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Examples of cliff failures along the shores of Mediterranean Sea and the role of bioerosion

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Abstract

It is known that some organisms can bore holes in rock formations consisting of such as limestone, sandstone, andesite and tuff. The authors investigated several sites along the Mediterranean Sea coasts and found many examples of rocks bored by organisms. The authors carried out some observations on bioerosion state and causes of rocks along sea-shores with cliffs in several locations of this region, particularly, Türkiye (Kuşadası Bay, Ekmeksiz Bay, Antalya, Ayvalık, Bodrum, Ören), Turkish Republic of Cyprus (from Magusa to Yeşilırmak), Croatia (Dubrovnik), Egypt (Alexandria) and Spain (Alicante). Rocks are various depending upon the geology of area surveyed. This study is concerned on the role of several organisms on the toe erosion along sea cliffs and their subsequent collapse. The erosion state and porous structure of some of rocks and their effect on their mechanical strength are assessed. Some available mechanical stability assessment methods are utilized to evaluate stability state of the stable and collapsed cliffs surveyed and their implications and findings are discussed. It is shown that the cliff stability can be assessed with the incorporation of the role of bioerosion.

Keywords

Bioerosion, cliffs, Mediterranean Sea shores, Organism, Rocks.

1 Introduction

It is reported that some organisms can bore holes in rock formations consisting of such as limestone, sandstone, andesite and tuff (e.g., Uğur and Aydan et al, 2023, 2024). The authors investigated some sites in the Ryukyus Islands, Japan and carried out some observations on bioerosion state and causes of rocks along sea-shores with cliffs in several major islands of Ryukyu Archipelago (Uğur and Aydan, 2023, 2024). They now extended their studies to several countries having the shores of Mediterranean Sea. These countries are Türkiye, Turkish Republic of Cyprus (TRC), Egypt, Croatia, Greece and Spain (Figure 1).



Fig. 1 Investigated locations of bioerosion state of rocks in Mediterranean Sea, Aegean Sea and Adriatic Sea.

Rocks are various depending upon the geology of area surveyed and they include limestone, sandstone, andesite and tuff. The erosion state and porous structure of rocks and their effect on their mechanical strength are assessed (Uğur and Aydan, 2023, 2024). Some available mechanical stability assessment methods proposed by Aydan and his colleagues are utilized to assess the stable and collapsed cliffs surveyed with the consideration of the state of rock masses (RMQR) and bio-erosion rates(Aydan, 2020; Aydan and Kawamoto 1992; Aydan et al. 2014; Horiuchi et al. 2019; Tokashiki and Aydan 2010, 2011).The methods involve numerical methods (such as classical finite element method (FEM) and sophisticated discrete finite element method (DFEM) as well as the physical and photo-elasticity model tests under static and dynamic conditions and analytical methods for cliffs as described in the publications of the authors since 1989. In addition, the authors recently initiated multiparameter dynamic monitoring system for cliffs in Miyagi Island of Ryukyu Archipelago (Aydan et al. 2025). The most likely mechanism would be the dissolution of constituents of rocks by the mechanical excavation or enzyme/salvia produced by these organisms and their subsequent discharge of debris from the holes as the UCS of rocks are generally greater than 25MPa. The length of bored holes ranges generally between 5 and 15 cm with a diameter of 1 to 25 mm. The bored rock sites are found to be within the tidal and splash zones.

Besides, the action of sea waves resulting from hurricanes and typhoons imposing some impact type forces, porous structures resulting from bored holes by organisms cause the strength reduction and cyclic degradation, which can be evaluated from the method proposed by the authors (Uğur and Aydan, 2023, 2024) and utilized in this study. Therefore, the cliff stabilityshould be assessed with the incorporation of the role of bioerosion in addition wave induced erosion and other causes. This study is concerned withbioerosion resulting from bivalve and other organisms and its effect on sea cliffs and their subsequent collapses at several sites along the Medirrenean Sea. It is anticipated that this study might be quite unique by bringing different disciplines of science and engineering together to these special kind problems and provide some scientific answers to the problems encountered in nature.

2 Organisms causing bioerosion

Boring bivalves: Some boring bi-valves range in size and they can be up to 80-100 mm in length and they have an ovoid shape shell as seen in Figure 2(a). Borer bivalve species use mechanical or chemical means to bore holes. They have mantle tissue and a foot modified for rapid and effective digging. They use not only their foot for burrowing into sediment but also erodes the substrate by acid secreted from mantle tissue.

Chitons: Chitons have a shell composed of separate shell plates, which overlap slightly at the front and back edges. While the shell structure provides a protection, it allows the chiton to flex upward when they need to over uneven surfaces (Figure 2b). They live on or under rocks, or in rock discontinuities. They eat algae on rock surfaces by scraping with their well-developed radulae resulting in bioerosion.

Limpets: Limpets are categorized as a group of aquatics nails with a conical shell shape and a strong, muscular foot. They live on hard rock surfaces in the intertidal zone and they are capable of moving over the hard surfaces (Figure 2c). They have teeth known as radula, which allows limpets to scrape off algae from rock surfaces, which results in bioerosion.

Crabs: Crabs live in seas, in freshwater, and on land (Figure 2d). They are generally covered with a thick exoskeleton, and have a single pair of pincers, six walking legs and two swimming legs. They often live in nearly all caves and crevices (discontinuities) on rocky sea shores.

Sea Urchins: Sea urchins are found on the seabed of every ocean and live at every depth zone from the intertidal seashore down to 5,000 meters. The shells of sea urchins are of rounded ovoid shape and covered in spines. While the primary diet of sea urchins isalgae, sea urchins may also eat slow-moving animals. The sea-urchins excavate V-shaped holes into rock as seen in Figure 2e. These V-shaped holes can grow in size and depth.

Gastropods: Gastropods are categorized as slugs and snails (Figure 2f). They live in the environment of saltwater, freshwater, and the land. The excretion of gastropods eventually results in ammonia or uric acid as a waste product, which is the main cause of the bioerosion. Furthermore, by the virtue of their radula teeth, they contribute to the overall biological wear process, even though they do not leave wear marks visible to the naked eye.

Polychaetes: Polychaetes are categorized as marine worms and they are segmented with a length generally less than 10cm. They are one of the well-known bioeroders in carbonate rocks. Polychaetes use both chemical secretions and mechanical excavation for dissolving the rocks. They cause long curved holes in rock, which results in a porous structure (Figure 2g).

Sponges: Sponges are prominent bioeroders on coral reefs and excavating sponges are demosponges, which have a siliceous skeleton. Sponge bioerosion involves initially chemical etching of $CaCO_3$ chips and acid regulation, later mechanical removal of the chips from the substrate (Figure 2h).

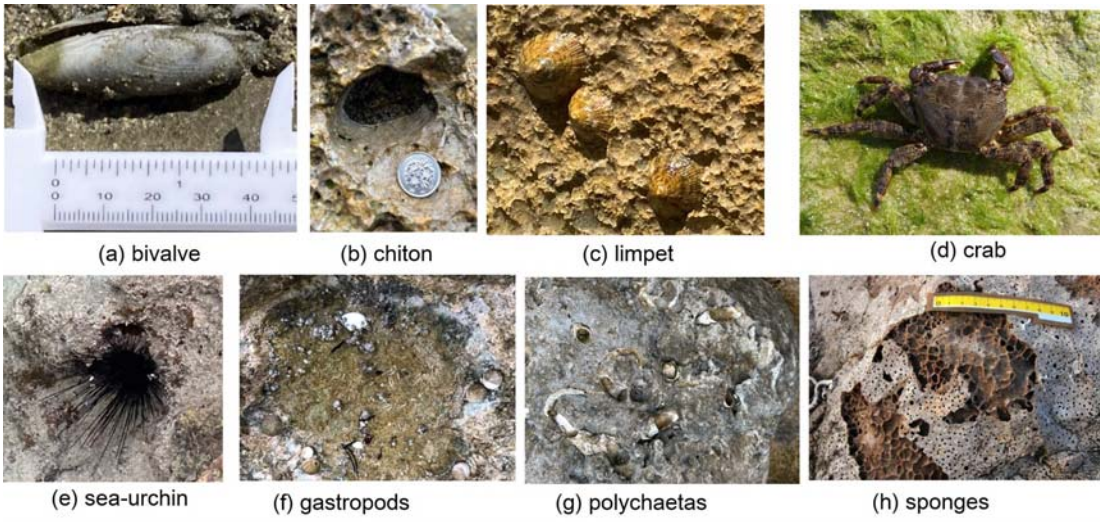


Fig. 2 Views of major organisms causing bioerosion.

3 Observations of the organisms and erosion at some locations along the Mediterranean Sea

The organisms causing bioerosion mentioned in Section 1 are observed at various localities along the shores of Mediterranean Sea investigated by the authors and the localities are marked in Figure 1. The bioerosion processes are fundamentally the same as those observed by the authors as well as others (Uğur and Aydan 2023, 2024; Alwany et al. 2009; Kázmér and Taboroši 2012). The picture of an Onyx vase displayed in a Museum in Alexandria is of great interest and one can easily notice bioerosion on the onyx vase recovered from the seabed along the shore of Mediterranean Sea.

4 The mechanism of bioerosion on cliff failures and some examples

In this section, we discuss how to model the bioerosion due to various organisms. As shown by Uğur and Aydan (2023, 2024), organisms habit within the tidal and splash zonesfor a typical cliff. Organisms such as bivalves, sponges, fishes, sea-urchins and polychaetas impose their bioerosion

actions on rocks below the low-tide level. The bio-rosion action of chitons, limpets and crabs will appear within the intertidal zone. This zone is generally about 2-3 m from the mean sea level. The effect of gastropods may also be observed above the high-tide bioerosion level. Nevertheless, this height might be restricted to the height of the splash zone.

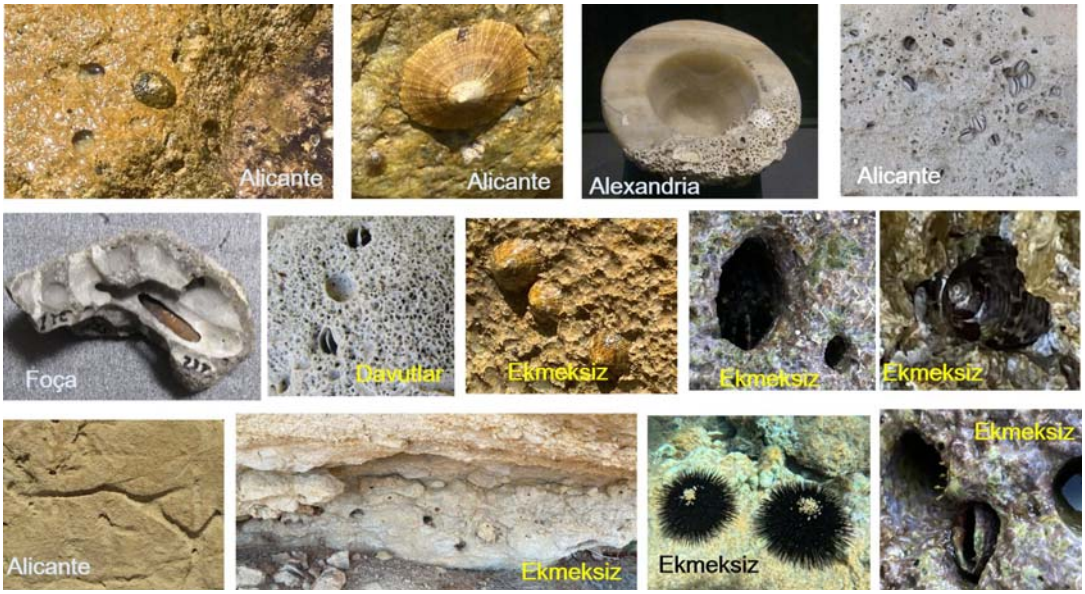


Fig. 3 Views of some organisms causing bioerosion in investigated localities.

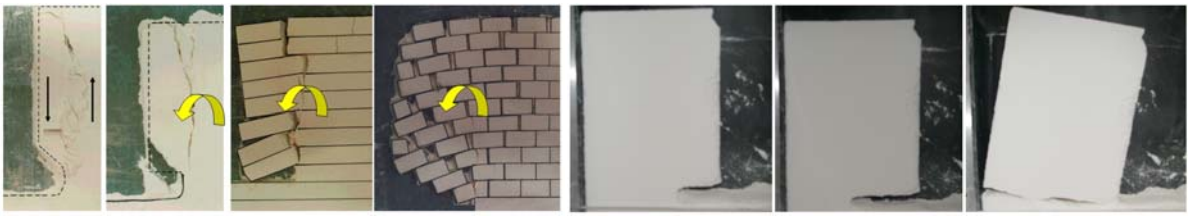
As discussed by Uğur and Aydan (2023, 2024), the bioerosion fundamentally results in a porous zone next to rock surface for a given depth. This rock becomes weaker within this zone due to porous structure, and the impact forces resulting from seawaves. Furthermore, the intrusion and extrusion of seawaters into pores further also weaken the porous zone. As these actions are progressive and cyclic, the weakened rock zone eventually collapses. Besides the mechanical action of winds and seawaves, the bioerosion result in the erosion of the cliff toe. This erosion would cause a cantilever-like rock structure. When the depth of the toe erosion reaches to a certain depth, the cliff fails under gravity and seismic forces. Uğur and Aydan (2023, 2024) proposed a mathematical model in order to consider the effect of bioerosion on the stability of cliffs. This model considered the effect of bioerosion on cliffs to be a linear erosion (l) with time. Thus, this situation is mathematically expressed as:

$$l = \lambda \cdot t \qquad (1)$$

where λ, t are coefficients depending upon rock type and time, respectively. Particularly, the evaluation of erosion rate require long-term observations and this aspect should be investigated in a multi-disciplinary procedure as done in this study.

5 The mechanism of cliff failures and Back-analyses

The cantilever-like cliffs with toe erosion may fail due to bending, shearing or the both as observed on Earth and Mars (Aydan 2020, 2022, 2023; Aydan et al. 1989; Aydan and Tokashiki 2016). Depending upon the distribution and number of discontinuity sets, they fail in several modes as shown in Figure 4a,b. In some cases, vertical discontinuities resulting from stress release may exist and this would result in the toppling of the column (Figure 4b). Figure 5 shows several examples of collapsed cliffs in the investigated localities. As noted, most of collapsed cliffs failed in bending mode.



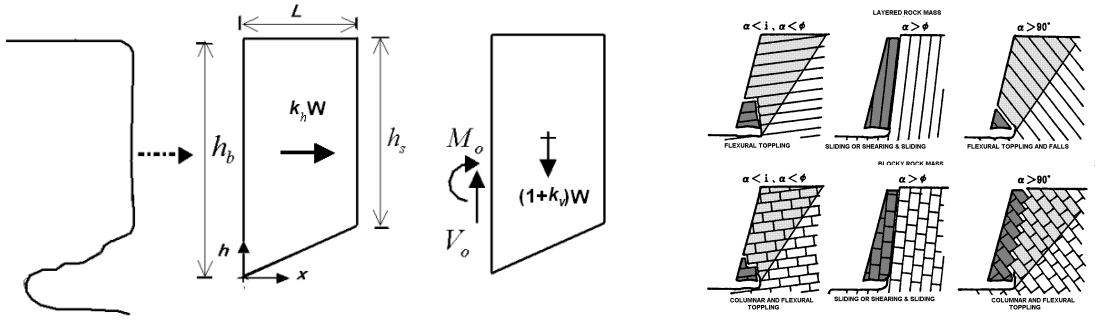
(a) Failure of continuum, layered and jointed cliffs (b) Various stages of a cliff having vertical discontinuity

Fig. 4 Views of model experiments on cliffs with toe erosion.

The mechanical model shown in Figure 6a would be the simplest for analyzing the stable and unstable cliffs with toe erosion. Under gravitational condition with/without seismic force, the limiting erosion depth (L) can be related to the cliff height (H) for bending and shear failure modes and they may be classified as continuum, layered or jointed rock masses (Aydan 2020). However it should be noted that the existence of discontinuities may also results in other forms of failure such as sliding, toppling and/or combined toppling and sliding as illustrated in Figure 6b (e.g., Horiuchi et al. 2019).



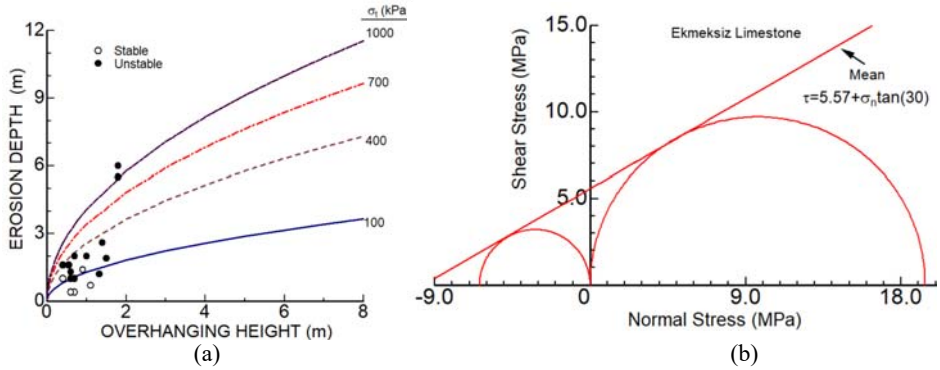
Fig. 5 Examples of cliff failures observed at several investigated localities.



(a) The cantilever model (from Aydan 2020) (b) Failure modes of cliffs with layered and jointed rock mass

Fig. 6 Mechanical models for stability assessment of cliffs and their failure modes with layered and jointed rock mass.

The results of back-analyses for cliffs at Ekmeksiz Bay, Türkiye are shown in Figure 7a. The authors gathered some rockblocks made of limestone from the site and carried out Brazilian and Uniaxial compression tests. The experimental results utilized in the back-analyses. Figure 7b shows the Mohr-Coulomb yield criterion for the limestone outcropping at Ekmeksiz Bay, Türkiye. The back analyses imply that the tensile strength of rock mass is greater than 100 kPa. Despite the tensile strength of the intact limestone was 6.4 MPa, the existence of discontinuities and high porosity resulting from bioerosion as well as from other actions resulted in the great reduction of the mass strength in accordance with the strength estimation from the RMQR rock classification system (see Aydan et al. 2014; Aydan and Tokashiki, 2016; Tokashiki and Aydan 2010 for details).



(a) (b)

Fig. 7 (a) Back-analyses results of stable and unstable cliffs; (b) Mohr-Coulomb yield criterion for intact limestone at Ekmeksiz Bay.

6 Conclusions

The authors carried outsome observations on bioerosion state and causes of rocks along sea-shores with cliffs in several locations along the shores of Mediterranean Sea. Some of conclusions from this study as follows:

Bioerosion occurs due to chemical and mechanical or both erosive activities of the organisms. The effect of bioerosion is mainly observed within the intertidal zone and/or close vicinity. In addition, the toe-erosion is highly affected by impact forces caused by winds and high seawaves.

The reduction of strength of rock mass is related to the porous structure caused by the cyclic bioerosion. The estimated strength reduction was due to bioerosion and the porosity increase due to the bioerosion was between 15-35% from the back-analyses of failed cliffs.

This study is a multi-disciplinary study between the fields of Biology, Rock Mechanics and Rock Engineering. As noted from the material presented, needless to say that there is still a great necessity to investigate the bioerosion rates caused various organisms in various rockformations as well as environmental conditions, quantitatively.

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