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Failure mechanisms of sea cliffs due to basal erosion

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ABSTRACT: Coastal communities face increasing exposure to climate change hazards, such as extreme weather events, sea level rise and tidal effects, which make rocky coasts susceptible to erosion and instability phenomena like rockfalls and cliff collapses. Addressing these challenges requires a deeper understanding of the failure mechanisms of sea cliffs for effective coastal management plans. The aim of this paper is to numerically investigate, through parametric 2D FEM analyses, the effects of a basal erosion on the stability of soft rock cliffs of different heights. As expected, the results reveal that increasing notch depth reduces stability. The effect of a joint, with variable depths and locations, is also investigated. It is demonstrated that its presence minimally affects stability when the joint-to-cliff-face distance is less than the notch depth. However, if the joint is located close to the notch end, its presence introduces a perturbation that negatively affects cliff stability.

INTRODUCTION

Coastal communities are increasingly exposed to the impending hazards of climate change and global warming. More intense and frequent extreme weather events, sea level rise and tidal inundations are making not only sandy coasts but also rocky coasts highly vulnerable to both erosion processes and instability phenomena (Hackney et al., 2013; Trenhaile, 2019). Rockfalls and cliff collapses are increasingly induced by the higher frequency-magnitude of atmospheric and marine processes, such as storm water events, nearshore current actions, hydrodynamic impacts of wind-induced waves and sea spray, which are responsible for rock weathering, basal erosion (undermining and notching), loss of defensive beaches and removal of protective fallen debris from the lower cliff face (Budetta 2011; Castedo et al., 2017; Sunamura 2015). The occurrence of such instability phenomena requires a deeper understanding of the failure mechanisms of coastal cliffs in order to develop appropriate management plans and coastal zone governance, so as to be able to increase public safety and reduce land loss and damage to structures, infrastructures and economic activities (tourism, industries, fishing, aquaculture, etc.).

This paper focuses on examining the impact of the notches, resulting from basal erosion, on the stability of soft rock cliffs. A parametric study was carried out on sea cliffs with a simple geometry using 2D Finite Element Method (FEM) numerical analyses, with the RS2 code from Rocscience. Firstly, homogeneous cliffs with variable notch depths (Ln) and heights (Hc) were modelled, to investigate the effects of the slenderness of the rock overhang on the cliff stability. Secondly, further analyses were carried out to investigate, in terms of global factor of safety, how cliff stability is influenced by the presence of a vertical joint of variable depth and located at different distances from the cliff face. To this aim, the popular tourist site of Punta Ferruccio, located in the Adriatic Sea (Abruzzo, Italy) and subjected to rockfalls, was used as a reference site (Calista et al. 2019; Miccadei et al. 2019; Napoli et al. 2023). This promontory is characterized by plunging cliffs with a height (Hc) of 25 m, and it is constituted by conglomerates with poorly cemented clayey sandstone and sandy clay interbedded layers in conglomerates (Miccadei et al. 2019). Notches, induced by basal erosion, are present at the cliff base, reaching up to 7 m in depth (Ln) and 4 m in height (hn). In addition, the shore platform at the base of the cliff is mostly characterized by sandy seabed with slopes about 2%.

1 STABILITY OF HOMOGENEOUS CLIFFS

In order to investigate the effects of a basal notch on the stability of sea cliffs, a parametric numerical study was carried out. Homogeneous cliffs with heights (H_c) from a minimum of 3 m to a maximum of 25 m, and a notch depth (L_n) of 3 m, 5 m, 7 m, and 10 m were analyzed. Such different geometries have made it possible to study how cliff stability is affected by variations in the slenderness of the hanging cliff volume above the notch, determined by the ratio between the cliff height and the notch depth (H_c/L_n). The mechanical properties of the sea cliff models were assumed to be those of Punta Ferruccio, whose stratigraphy was simplified by considering only the main conglomeratic lithology, whereas the sandy-clay layers, as well as the covers such as eluvial and colluvial deposits, were neglected (Fig. 1 and Table 1).

To analyze the stability of the sea cliff in its triggering phase, getting a clear idea of its possible failure processes, the widely used Finite Element Method (FEM), implemented in the RS2 software (version 11.016), was applied, and the global stability of the modelled system was analyzed in terms of global factor of safety (SRF), by using the Shear Strength Reduction (SSR) method (Rocscience, 2020).

As illustrated in Figure 1, the models were discretized with a uniform mesh with 6-nodes triangular elements. An increase of discretization and mesh element density was applied in the area close to the cliff face and notch with respect to the surrounding areas.

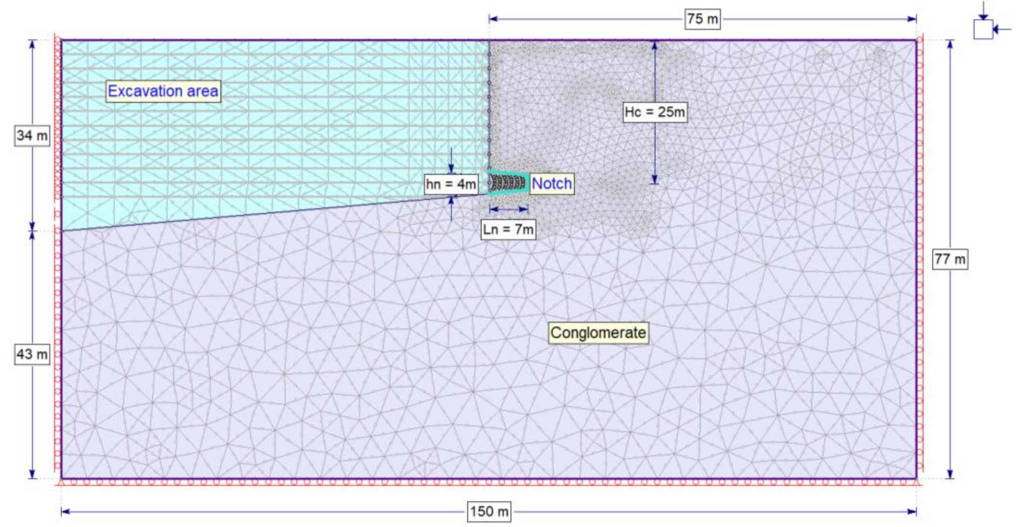

Figure 1. Example of a conglomeratic homogeneous cliff model in RS2, with a height of 25 m (H_c), and a basal notch 7 m deep (L_n) and 4 m high (h_n). Two excavation processes, named “Excavation area” and “Notch”, are simulated to avoid stress modeling disturbance.

The linear elastic-perfectly plastic Mohr-Coulomb model was adopted for all the models.

The mechanical parameters used as input for the 2D parametric FEM analyses are listed in Table 1.

Table 1. Input parameters for cliff stability analyses. From Calista et al. (2019). E and ν: deformation Modulus and Poisson coefficient of the rock; γ: unit weight of the rock; c and φ: cohesion and friction angle of the rock; σ_t: tensile strength of the rock

E [MPa]	ν [-]	γ [kN/m^3]	c [kPa]	φ [°]	σ_t [MPa]
240	0.3	21	380	45	0.38

As shown in Figure 2d, cliff stability reduces (i.e. lower SRFs are obtained) as the notch depth, L_n, increases, and such a SRF decrease has different rates depending on the value of H_c (i.e. the weight of the rock overhang). The numerical analysis results, in terms of stresses concentration and failure processes (Figs 2a-c), suggest that the observed trend of the SRFs reflects different mechanical failure modes of the cliff, affected by a combined state of tensile, compressive and shear stresses that depend on the applied stress (in this case, the self-weight of the rock overhang) and on the H_c/L_n ratio. Specifically, for a given L_n, the behavior of the hanging rock moves from a prevalent tensile failure to a prevalent shear failure with increasing H_c/L_n.

Hence, the depth of the notch plays a significant influence on cliff stability, which decreases as the notch depth increases (for a given H_c). Sea cliffs weathering and consequent basal erosion (mainly induced by sea waves) are, therefore, important processes to analyze and quantify.

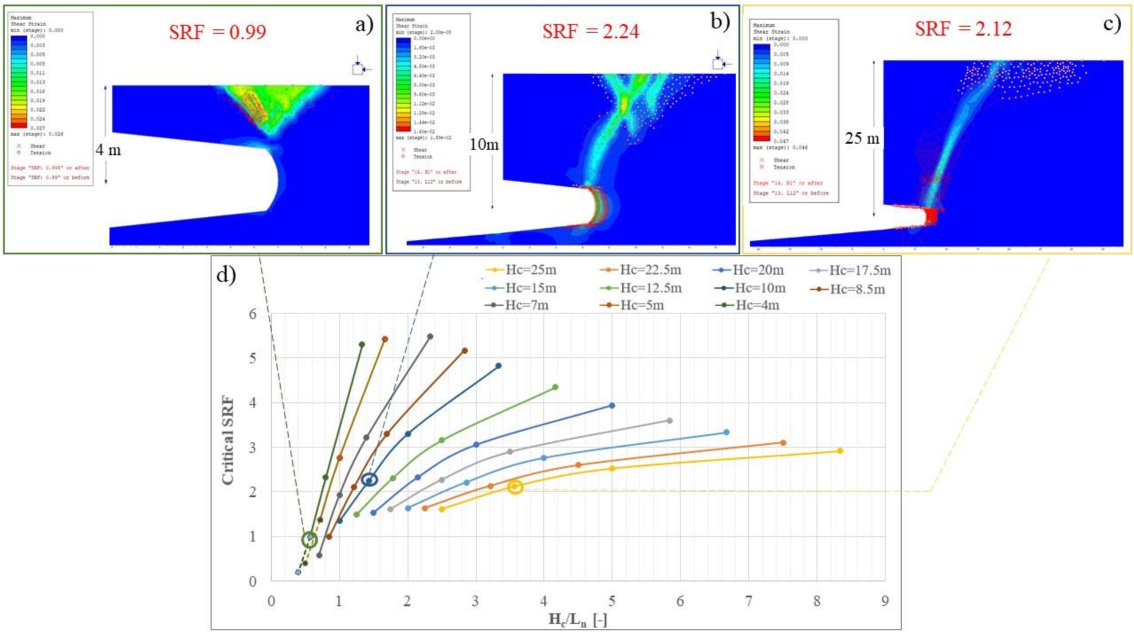

Figure 2. a-c) Maximum shear strains and plastic elements of the cliff models with minimum, average and maximum slenderness, and notch depth L_n=7m; d) correlation between the slenderness ratio (H_c/L_n) and SRF values of homogeneous cliffs with different heights.

2 STABILITY OF HOMOGENEOUS CLIFFS WITH JOINT

This part of the study is devoted to the investigation of the effects of the presence of a vertical joint (with variable depths and positions) on the stability of sea cliffs. To this aim, as shown in Figure 3, a vertical joint was inserted in the highest cliff model (H_c=25 m) characterized by a basal notch with L_n=7 m and h_n=4 m, previously analyzed and characterized by a SRF = 2.12, as shown in Figures 2c, d. The properties of the joints are listed in Table 2, and were derived from previous studies (Calista et al. 2019; Napoli et al. 2023).

The analyses were carried out with joint lengths of 13.75 m (short joint, equal to 55% H_c) and 23.75 m (deep joint, equal to 95% H_c) from the ground surface to the joint tip. Moreover, several sea cliff configurations were modelled by horizontally shifting the joint of a distance, *d*, equal to 4 m, 5 m, 6 m, 7 m, 8 m, 9 m, and 10 m, with respect to the cliff face. In order to improve the results provided by the sea cliff models with a deep joint and better fit the curve shown in Figure 4, further models were analyzed, featuring a joint positioned at a distance equal to 5.5 m and 8.5 m from the cliff face. The results obtained are shown in Table 3 and Figures 4 and 5.

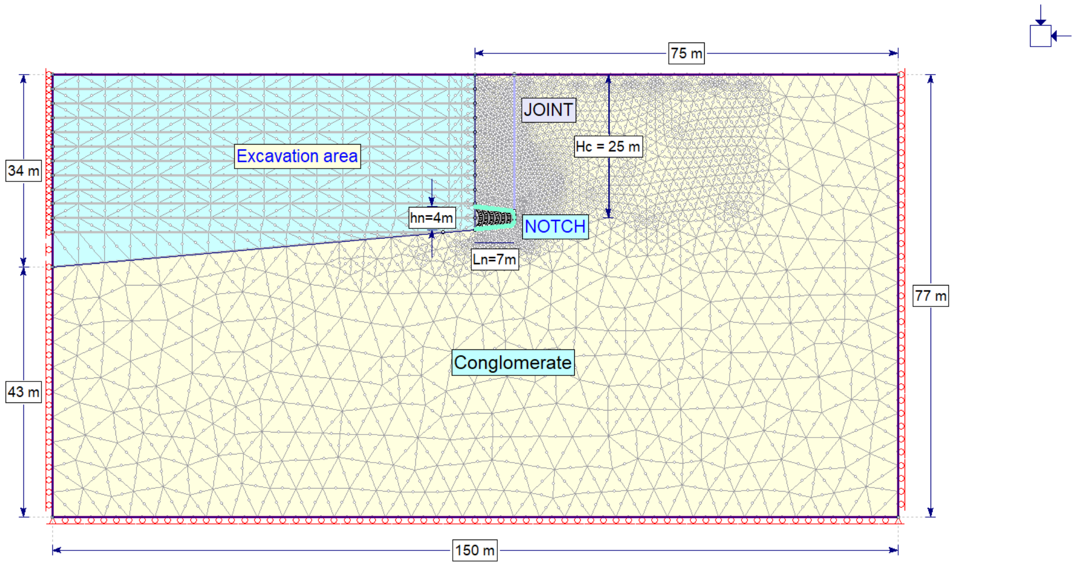

Figure 3. A homogeneous cliff with a vertical joint in RS2.

Table 2. Input parameters of the joint. jp: joint persistence; jφ and jc: friction angle and cohesion of the joint; jσ_t: tensile strength of the joint; jk_n and jk_s: normal and shear stiffness of the joint.

jp [%]	jφ [°]	jc [kPa]	jσ_t [MPa]	jk_n [MPa/m]	jk_s [MPa/m]
62.4	35.6	149.1	142.9	120	120

Table 3. Critical SRF of homogeneous models with different horizontal locations of the vertical joint.

Joint length of 13.75 m (55% H_c)		Joint length of 23.75 m (95% H_c)	
Distances, d, from the cliff face [m]	SRF [-]	Distances, d, from the cliff face [-]	SRF [-]
4	2.11	4	2.11
5	2.1	5	2.11
6	2.04	5.5*	1.92
7	1.99	6	1.6
8	1.95	7	1.26
9	1.95	8	1.7
10	1.97	8.5*	1.81
		9	1.86
		10	1.96

*Additional configurations analyzed to best fit the curve shown in Figure 4

As shown in Table 3 and Figure 4, the presence of a joint, whatever its length, has no influence on the safety factor of the cliff when its distance from the cliff face is significantly lower than the notch depth (i.e., d<L_n). Conversely, when the joint is positioned at a distance from the cliff face nearly equivalent to (or surpassing) the notch depth, the joint produces a disturbance that results in a decrease of the cliff stability. Such a decrease is minimal for the short-joint sea cliff models that experience only a slight reduction in the safety factor (Δ_{SRF_max} = -7.6%). On the contrary, a significant drop in the SRF (from a maximum of 2.11 when d=4m, to a minimum of 1.26 when d=7m) occurs when the joint length is 23.75 m, followed by a gradual recovery leading to a critical SRF close to 2 for d=10 m. This result indicates that the presence of a vertical joint has a negative effect on the stability of sea cliffs (i.e. in a reduction in the safety factor), the more significant the deeper the joint and the greater the distance from the cliff face.

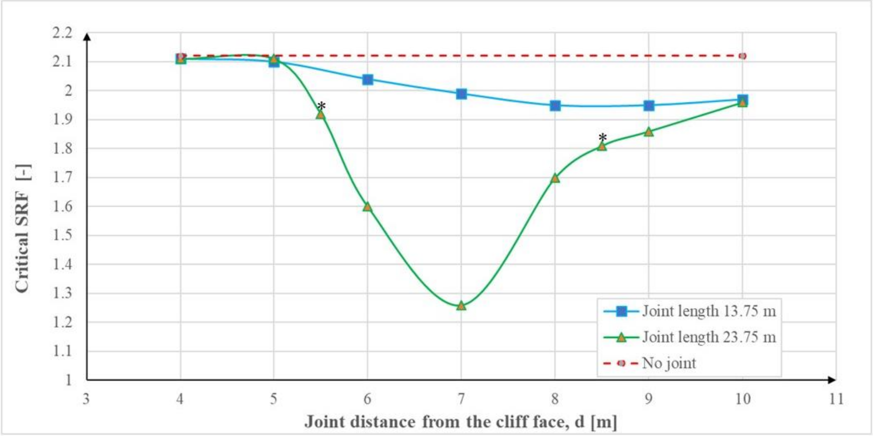

Figure 4. Correlations between SRF and joint distance from the cliff face of homogeneous cliffs with joint. *Additional configurations analyzed to best fit the 23.75 m joint length non-linear curve.

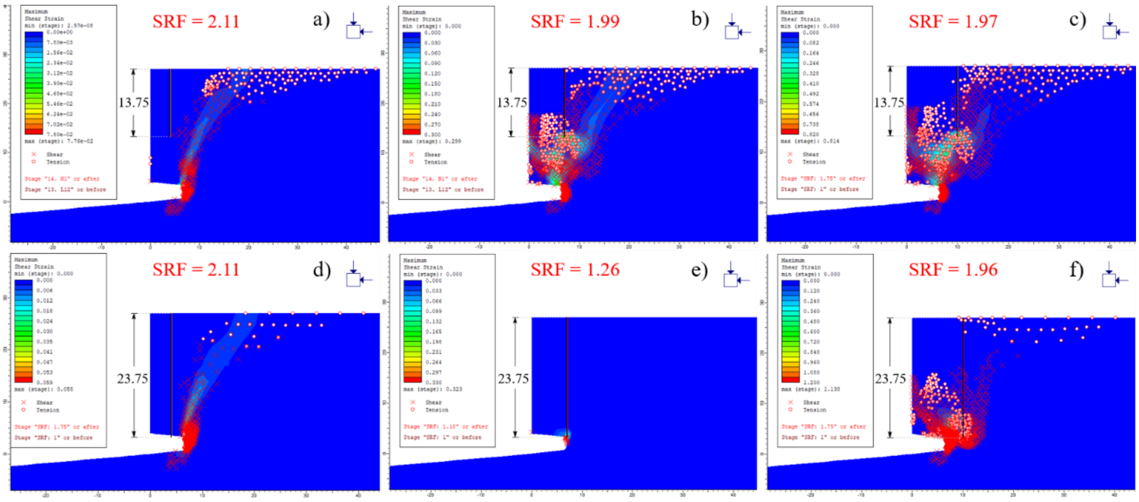

Figure 5. Comparison of the maximum shear strains and plastic elements of the cliff models with a vertical joint located at different horizontal locations (at 4 m, 7 m, and 10 m) from the cliff face; a, b, c) models with a joint length of 13.75 m; d, e, f) models with a joint length of 23.75 m.

A comparison between short- (13.75 m) and long- (23.75 m) joint cliff models with 3 different distances from the cliff face (d=4, 7, 10 m) is presented in Figure 5. Specifically, Figures 5a and 5d indicate that a joint located close to cliff face doesn't cause modifications in the failure mechanism observed in the same cliff without the joint (Fig. 2c), where a clear shear band propagates from the notch apex upwards, and tensile failures occur close to the surface. On the other hand, when the joint is located close to the notch end ($d=L_n=7$m), the discontinuity plays a crucial role in controlling the failure mechanism of the cliffs, representing a release of the rock mass. The short-joint cliff model (Fig. 5b) experiences a shear band concentrated from the notch apex to the joint tip, which induces a toppling of the (free) hanging rock volume (an opening displacement of about 4 m is observed at the top of the unstable volume). Tensile failures are shown on both sides of the joint. The deep-joint cliff model (Fig. 5e) experiences a significant concentrations of shear strains and failures in a very limited portion of the rock mass, close to the notch, which tends to induce a toppling of the hanging rock volume. When the discontinuity is located far from the cliff face (Figs 5c, f), more diffuse areas of shear and tensile failures are observed behind the joint, close to the notch and towards the ground surface.

CONCLUSIONS

This study investigates how the presence of a notch influences the global stability of plunging soft rock cliffs characterized by different notch depths. To this aim, parametric analyses were carried out. The results obtained indicate that, for a given height of the overhang (H_c), the global safety factor decreases with the increase of the notch depth, and the expected mechanism of failure triggering changes, moving from a prevalent shear failure due to high concentration of stresses at the tip of the notch to a prevalent tensile failure at the top of the cliff. Further parametric simulations were carried out to investigate the role of a vertical joint, of variable locations and depths, on the stability of sea cliffs. These analyses demonstrate that when the discontinuity is close to the cliff face, no disturb is induced in the rock mass. On the other hand, when the joint is far from the cliff face, it causes a release of the hanging rock, the failure mode changes from sliding to toppling, and a decrease in the stability is registered. Specifically, when the joint is deep and reaches the notch end, a localized concentration of shear strains at the notch apex and a marked reduction in the cliff stability are observed. In the other cases, the discontinuity induces more diffuse damaged areas, which develop from the joint tip and notch apex, also reaching the ground surface and the cliff face. In order to extend and detail the results of this study, future research will resort to a FDEM code, in order to simulate the evolution of the failure processes, and further analyses will be devoted to the influence of the joint properties on the stability of the cliff.

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REFERENCES

Calista, M., Mascioli, F., Menna, V., Miccadei, E. & Piacentini, T. 2019. Recent Geomorphological Evolution and 3D Numerical Modelling of Soft Clastic Rock Cliffs in the Mid-Western Adriatic Sea (Abruzzo, Italy). *Geosciences* 9, 309.

Miccadei, E., Mascioli, F., Ricci, F. & Piacentini, T. 2019. Geomorphology of soft clastic rock coasts in the mid-western Adriatic Sea (Abruzzo, Italy). *Geomorphology* 324, 72–94.

Napoli, M.L., Barbero, M., Mascioli, F. & Miccadei, E. 2023. Gravity-induced collapse of a soft rock cliff due to notch growth. Submitted.

Rocscience 2020. RS2 Version 11.0-Finite Element Analysis for Excavations and Slopes.

Sunamura, T. 2015. Rocky coast processes: With special reference to the recession of soft rock cliffs. *Proc. Japan Acad. Ser. B Phys. Biol. Sci*. 91, 481–500.

Budetta, P. 2011. Stability of an undercut sea-cliff along a Cilento coastal stretch (Campania, Southern Italy). *Natural Hazards*, 56, 233–250. https://doi.org/10.1007/s11069-010-9565-y

Castedo, R., Paredes, C., Vega-Panizo, R. & Anastasio, P. S. 2017. The Modelling of Coastal Cliffs and Future Trends. In *Hydro-Geomorphology - Models and Trends* (Issue October, p. 26). INTECH.

Hackney, C., Darby, S. E. & Leyland, J. 2013. Modelling the response of soft cliffs to climate change: A statistical, process-response model using accumulated excess energy. *Geomorphology*, 187, 108–121.

Trenhaile, A. S. 2019. Hard-rock coastal modelling: Past practice and future prospects in a changing world. *Journal of Marine Science and Engineering*, 7(34).