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Numerical Analysis of Cervo Cliff Stability Due to Basal Marine Erosion

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Abstract

This study presents a numerical analysis of a retreating sea cliff located along the SS1 “Aurelia” in the Italian Municipality of Cervo (Liguria Region, Italy), between Capo Mimosa and the town of Andora (Savona). The area is exposed to atmospheric and marine processes (wave action, sea spray and tidal cycles) that promote rock weathering and cliff erosion. Several instability events have occurred, the most recent in November 2023 and March 2024, posing a potential threat to nearby structures and infrastructures, including a building situated directly above the cliff where ongoing toe erosion may exacerbate structural instability.

Numerical simulations were carried out using the Finite Element Method (FEM) implemented in the Rocscience RS2 code. Because the cliff is largely inaccessible, detailed in-situ investigations were not feasible. The geometry of the analysed sections and the main rock-mass structure were assessed via drone flight surveys. Geotechnical parameters were assigned based on an extensive literature review and an experimental campaign on cored samples collected at a nearby site belonging to the same geological formation. A back analysis of the most recent rockfall event was used to refine the mechanical parameters and calibrate the model. Future cliff instability was investigated by simulating the progressive retreat of the basal notch generated by erosion. Several incremental erosional stages were modelled to identify potential failure scenarios under continued natural degradation. The results provide insights into the expected failure mechanisms of the coastal cliff and support the identification of potentially critical conditions associated with notch development, with implications for risk awareness and the management of exposed elements along the SS1 corridor.

Keywords

Coastal cliff stability, Basal marine erosion, Notch retreat, Back-analysis, Finite-element modelling.

1 Introduction

Rocky coastal cliffs are increasingly affected by marine erosion and changing weather conditions, which accelerate basal undercutting and promote instability. Wave impacts, sea spray, and repeated wetting–drying cycles enhance weathering and notch formation at the cliff toe, progressively reducing the mechanical strength of the rock (Khajevand and Fereidooni, 2022) and favouring rock block collapse (Budetta, 2011; Castedo et al., 2017; Sunamura, 2015). Where cliffs interact with buildings and infrastructures, these processes directly increase the risk to structures and transportation networks. This highlights the need to account for both basal erosion and time-dependent weakening when assessing coastal cliff hazards.

This study investigates a retreating coastal cliff along the SS1 “Aurelia” road in the Municipality of Cervo, a picturesque village situated in the Liguria region of north-western Italy, perched on a hill along the Italian Riviera. It is renowned for its well-preserved medieval architecture and stunning sea views. The village's elevated position provides panoramic vistas of the Ligurian Sea, making it a favoured spot for tourists seeking both cultural heritage and natural beauty.

The lithological nature of the rock mass, a flysch formation, is characterized by alternate layers of limestones, mudstones and sandstones (the latter are usually harder), and clayey layers with weaker mechanical behavior. This setting leads to differential erosion processes: the more erodible clayey levels are progressively removed by wave action, resulting in the formation of cavities and indentations; conversely, the more resistant layers tend to remain as overhanging rock ledges. The progressive undercutting at the toe of the slope, induced by marine action, reduces the overall stability of the rocky cliff and, in conjunction with intense and/or prolonged rainfall events (and consequent water infiltration in the rock fractures), promotes the triggering of landslides. Over time, these processes lead to a gradual retrogression of the cliff edge. Significant examples of such dynamics are represented by the instability events that occurred in recent years, particularly those of November 2023 and March 2024.

At present, signs of potential instability are also evident along the rock face. These conditions may evolve during future storm surges and/or intense rainfall events, potentially causing further retrogression of the cliff edgethat could undermine the stability of nearby structures and infrastructures, including a two-storey building located directly above the cliff edge.

The cliff, modelled as a homogeneous arenaceous rock mass, was analysed using the two-dimensional finite-element method implemented in the Rocscience code RS2 v11.023. A back-analysis of the March 2024 event was first carried out to refine the mechanical parameters. The critical Strength Reduction Factor (SRF) and the corresponding patterns of shear strains and total displacements were used as reference indicators. Post-collapse conditions were then investigated by simulating progressive basal notch retreat through incremental stages to identify plausible failure mechanisms under continued erosion. This approach provides a mechanically consistent interpretation of the observed event and a basis for evaluating the temporal evolution of cliff stability along the SS1 corridor.

2 Back-analysis of the coastal cliff stability

The geometry of the analysed cliff section and the main rock-mass structure were reconstructed from DTM data and a drone-based survey to generate the profile used for numerical modelling. A 2D cross-section of the cliff was analysed under plane-strain conditions. The model geometry is characterised by a cliff height (Hc) of 21 m, an overall slope inclination of 59°, and a cliff width (Wc) of 12.4 m (Fig. 1b, c). Based on on-site observations, a basal notch was explicitly included at the cliff toe, with a height (Hn) of 4 m and a depth (Ln) of 6.3 m (Fig. 1c). The model setup and boundary conditions are illustrated in Fig. 1a, together with a field photograph of the actual cliff and basal notch. Roller boundary conditions were imposed along the base and vertical boundaries, while pinned constraints were applied at the lower corners. Gravitational loading was introduced to initialise the in-situ stress state. The numerical mesh consists of six-noded triangular elements and is largely uniform, with local refinement in the notch and cliff-toe region to capture stress and strain localisation (Fig. 1c). The geotechnical parameters were defined based on an extensive literature review and an experimental campaign carried out on cored samples collected at a nearby site belonging to the same geological formation. The rock mass behaviour was modelled using the Hoek–Brown failure criterion. Two material zones were defined to represent the (inner) intact and (external) weathered rock-mass

conditions. The uniaxial compressive strength and Young's modulus of the intact rock were derived from UCS laboratory tests performed on undisturbed core samples. Additional Schmidt hammer and point-load tests conducted on rock outcrops and samples exposed to the marine environment were used to estimate the compressive strength of the weathered rock. The rock-mass Hoek–Brown parameters and deformability modulus were estimated assuming a Geological Strength Index (GSI) of 30, according to the chart proposed by Marinos and Hoek (Marinos & Hoek, 2000). The parameters adopted in the numerical analyses are summarised in Table 1. External distributed loads were applied to account for the presence of the building and the adjacent roads (Table 2; Fig. 1b).

Table 1. Rock-mass parameters adopted in the numerical analyses (Hoek–Brown model).

Zones	**(γ) (kN/m³)**	**(ν) (–)**	**(E) (MPa)**	**(σ_{ci}) (MPa)**	**(m_β) (–)**	**(s) (–)**
Altered	25	0.27	1628	86	0.739	0.00042
Older rock	25	0.27	1628	101	0.739	0.00042

Table 2. External actions applied in the numerical model as equivalent uniformly distributed loads: building first-floor load, building second-floor load, service road loads (roads 1 and 2), and main road load.

first floor kN/m²	**second floor kN/m²**	**Service road kN/m²**	**Main road kN/m²**
74	148	43	62

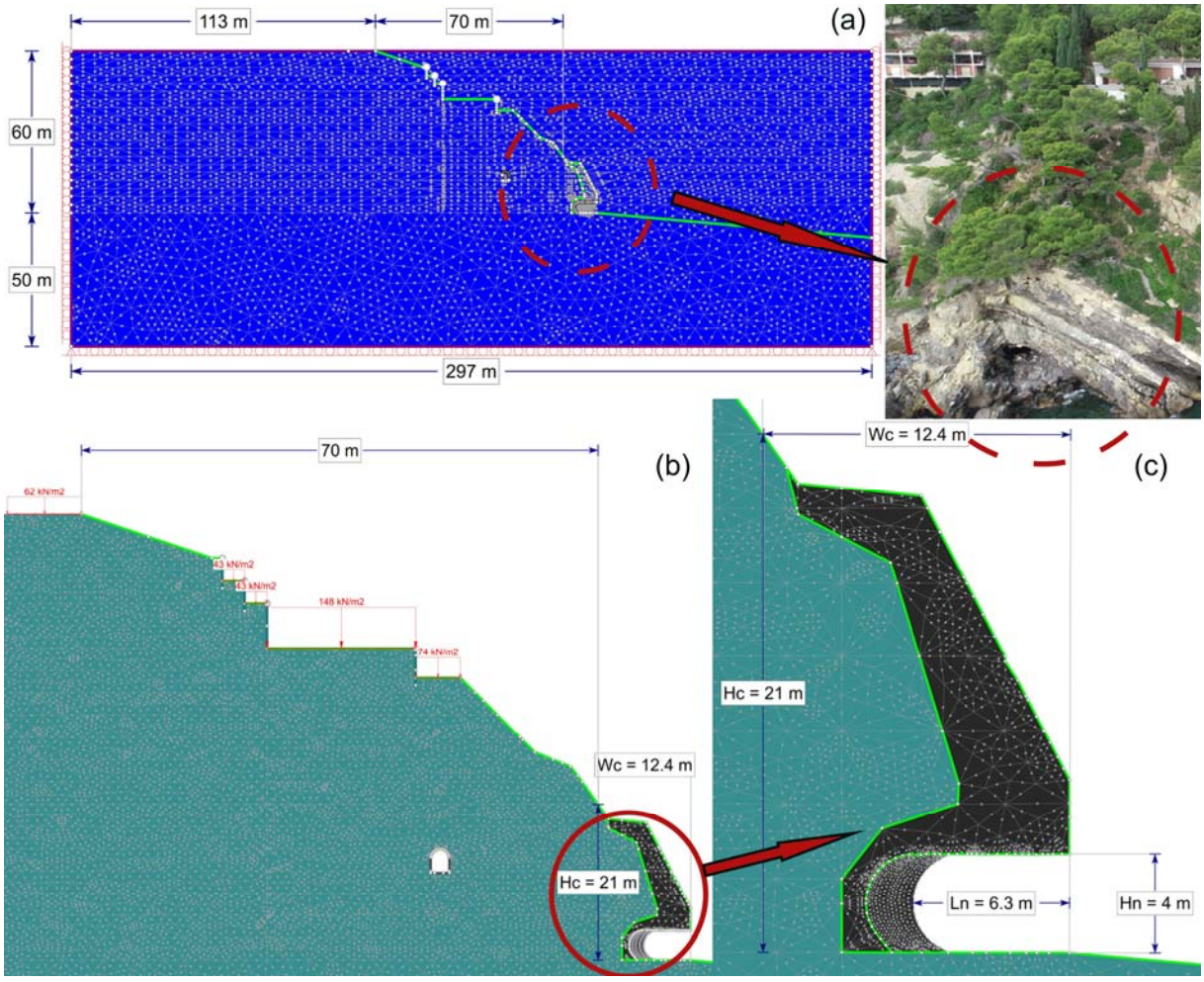


Fig. 1 Numerical model setup: (a) overall geometry, dimensions, and boundary conditions, together with a field photograph of the cliff and basal notch; (b) applied external actions represented as equivalent uniformly distributed loads (building floors and road surfaces); (c) detail of the cliff-toe region showing the cliff geometry (Hc, Wc) and notch geometry (Hn, Ln), with local mesh refinement. The black layer represents the weathered rock layer.

The analysis was performed using the shear strength reduction (SSR) method to determine the strength reduction factor (SRF). The alteration of the external layer of the slope and the progressive notch retreat was simulated through a staged excavation scheme (Fig. 1c). The numerical model includes 32 stages, of which: 20 provide the creation of the slope profile by progressively removing the ground layers (Fig.1a), the following one is used for applying external loads and excavating the tunnel, and the final nine simulatethe notch-retreat phases. The critical condition (SRF = 1.01) was reached after seven stages of notch retreat, corresponding to a final notch depth of 6.3 m. At this stage, progressive shear strain localization led to the collapse of the rock volume above the notch. The resulting failure mechanism, shown in Figure 2 in terms of maximum shear strain and total displacement, is consistent with field observations, confirming the representativeness of the model. These results are also consistent with the findings of Napoli et al. (2024a, b), who observed that when the ratio between the height of the cliff overhang (above the notch) and the notch depth is high, a shear failure mechanism is expected.

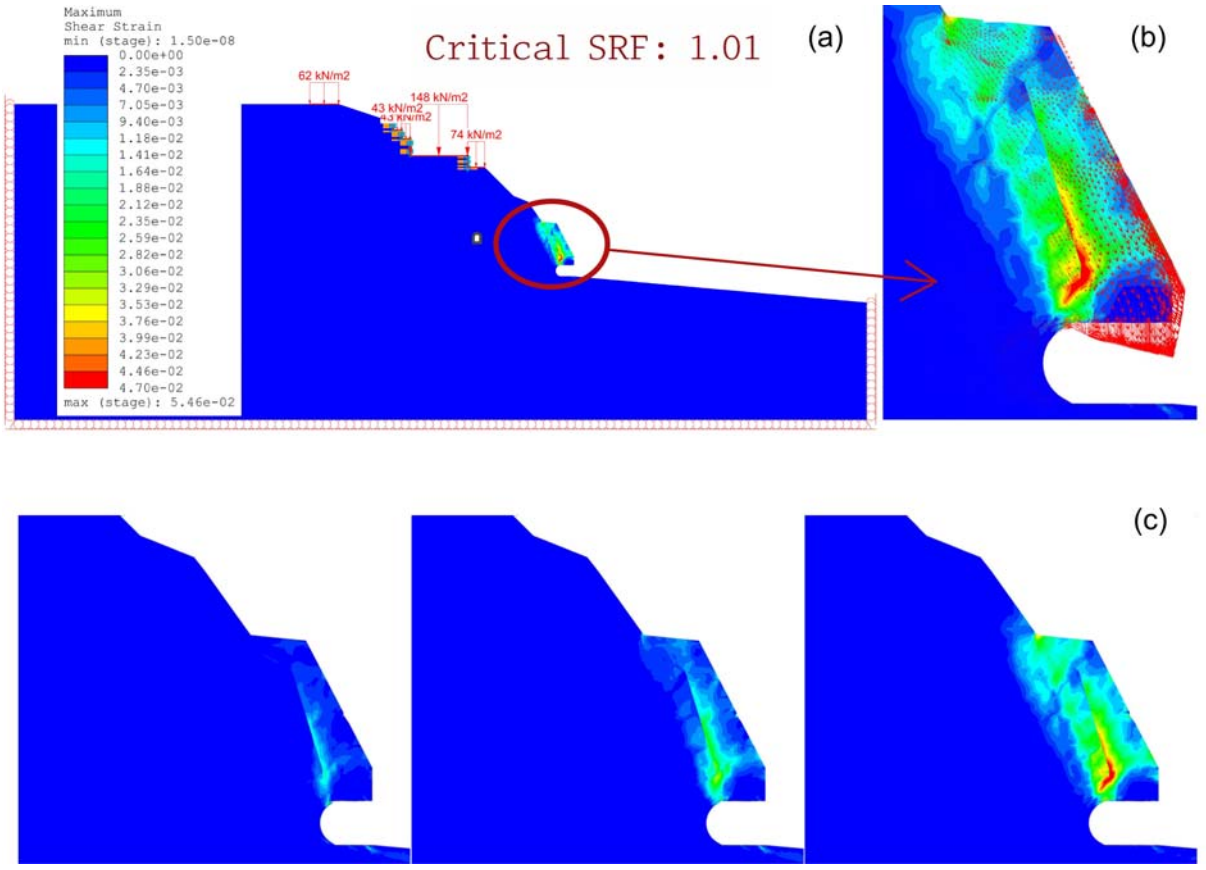


Fig. 2 Maximum shear strain contours and critical SRF (a); maximum total displacements (b); evolution of the maximum shear strains with the progressive retreat of the notch (c).

3 Analyses of the post collapse scenarios

Two post-collapse scenarios were analysed to investigate the current stability condition of the rock cliff and its possible potential evolution driven by progressive rock-wall alteration and the deepening of the notch over time. The model geometry was updated to represent the post-collapse condition, modifying the cliff profile to account for the failure of the seaward portion (Fig. 3a). As shown in Fig. 3b, the cliff currently exhibits global and local stability with a factor of safety of 1.99, millimetric maximum displacements at the roof of the residual notch and negligible concentration of shear strains.

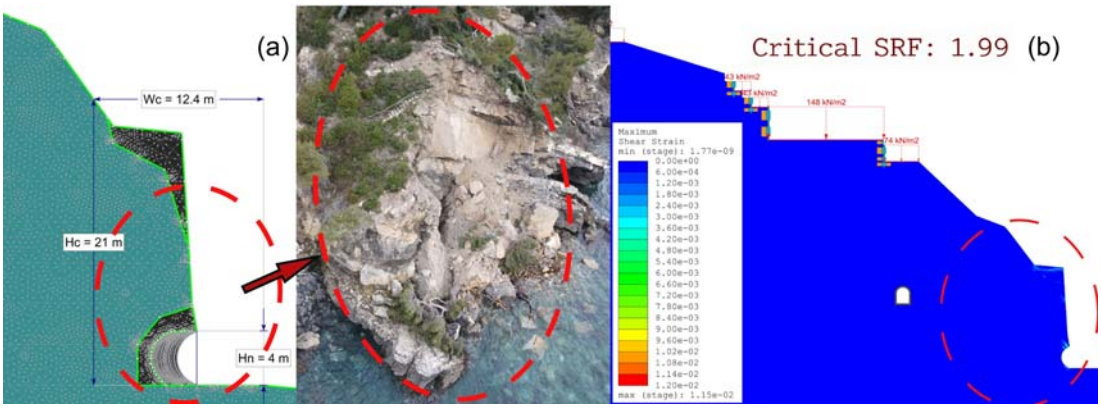


Fig. 3 (a) Cliff geometry used for the current (post-collapse) scenario, together with a field photograph of the post-rockfall condition; (b) maximum shear strains.

A predictive scenario was modelled to evaluate the impact of marine-induced weathering. The model incorporates a propagation of the weathered layer of approximately 0.5 m in the shallow part of the wall most exposed to marine actions, along with a progressive basal erosion of the rock for additional 2 meters. The deepening of the notch was simulated in 2 additional stages (Fig. 4 a). Under these conditions, the critical SRF was found to be 1.49, indicating a reduction of the global stability but a general still stable configuration (Fig. 4 b).

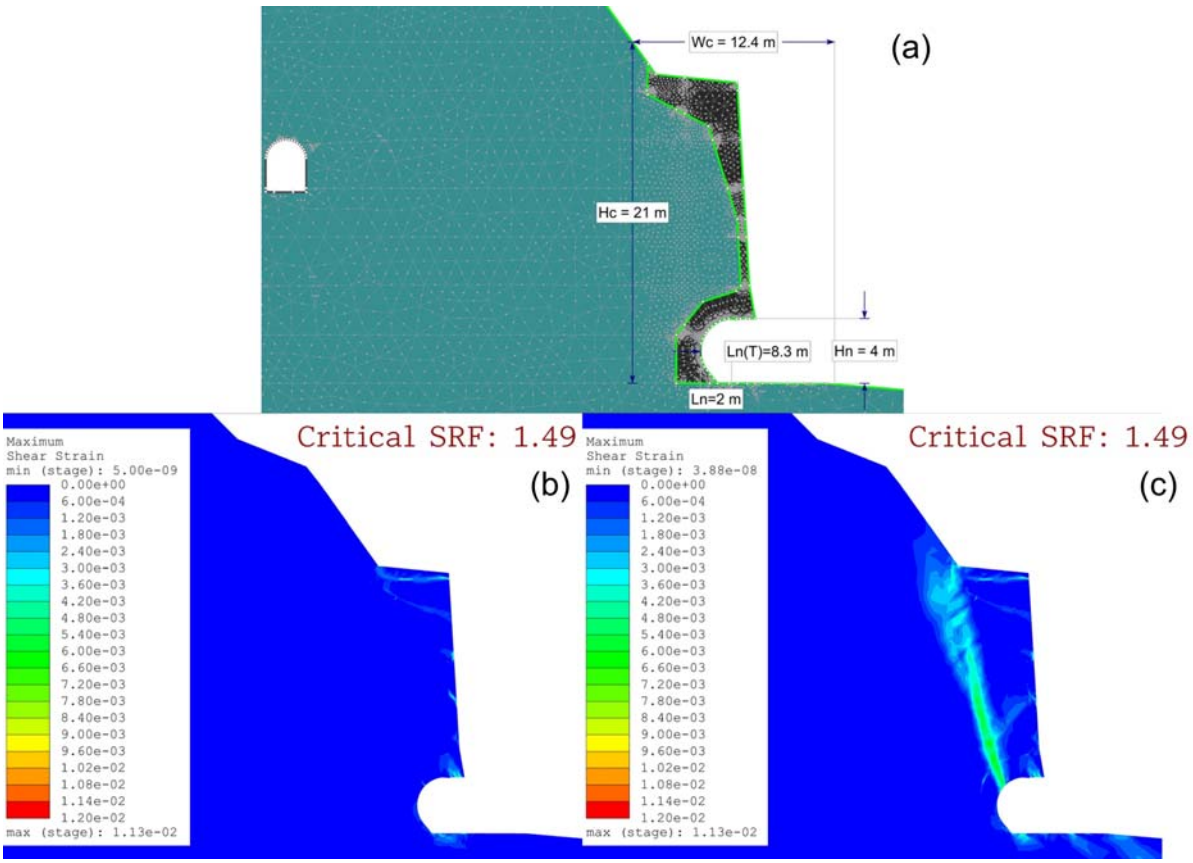


Fig. 4 (a) Post-collapse cliff geometry used for the forecasting scenario; (b) maximum shear strains; (c) progressive increase of the maximum shear strain up to limit conditions.

Based on the maximum shear strain and total displacements obtained at limit conditions (SRF = 1.49), it can be stated that the damage induced by the marine environment is concentrated at the base of the cliff, close to the notch, and can spread progressively upslope (Fig. 4b, c). According to the slenderness of the cliff above the notch, shear failure is expected within the potential unstable rock volume. This effect seems not to affect the above structures, while remaining a hazard for the sea area below the cliff.

4 Conclusion and remarks

This study provides a mechanically consistent interpretation of the instability processes affecting the coastal cliff along the SS1 "Aurelia" in the Municipality of Cervo (N-W Italy), highlighting the key role of marine-induced basal erosion in controlling cliff retreat and failure mechanisms. Despite the limitations imposed by the inaccessibility of the site, the integration of drone-based surveying, laboratory data, and back-analysis techniques allowed to reconstruct a reliable numerical model. The back-analysis of the March 2024 rockfall event successfully reproduced the observed failure mechanism, confirming that the progressive development of a basal notch, together with the weathering of the cliff face, is the main predisposing factor governing instability. In particular, the results show that once a critical notch geometry is reached, the cliff undergoes shear-controlled collapse, in agreement with field evidence and existing literature.

The analysis of post-collapse conditions indicates that the current cliff configuration remains globally stable, with a satisfactory safety margin. However, the forecasting scenarios demonstrate that continued weathering and further notch deepening can significantly reduce stability, although not immediately leading to large-scale failure. The concentration of shear strains and displacements at the cliff toe confirms that future instabilities are likely to initiate at the base and may primarily involve localized rock volumes. From an engineering and risk-management perspective, these findings underline the importance of continuous monitoring of notch evolution and weathering processes, especially in coastal settings where infrastructure and buildings are located close to cliff edges. Furthermore, experimental studies are needed to investigate the temporal evolution of weathering in carbonate rocks exposed to saltwater, as well as the erosive effects caused by the mechanical impact of sea waves. Such studies would improve the ability to predict cliff stability over time.

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