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Measuring and modelling the sea-waves impact on a cliff: first results from the Ventotene Field Laboratory (Italy)

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Abstract
This study explores the impact of sea waves on coastal landslide mechanisms at the Ventotene Field Laboratory (Italy). The laboratory represents a pioneering integration of real-time monitoring and numerical modeling to assess the dynamic interplay between marine forces and slope stability in natural coastal cliffs. The monitoring system is installed on an 18-meter-high tuffaceous cliff and is equipped with advanced sensors that continuously record rock mass deformation and meteorological and sea wave parameters. This test site is one of the first systems in the world specifically designed to measure the influence of sea wave impacts in the context of landslide studies. A computational fluid dynamics (CFD) analysis was performed to simulate sea wave impacts on the cliff, and results were integrated into stress-strain numerical modelling to simulate the mechanical response of the slope. Numerical modelling results highlight the influence of the rock mass geostructural configuration on its destabilization, with the outermost parietal block showing pronounced overturning moments under wave-induced pressures. Monitoring data indicate that daily and seasonal variations in temperature and precipitation may further influence the behavior of joints by constraining the rock mass response to sea wave impacts. These findings provide insights into the mechanisms driving coastal slope instability, underscoring the role of marine forces in triggering toppling dynamics. This research provides a novel framework for evaluating and mitigating risks to coastal cliffs and the cultural heritage they sustain, aligning with the objectives of the H2020 TRIQUETRA European project, which funded and supported this study.

Keywords
Slope stability, numerical modelling, monitoring system

1 Introduction
Approximately 60% of the world's population is located within 60 km of the coast (Castedo et al., 2017) as well as many cultural assets such as archaeological sites (Ioannidis et al., 2024). Coastal retreat processes and related landslide phenomena therefore represent a significant source of geological risk, particularly susceptible to changing climate conditions (Crozier, 2010; Barton 2015, Gariano & Guzzetti 2016).
Coastal cliff retreat processes are in general analyzed using erosion predictive models (e.g. Sunamura, 1992; Walkden & Hall, 2005; Castedo et al., 2017) that consider the evolution of cliff systems without detailing failure mechanisms governing the retreat processes. On the other hand, most of the studies focused on investigating cliff failure mechanisms take into account the role of predisposing (e.g.,

fracture networks) or preparatory (e.g., notch formation) factors related to the geostructural setting of the slope (Allison & Kimber, 1998; Styles et al., 2011; Calista et al., 2019; He et al., 2022; Alberti et al., 2022; Napoli et al., 2024), without delving into the preparatory and triggering contribution yielded by sea wave impacts.

The impact of sea waves has been investigated through analogical laboratory tests (Cuomo et al., 2010; Attili et al., 2023), hydrodynamic modelling simulations (Hasanpour et al, 2021; Hasanpour & Istrati, 2022) or site-based measurements (Larroque et al., 2018). Despite much research on the sea waves impact, most analyses have been developed for coastal engineering structures, and applications to natural case studies are still rare (Deng, 2024). Examples of this latter case are the ones of Thompson et al. (2019) and Varley (2019), where the vibrational response of the cliff and the entity of the applied pressure caused by the sea wave impacts have been studied using instruments not directly installed on the cliff face.

This research presents the first results obtained at the Ventotene Field Laboratory (Italy), where the influence of sea waves on coastal landslides is being studied. In particular, we report on the preliminary results of coupling hydrodynamical and stress-strain numerical modelling to characterize the mechanical response of a coastal cliff system to sea wave impacts.

2 The Ventotene Field Laboratory

The Ventotene Field Laboratory (VFL) is located on the island of Ventotene, Italy, approximately 50 km off the Gaeta coast. The island represents the tip of a large volcanic structure composed of lavas covered by pyroclastic products that erupted during the last 0.2 Myrs (Perrotta et al., 1996). To correctly design the monitoring system, an engineering-geological model of the rock wall was reconstructed through geomechanical surveying (sensu ISRM, 2017), drone photogrammetry and an underwater video survey. The VFL monitors a tuffaceous coastal cliff susceptible to rockfall and rock toppling, and its retreat poses a significant threat to the Roman archaeological site of Villa Giulia (Feliziani et al., 2024). In particular, the instrument suite is installed on an 18 m high cliff sector dissected by three vertical joints (J1, J2, J3) isolating two rock blocks that are subjected to sea wave impacts (Figure 1).

The monitoring system encompasses three categories of instruments to continuously record: i) the deformational response of the rock mass, ii) meteo-climatic parameters and iii) sea wave-related parameters. Monitoring time series are recorded by a CRX1000 Campbell Scientific and a QuantumX HBM data loggers, respectively dedicated to static and dynamic measurements. Since May 2024, data are transmitted in real-time to a cloud server of the Earth Sciences Department of Sapienza University of Rome.

2.1 Rock mass and meteo-climatic monitoring

The three rock joints play an important role on the rock mass deformation of the Ventotene cliff. At the same time, the slope mechanical behaviour is also influenced by specific environmental factors (e.g., temperature and moisture), which primarily affect the rock matrix at the microscale. These considerations guided the installation of the following instruments:

- n. 4 crack-meters for monitoring the opening/closing pattern of joints;
- n. 1 load cell, installed inside a rock-cut created by straddling a joint, and designed for measuring changes in mechanical stress state within the joint due to varying environmental conditions or increasing instability;
- n. 1 biaxial tilt-meter, located on the outermost rock block, measuring static tilt angles along two perpendicular directions (normal and parallel to the coastline).
- n. 1 thermocouple for near-surface rock matrix temperature monitoring;
- n. 1 moisture sensor for measuring rock matrix moisture content, temperature and conductivity;
- n.1 fully equipped weather station composed of air thermometer, hygrometer, rain gauge, and an ultrasonic anemometer.

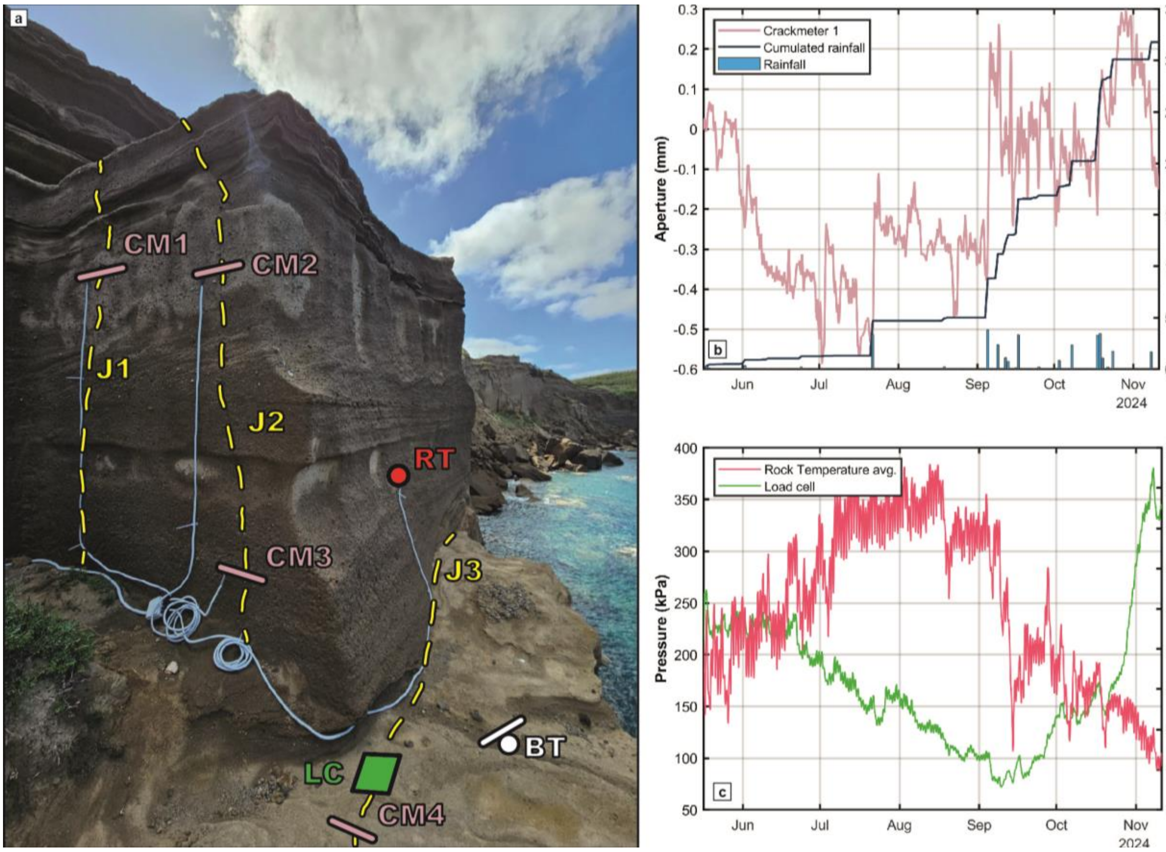

Figure 1 Monitored rock-blocks isolated by J1, J2 and J3 joints, with some of the sensors installed at the Ventotene Field Laboratory (a): CM = crack-meter; LC = load cell; BT = biaxial tilt-meter; RT = rock thermometer. Crack-meter 1 and rainfall (daily and cumulated) time series (b). Rock temperature and load cell pressure time series (c).

2.2 Sea waves monitoring

The VFL is one of the first examples worldwide where the continuous monitoring of sea wave parameters has been coupled to geotechnical monitoring for the investigation of rocky coast landslides. One of the greatest innovations of the VFL is the recording of sea wave characteristics and induced stresses at the surface of the monitored rock cliff. Sea wave characteristics are obtained through an Acoustic Wave and Current Profiler (AWAC 1 MHz) manufactured by the Nortek Group, that was installed on the seafloor at 30 m from the coast and at a depth of 5 m. This sensor performs a signal and spectral analysis of the waves and current profiles, returning as results the wave and current characteristics (i.e., wave heights, wave periods, wave velocities and directions, etc.).To quantify the sea wave-induced stresses on the cliff surface, we installed three pressure transducers (Keller-25Y) along a vertical profile with measuring points located at 1 m b.s.l., and 1 and 2 m a.s.l. We selected these locations to describe the stress distribution under variable wave conditions: during typical wave conditions, where only the underwater sensor experiences changes in the applied pressures, and during storm events with higher wave run-up heights, where all sensors might record wave-induced stresses. These sensors work in a dynamic configuration in which the sampling frequency (SF) controls the possibility of recording rapid and impulsive pressures representative of the real nature of the wave impact on the cliff. A high SF (in the order of kHz) should be set to avoid underestimation of the recorded pressures (Cuomo et al., 2010; Varley et al., 2019).

2.3 First outcomes from the monitoring system

The short monitoring period to date (May 2024 to November 2024) served to verify the functionality of the entire monitoring system, as well as to set up routines for collecting, transmitting and preprocessing data.

The collected dataset have been also useful in understanding the preliminary sensitivity of the rock mass to the monitored weather and sea wave actions. The mechanical behaviour of the three vertical joints and the tilting of the parietal rock block are mainly controlled by temperature fluctuations and rainfalls (Figure 1b, c). In particular, the load cell installed in correspondence with J3 clearly describes a cyclical behaviour at daily scale that suggests a primary thermal control on the expansion-contraction cycles of the rock mass. An increase in temperature causes the joint to contract (i.e., crush the load cell sensor), which is detected by an increase in pressure. On the other hand, a drop in temperature causes the joint to expand (i.e., the load cell sensor to expand), which is detected by a drop in pressure. However, the transient changes in the stress response of J3 can be observed due to significant precipitations (Figure 1b, c). Since the beginning of the rainy season (September 2024), stresses at J3 have started to rise, suggesting a potential tilt towards the inland portion of the block that J3 isolates. Similar observations can be made considering the crack-meter deformational pattern. In particular, J1 exhibits the same daily temperature-controlled opening-closing cycles, and an opening trend strongly influenced by the occurrence of precipitations (Figure 1b).

Regarding sea wave characteristics, statistical analysis of wave data collected by the AWAC revealed peaks in the probability density (PD) at a mean wave spectral period (Tm) of 2 s and significant wave height (Hs) of 0.2 m (Figure 2a, b). These results provide insights into the most common sea wave properties impacting the sea cliffs of Ventotene. Strong wind conditions were still able to produce waves with amplitude in the order of 2 m associated with periods of 5 s (Figure 2c, d).

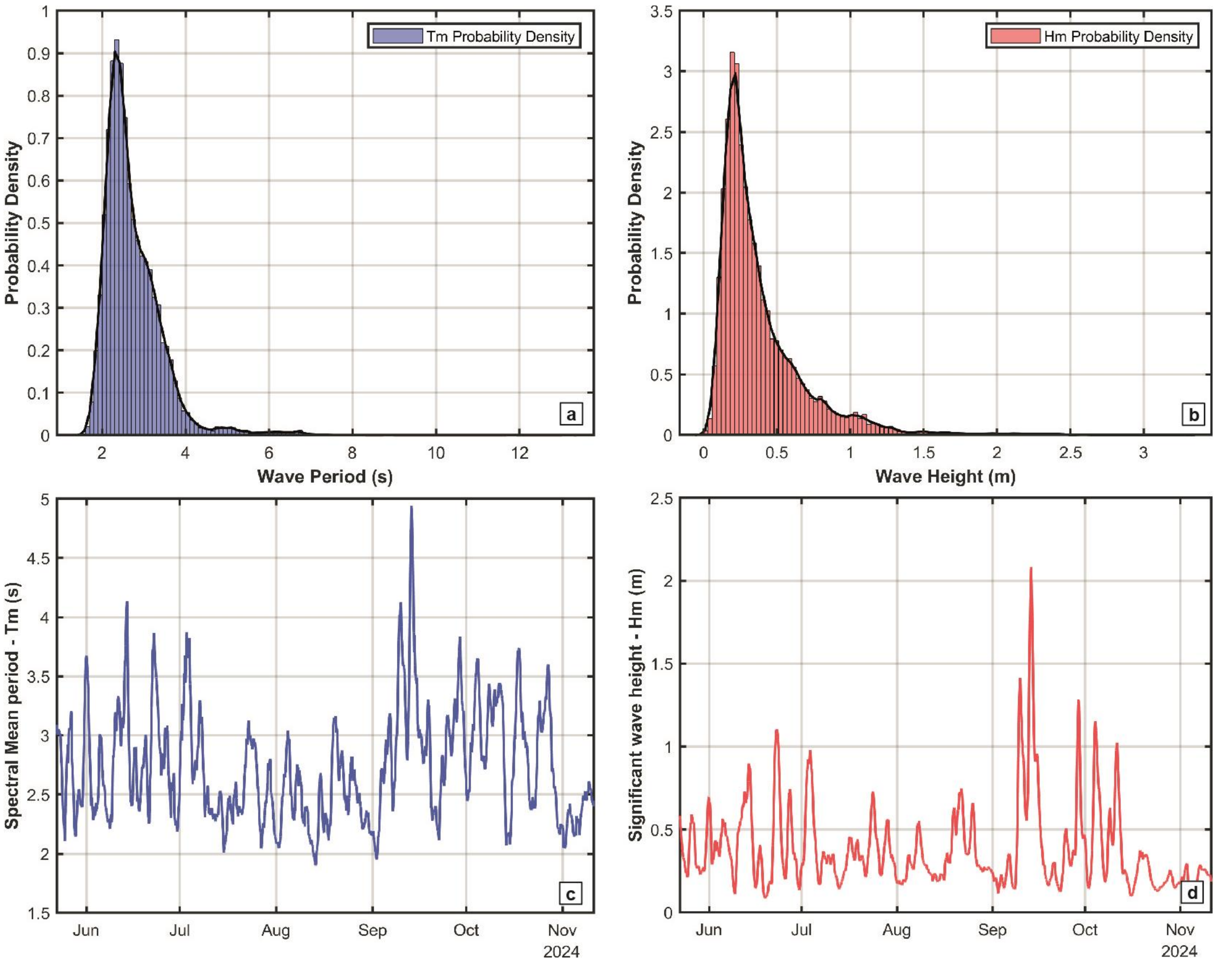

Figure 2 Spectral mean period (Tm) and Significant wave Height (Hm) probability density analysis (a, b), and related time series (c, d).

3 Numerical modelling

3.1 Stressors analysis: hydrodynamic modelling of the sea-waves impact

The hydrodynamic numerical simulations were conducted using the computational fluid dynamics (CFD) software OpenFOAM designed for solving a wide variety of fluid mechanics problems. Specifically, the interFoam solver was utilized, which is tailored for two-phase incompressible flows and employs a modified Volume of Fluid (VoF) method to capture the interface between immiscible fluids (Jasak et al., 2007; Deshpande et al., 2013). The interFoam solver employs the Finite Volume Method (FVM) for spatial discretization, enabling it to handle complex geometries and polyhedral meshes effectively.

The interFoam solver is based on fundamental governing equations of fluid dynamics. The momentum equation accounts for fluid inertia, viscous forces, interfacial forces due to surface tension, and body forces such as gravity:

$$\frac{\partial(\overrightarrow{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) - \nabla \cdot (\mu \nabla \vec{U}) - f_b = -\nabla p - f_{st}$$

In these equations, ρ denotes the density, p represents pressure, τ is the viscous stress tensor, f_{st} denotes surface tension forces, and f_b represents body forces. On the other hand, mass conservation is ensured through the continuity equation:

$$\nabla \cdot \vec{U} = 0$$

where $\vec{U}$ represents the velocity field. The transport of the volume fraction, α, is governed by the following equation, which incorporates interfacial compression to maintain a sharp interface:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{U}) + \nabla \cdot (\alpha(1-\alpha)\vec{U}_\alpha = 0$$

Here, $\vec{U}_\alpha$ is the relative velocity at the interface (Chen et al., 2014).

The laminar StokesV wave theory case was adopted to generate incident waves precisely where wave height H=1.5 m with period T=12 s. The computational domain length was set to 250 m to avoid reflection waves from the cliff into the inlet boundary to prevent simulation convergence. It consists of a 200 m horizontal and 50 m sloped bathymetry that reflects an average of measured bathymetry in the area. This research has come up with the cell height of 0.05 m and maxCo equal to 0.2 that is able to produce stable waves along the domain length and is physically correct. Finally, we kept the cell aspect ratio equal to 2 and put the cliff boundary condition noSlip in order to ensure that the wall realistically resists fluid motion and captures wave reflection near the wall.

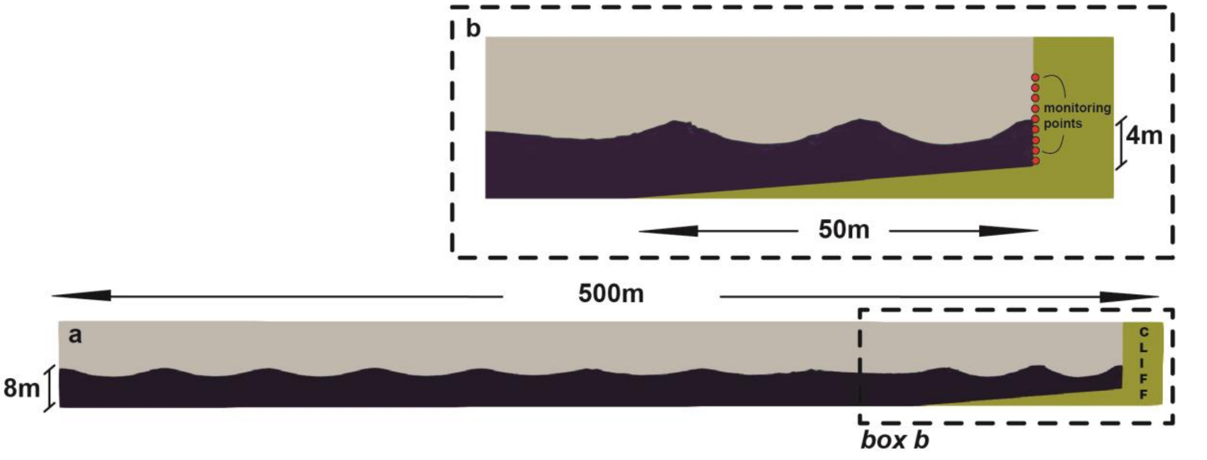

Figure 3 CFD computational domain replicating the average bathymetry at Ventotene site (a), with a zoom on the cliff. Red dots are referred to the monitoring points on which the applied pressure is recorded.

The hydrodynamic analysis allowed to reproduce the sea wave applied pressure on the cliff for the whole analysed simulation time, and revealed a maximum wave runup on the cliff of 2.3 m. By neglecting the submerged portion of the model, which is influenced by the hydrostatic pressure, at each time step the maximum pressures are concentrated at the still water level (SWL), and gradually diminish along the cliff face reaching the zero value at the wave runup level. This has led to an analysis of the pressure time series referred to the SWL. With a maximum applied pressure of about 19.5 kPa, the pressure time series displays a periodic signal that reflects the 12 s periodicity of the sea waves that were modelled (Figure 4b). A one wave period of 12 s was therefore chosen as representative wave for the stress strain numerical modelling (Figure 4c).

3.2 Cliff response analysis: stress-strain modelling of the sea-cliff response

A numerical modelling was carried out using the finite difference code FLAC 2D 8.0 (ITASCA). We created a 500x500 regular squared mesh with geometrical resolution of 10 cm to reproduce a geological cross section of the monitored sea cliff. Since a half-space was assumed, the horizontal displacements were fixed on the left lateral boundary of the model, while vertical and horizontal displacements were avoided at the model bottom during mechanical equilibrium. Three joints were simulated in the continuous model by refining the mesh resolution (set to 4 cm) along each joint path, and assigning to those zones different mechanical properties compared to the rock matrix. A Mohr-Coulomb constitutive model was assigned to the whole model considering material properties derived from laboratory tests and literature (De Silva et al., 2022). We calibrated mechanical parameters of joints by linearizing the Barton (1973) envelope for the in situ stress state range and deriving equivalent cohesion and friction angle values. An elasto-plastic equilibrium was reached assuming a hydrostatic pressure distributed on the bottom part of the cliff and on the seafloor, reproducing a 4 m high sea level.

According to Blackmore (1982), a triangular pressure distribution with peak pressure (PP) located at the still water level (SWL) was adopted to reproduce the impact of a single sea wave on the cliff. Applied pressures vary linearly from the PP to 0 along the cliff face (i.e., from the SWL to the max. runup height) (Figure 4a). PP values were varied during the analysis in accordance with the selected representative pressure time series obtained from the hydrodynamic modelling (Figure 4b, c).

Induced horizontal displacements reflect a peculiar distribution strongly controlled by the geo-structural setting of the rock mass (Figure 4d). At the end of the simulation, cumulative displacements indicate an overturning moment solicitation on the cliff, in which displacements directed toward the sea (i.e., positive displacements) are concentrated on the top of the parietal rock block isolated by J1 (Figure 4d). The other two rock blocks isolated by J2 and J3 do not exhibit the same displacement pattern. In fact, the upper parts of these two blocks exhibit displacements directed toward the inland (i.e., negative displacement), which prevents a similar overturning moment also in this portion of the numerical domain.

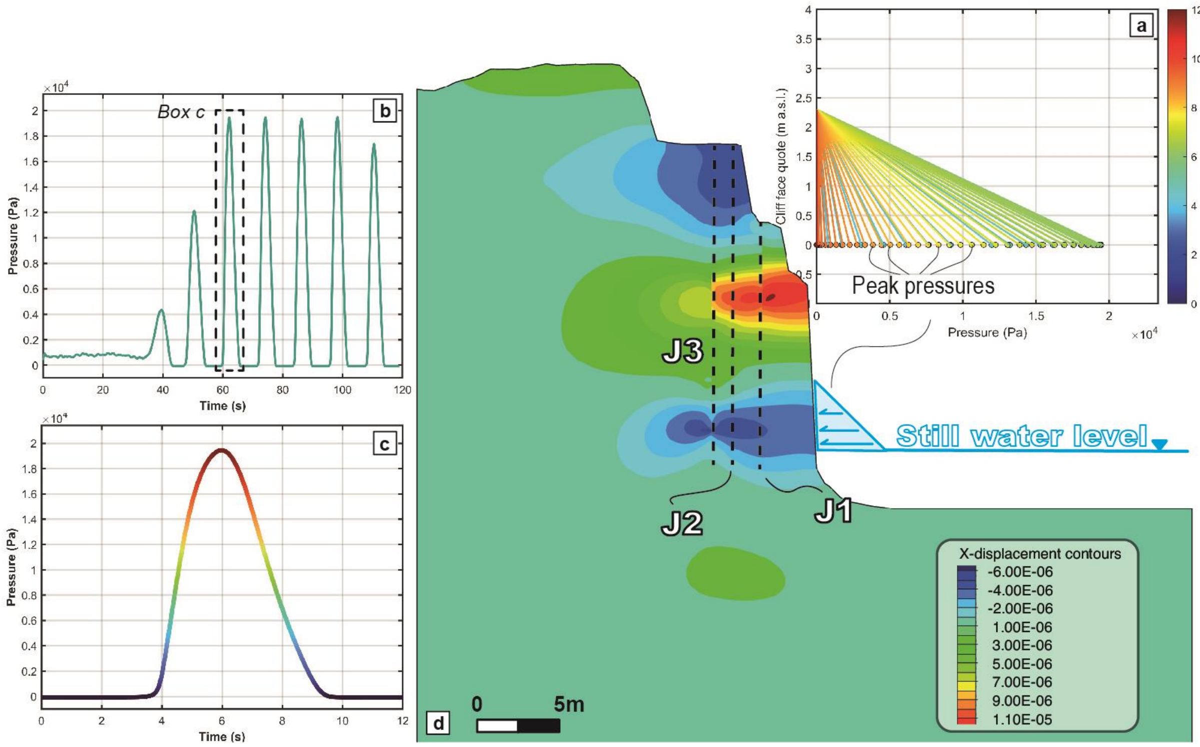

Figure 4 Triangular wave pressure distribution time series applied on the cliff face (a). Sea wave impact pressure time series resulting on the still water level (i.e., 0 m a.s.l.) during the whole period modelled by the CFD analysis (b). Representative wave impact time series referred to a single period of 12 s (b) extracted from Fig. 3b. Horizontal displacement contour after the application of a single wave impact obtained from the stress-strain numerical modelling (negative displacements are left-oriented while positive displacement are right-oriented).

4 Conclusions and Future Perspectives

The presented results provide a preliminary research outline that could pave the way for a deeper understanding of the effects induced by sea wave impacts on coastal landslides susceptible to toppling and rock-fall. Hydrodynamic and stress-strain numerical modelling revealed that the entity of the destabilizing action of sea wave impacts is strongly controlled by the geo-structural setting of the coastal cliff. Our integrated numerical modelling approach sheds light on how single sea waves can generate an overturning moment only on the parietal rock block, evidencing how the considered destabilizing factor may contribute to the toppling failure dynamics characterizing such landslide phenomena. Such a result is in agreement with the field observation which return detached rock blocks from the cliff due to toppling mechanisms. The results have shown how the Ventotene Field Laboratory cutting-edge monitoring system may aid in the comprehension of the preparatory and triggering mechanisms controlling coastal landslides.

Future analyses will be devoted to modelling the action of multiple sea-waves impacts analyzing the cumulative effect induced on the cliff. Real monitoring data gathered from the monitoring system will allows us to better calibrate and constrain hydrodynamic and stress-numerical models.

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