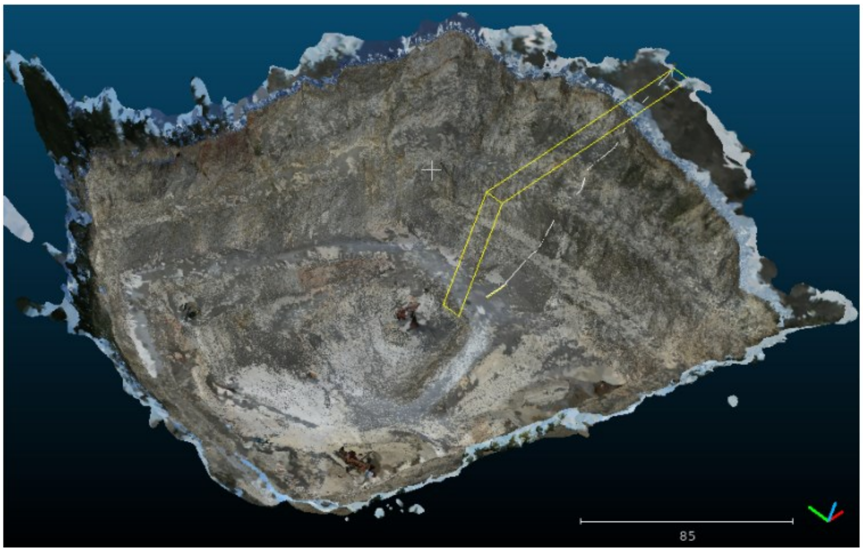

Figure 1. 3D model of the mine generated from photographs. The examined wall can be seen in yellow. (courtesy of Gábor Németh)

Analytical methods included kinematic analysis using stereographic projection to identify potential failure mechanisms such as planar, wedge, and toppling failures Fig. 2. Stability was further assessed using empirical approaches, including the Slope Mass Rating (SMR) and Q-Slope systems. Pseudo-static analysis was conducted with RocScience RocPlane software, calculating the factor of safety (FoS) for seismic coefficients kH=0.15gk and kH=0.25gk. The input parameters for these analyses, including joint orientations and material properties, were derived from field and laboratory data. Numerical modelling was performed using RocScience RS2 software to simulate both static and dynamic conditions [11]. The slope geometry was simplified to reflect typical open-pit mine configurations, and

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finite element models were created with varying mesh densities and boundary conditions to ensure robustness. Dynamic analysis incorporated acceleration time history data from the 2004 Parkfield earthquake, scaled to match the seismic design parameters for the site. Rayleigh damping was applied to simulate realistic energy dissipation during seismic events, and horizontal displacement trends were analysed under different loading conditions [9].

a) b)

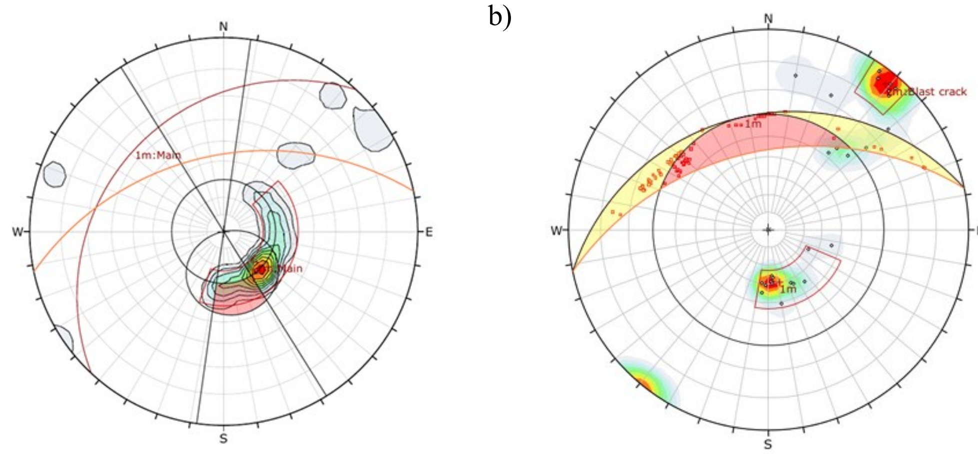
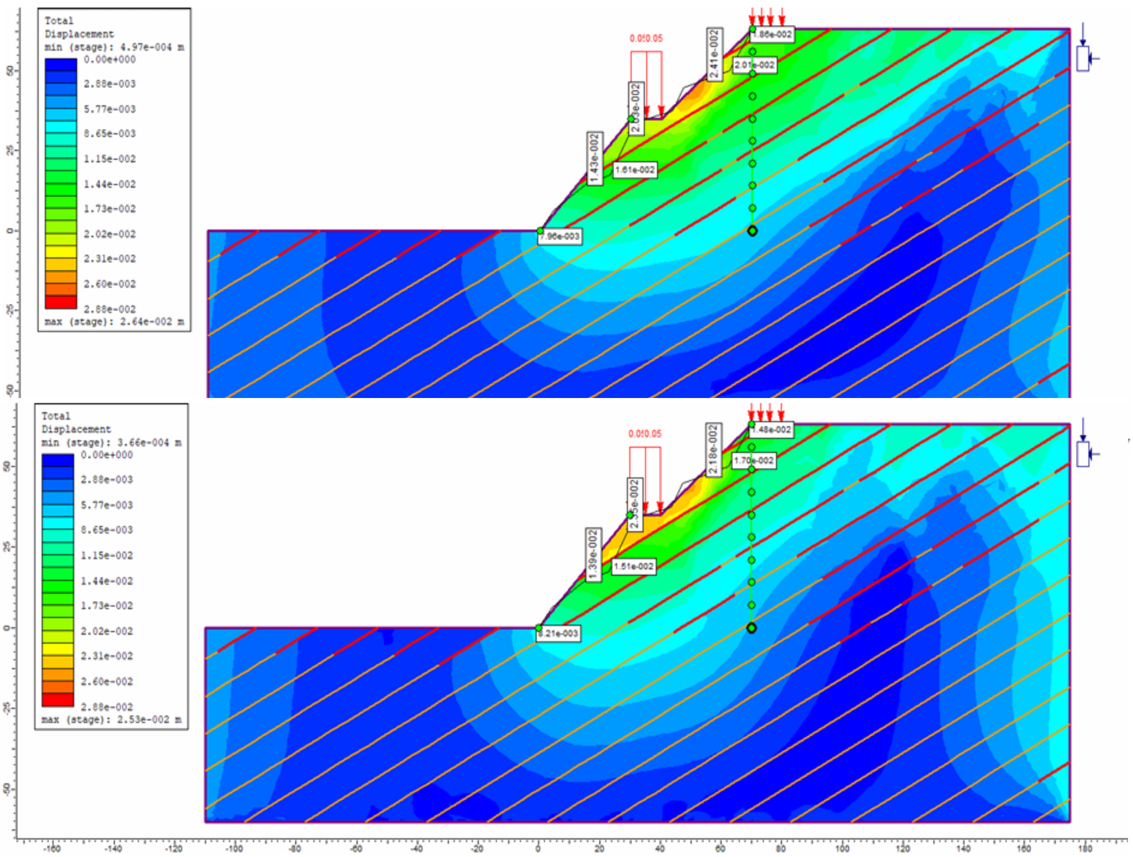


Figure 2. Kinematic analysis of wall 3 a) Possibility of plane failure; b) Possibility of wedge failure

Sensitivity analyses were conducted to examine the effects of mesh density, slope geometry, and joint stiffness on stability outcomes. The robustness of the numerical models was verified through comparative analyses with empirical methods. Figures of total displacements (Fig. 3 and 4) shows critical zones of instability. Horizontal displacements of the dynamic earthquake can be acquired on the base of the ramp geometry and dynamic model with large mesh. These detailed investigations provided a comprehensive understanding of the seismic response of the dolomite slope, forming the basis for recommendations on slope reinforcement and design adjustments.

a)
b)
c)



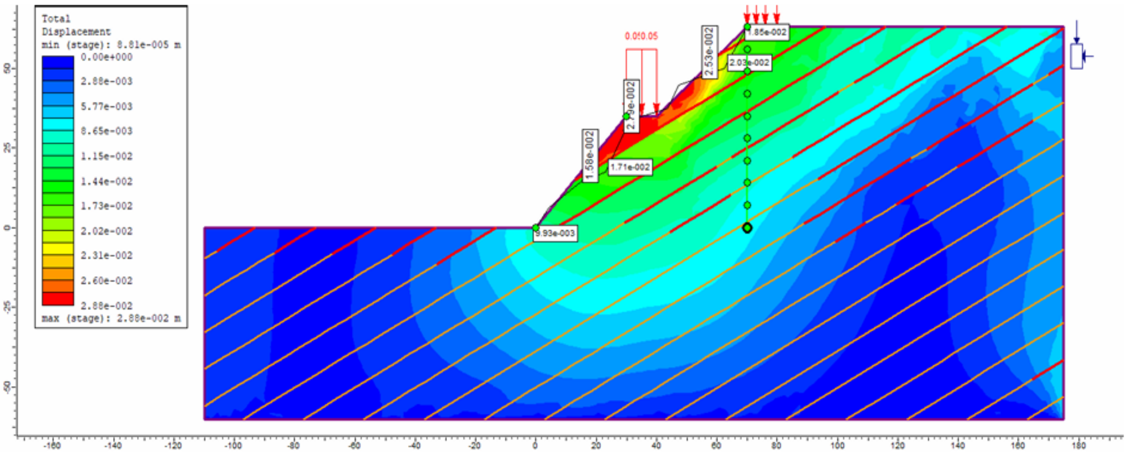
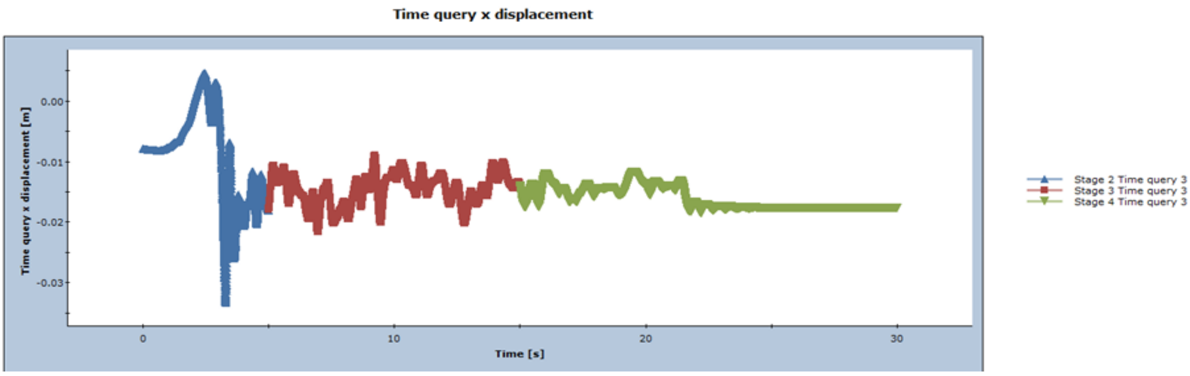


Figure 3. Displacement diagrams of dynamic model showing the yielded joints.
a) Dynamic loading at 5s; b) Dynamic loading at 15s; c) Dynamic loading at 35s

a)



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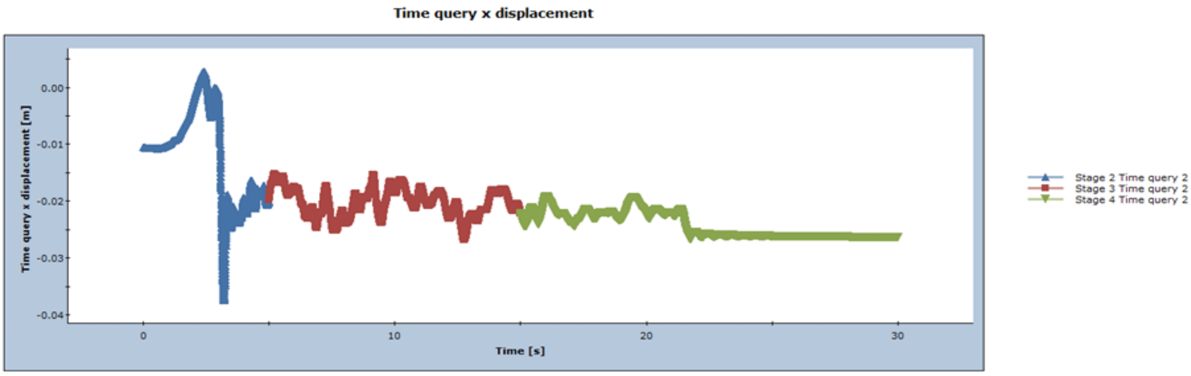

c)

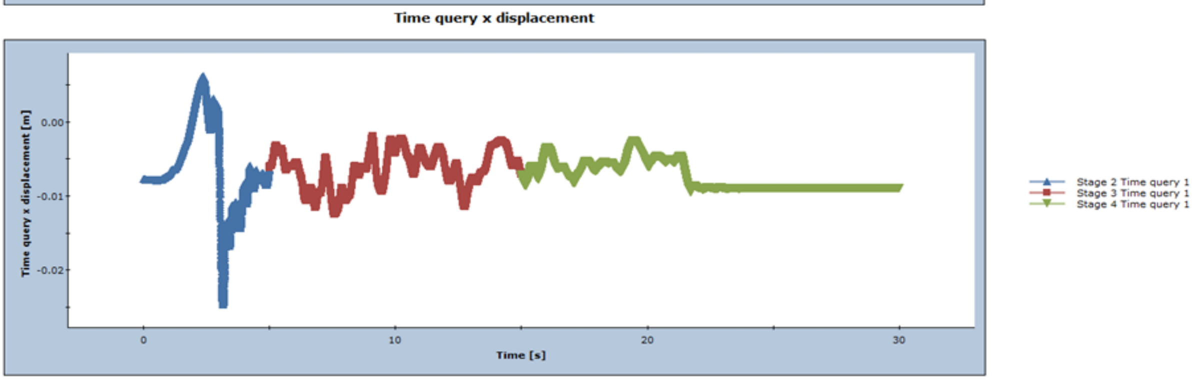

Figure 4. Horizontal displacements during the earthquake shows twofold increase of the static displacements. a) crown; b) ramp; c) base

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5. Results and Discussion

The results of this study highlight critical insights into the stability of dolomite quarry slopes under static and seismic loading conditions. Analytical methods, such as SMR and Q-Slope, classified the slope as stable under static conditions, aligning with conventional expectations for strong, jointed rock masses like dolomite. However, the pseudo-static analysis indicated significant sensitivity to higher seismic accelerations [12, 13], with the factor of safety dropping below the acceptable limit at kH=0.25gk. Dynamic finite element modelling confirmed these findings, showing substantial horizontal displacements and yielded joint zones near the crest and mid-slope regions during peak seismic events. The deformation trends observed in the numerical models underscore the slope's vulnerability to seismic loading beyond the design-level acceleration.

Comparing these findings with existing literature, the observed behaviour aligns with studies on jointed rock masses under seismic loading. For instance, works like those by Sarma (1973) and recent publications on probabilistic seismic slope stability Qing Lu (2019) report similar trends where joint orientation and dynamic acceleration significantly influence failure mechanisms. These studies emphasize the importance of joint geometry and seismic coefficients, consistent with the sensitivity analyses conducted in this research. However, the specific findings for dolomite, particularly the critical role of joint roughness and residual strength, provide a more tailored perspective for regions with similar geological conditions [2].

From a theoretical standpoint, this study demonstrates the necessity of integrating dynamic analyses into slope stability evaluations. While traditional methods provide an initial assessment, they lack the capability to account for time-dependent seismic effects, which finite element models effectively capture. Practical implications include the need for designing slope reinforcements, such as rock bolts and anchors, particularly in areas with a history of significant seismic activity. The findings advocate for a shift towards incorporating seismic loading in quarry planning to ensure operational safety.

However, there are some limitations. The unavailability of site-specific time-history seismic data required the use of approximate data from a comparable event, which may not fully capture the unique seismic characteristics of the region. Additionally, the numerical models were limited to two-dimensional analysis, which does not account for potential three-dimensional effects. Future research opportunities include the development of three-dimensional models to better understand complex failure mechanisms and the integration of probabilistic approaches to account for the variability in seismic and geological parameters.

6. Conclusion

This study investigated the effects of seismic loading on the stability of a dolomite quarry slope, addressing key research questions about the behaviour of jointed rock masses under both static and dynamic conditions. The results directly support the hypothesis that seismic loading significantly influences the stability of slopes in seismically active regions [14]. Analytical methods, including SMR and Q-Slope, demonstrated that the slope is stable under static conditions, but pseudo-static and dynamic analyses revealed reduced stability when subjected to higher seismic accelerations, particularly at kH=0.25gk. The observed yielding of joints and increased horizontal displacements in dynamic finite element models confirm the hypothesis that dynamic seismic effects exacerbate potential failure mechanisms in jointed rock masses.

A clear cause-and-effect relationship was established between seismic loading and slope deformation. The results showed that jointed rock slopes like dolomite are particularly sensitive to dynamic seismic forces, with the magnitude and orientation of joint sets playing a critical role in failure. The study demonstrated that under design-level seismic accelerations, the slope remains stable, but peak accelerations cause significant instability, leading to potential failure. These findings emphasize the importance of considering both joint geometry and seismic inputs in slope design, particularly in regions prone to earthquakes.

The practical significance of these results lies in their application to quarry slope management and safety. The findings suggest that traditional static and pseudo-static methods, while valuable for initial

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assessments, may underestimate risks in seismically active areas. Incorporating dynamic analyses into design practices can help engineers identify critical zones of instability and implement targeted reinforcement measures, such as rock bolts or anchors, to mitigate failure risks. The study also provides a framework for adapting quarry operations to dynamic loading scenarios, ensuring safe and sustainable mining practices.

Theoretically, the study contributes to the understanding of seismic effects on jointed rock masses by integrating empirical methods with advanced finite element modelling. It highlights the necessity of dynamic modelling for capturing time-dependent failure mechanisms that traditional methods overlook. The sensitivity analysis of key parameters, such as joint stiffness and mesh density, offers insights into optimizing numerical models for improved accuracy. Furthermore, the approach demonstrates how approximate seismic time-history data can be effectively used in the absence of site-specific records, broadening the applicability of the findings to similar geological and seismic contexts.

In summary, the results of this study validate the initial hypothesis and provide robust answers to the research questions, linking seismic loading to slope stability in jointed dolomite formations. The cause-and-effect relationships identified and the integration of practical and theoretical insights underline the significance of this work for advancing slope stability analysis and enhancing safety in seismically active quarrying environments.

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