Investigation of the Hydrogeology at a Chalk Cliff Site in Normandy Using Multiple Research Approaches

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Abstract

This study uses a multidisciplinary approach combining optical and geophysical methods to analyze the stability and seawater intrusion in chalk cliff at Sainte-Marguerite-sur-Mer, Normandy (France). Techniques employed include photogrammetry, thermal infrared spectroscopy (TIR), electrical resistivity imaging (ERI) and the towed transient electromagnetic (tTEM) method.

The study focused on a 20-40 meter high cliff with a rocky platform at its feet. A visible and thermal photogrammetric model were made in September 2022. A total of six ERI profiles were carried out. The tTEM survey provided a resistivity mapping of the plateau as well as at the foot of the cliff.

ERI and tTEM methods identified the presence of a conductive body interpreted as a saturated saline to brackish aquifer beneath the cliff, with marine intrusion only in the southwestern part. The interface between the salt water and the aquifer shows instabilities with haline convection and upwelling of brackish water at different places on the rock platform to the northeast. TIR spectroscopy complements ERI by helping to identify areas vulnerable to collapse at the top of the cliff.

Introduction

Climate change is the main factor responsible for sea level rise, thus creating many challenges for coastal areas around the world. Nearly 40% of the world's population lives in these coastal regions and their number is expected to increase significantly between 2030 and 2060 (Neumann et al., 2015). Sea level rise could accelerate rock cliff erosion by up to an order of magnitude by 2100 (Shadrick et al., 2022). Among these, the coasts of Normandy, located in the northwest of France, are particularly vulnerable. Between Cap d'Antifer and Le Tréport, coastal retreat speeds ranging from 0.09 to 0.18 m/year were observed and between Saint-Valéry-en-Caux and Dieppe, higher retreat speeds with 0.23 m/year (Letortu et al., 2014).

This rise is likely to cause many problems for coastal regions, including an inevitable inland retreat and saline intrusion into freshwater aquifers. Identifying the interface between fresh water and salt water is therefore of capital importance for the direct uses of groundwater, impacting agriculture, industry, the supply of drinking water and biodiversity. The shape of the salt wedge depends on the difference in density between salt water and fresh (Pool and Carrera, 2011). A mixing zone exists because fresh water and salt water are mutually soluble liquids. The thickness of this mixed zone can vary considerably and depends on the geological and hydrodynamic properties of the aquifer.

Geophysical methods allow to analyze the internal characteristics and properties of geological formations without directly disturbing their structure. These methods can be powerful and appropriate tools to assess stability as well as seawater intrusion in different areas and have the advantage of not requiring expensive drilling (Kumar et al., 2016). The presented study was conducted on a chalk cliff site located in Sainte-Marguerite-sur-Mer, Normandy (France). A multidisciplinary approach, combining optical and geophysical methods was adopted to obtain detailed information about the study area. Among the optical methods, a visible photogrammetric model was performed from images captured by a UAV (Unmanned Aerial Vehicle), also equipped with TIR camera. In addition, geophysical methods have been deployed, such as electrical resistivity imaging (ERI). Six ERI profiles were carried out in late summer 2022. The towed transient electromagnetic (tTEM) method was applied in 2023 to provide a 3D detailed resistivity mapping.

These different techniques aim to carry out a complete analysis of the hydrogeology of the site, integrating various aspects such as geomorphology, geology and geophysics. The results reveal several areas vulnerable to the risk of collapse and marine intrusions under different parts of the chalk cliff.

The cliff of Sainte-Marguerite-sur-Mer

The chalk cliff of Sainte-Marguerite-sur-Mer (N 49°54′34″, E 0°56′18″) was selected as the study area (**figure 1**). These coastal cliffs are located in the Pays de Caux, a natural region located on the coast of Seine-Maritime. They are about 20-40 m high. The cliff foot is characterized by a rocky shore platform (about 150 to 200 m wide at low tide) of homogeneous slope and a pebble barrier (about 15 to 20 m wide and 2 to 3 m thick) in top of the beach against the cliff (Letortu et al., 2014). The cliff is characterized by a very diaclased flint chalk (stratified and constant).

Methods

The location of the ERI profiles is detailed in **figure 1**. Two ERI longitudinal profiles were carried out on the plateau of the cliff, near and far from the main scarp. In addition, four transverse profiles starting from the plateau, crossing the cliff and arriving on the rocky platform have been produced. ERI data were acquired using a Terrameter LS2 system (ABEM). The transverse profiles were made in Wenner configurations, composed of 64 electrodes (except the P4-22 with 128 electrodes) with an inter-electrode spacing of 2 m. The longitudinal profiles were made with a device of 64 electrodes used in roll along in Schlumberger configurations (inter-electrode spacing: 4 m) over 500 m.

The recent tTEM system, developed by Aarhus GeoInstruments, enables high-resolution imagery of subsurface layers at greater depth, facilitating detailed mapping of complex geology for hydrogeological models (Auken et al., 2018). The tTEM 3x3 has been deployed in its classical acqsuisition mode using a low and a high moment, respectively with 3 and 30 Ampers. Data processing and inversions have been carried out using the Aarhus Workbench software package.

The use of UAV (DJI Matrice 600 Pro) equipped with a visible and TIR camera made it possible to obtain a Digital Surface Model (DSM) of the study area thanks to the photogrammetry. The visible camera model was an FC350 (3.61 mm) with a resolution of 4000 x 3000. The TIR camera used was an InfraTec VarioCAM® HD (image size is 1024×768 pixels).

Finally, at the top of the cliff, 38 m from the main scarp, a 30 m deep piezometer has been installed to follow the water table parameters, such as the level and the salinity of the water.

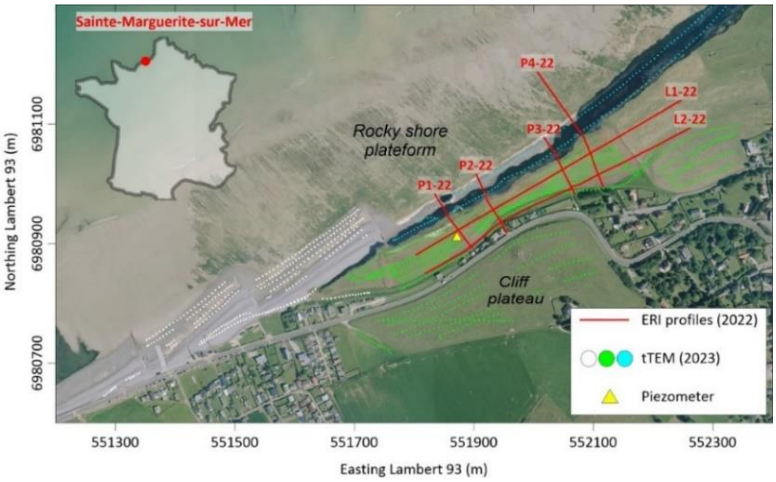

Figure 1 *Coastal chalk cliff of Sainte-Marguerite-sur-Mer (Normandy, France). Location of the Electrical Resistivity Imaging (ERI) profiles, the tTEM soundings and the piezometer.*

Results and discussion

The low resistivities observed under the cliff are mainly attributed to the presence of aquifers saturated with saline to brackish water. This characteristic is highlighted thanks to the ERI profiles (**figure 2**) which reveal a conductive zone corresponding to a saline water intrusion at the base of the cliff. Interestingly, this intrusion only occurs in the southwestern part, as shown by ERI as well as tTEM data (**figure 3**). In this specific area, seawater has managed to penetrate and salinize the water table.

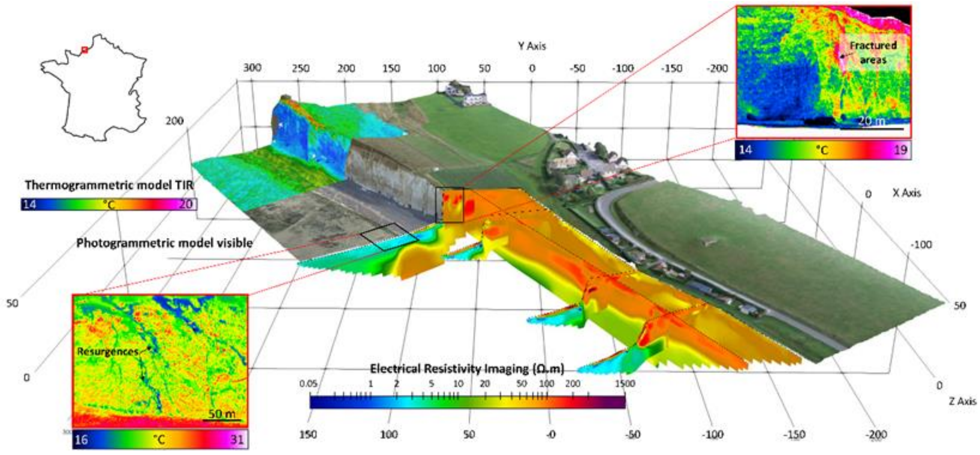

Figure 2 *Thermogrammetric, photogrammetric model and inverted electrical profiles.*

The P4-22 profile showed brackish water migration at the base of the cliff and at the level of the rocky platform. The instabilities result in haline convection, driving free downward convection of lobe-shaped fingers of dense salt water and ascending fingers of less dense fresh water (Cantelon et al., 2022). The Rayleigh number (Ra) can be used to predict the occurrence of instabilities. It represents the ratio of buoyant forces to resistance forces caused by diffusion and dispersion (Post and Kooi, 2003). Ra is defined by: $Ra = \Delta\rho g k \mathrm{H}/\mu\mathrm{D}$. A Ra greater than a certain critical Ra_c of $4\pi^2$ is assumed to indicate free convection. Using standard values often applied along the coast (**table 1**), a Rayleigh number of 438 is obtained indicating that free convection may occur within the medium.

Table 1 *Model parameters for Ra=438*

Δρ	Difference in density between fresh and saline water	25	$kg.m^{-3}$
g	Gravitational acceleration	9.81	$m.s^2$
k	Intrinsic permeability of the porous media	1×10^{-13}	m^2
H	Aquifer thickness	50	m
μ	Dynamic fluid viscosity	1×10^{-3}	$kg.m.s^{-1}$
D	Coefficient accounting for dispersion and diffusion	2.8×10^{-9}	$m^2.s^{-1}$

The density (saline) water plume goes downward, while brackish water plume moves upward. This migration was observed on the ground in TIR with resurgences observed at certain places on the reef flat (**figure 2**). The variations in permeability linked to the cracking of the cliff or the rocky shore platform can disturb this flow and would cause the underlying water to rise randomly at different places on the platform.

The high resistivity at the top of the cliff coincides with the areas of high temperatures detected in TIR (**figure 2**). We suggest that a heavily damaged area be exposed to significant underground airflow. Fractures, joints and karst cavities facilitate efficient air circulation and cause considerable drying in a wet chalky environment. Thus, the surface temperature of a fissured ground will be constantly higher than that of a wet rock (Sabins, 1986). According to the ERI profiles, this anomalous zone at the top of the cliff extends for 10 to 20 m before joining the main scarp. Areas of elevated temperatures like this could serve as an indicator to identify unstable areas that may be involved in future rockfalls.

TTEM resistivity models have been computed separately and are presented for two of the three different sectors (**figure 1**). Data collected over the cliff (**figure 1**, green dots) reveal the presence of a well-defined conductive layer deepening northeastwards, where a minimum resistivity is observed at the southwest, in perfect agreement with the ERI and attributed to salt water intrusion, or brackish water. At depth, other conductive layers (also visible on the beach sector, **figure 4**, white dots) demonstrate that the complexity of this phenomenon is related to petrophysical properties (porosity, permeability) of the lithostratigraphic units and/or their state of fracturing. Further along the foot of the cliff (model not presented, blue dots), resistivity data show that conductive intrusions zones can be clearly identified revealing the spatial variability of this phenomenon. Its potential impact on groundwater management and cliff stability will be now explored.

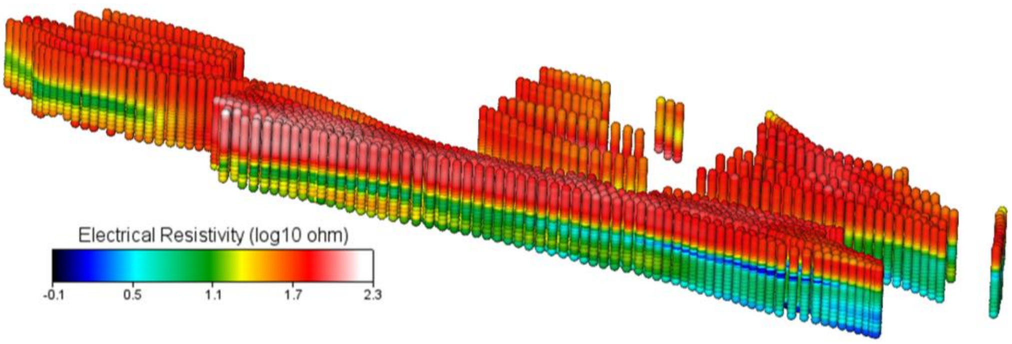

Figure 3 *3D resistivity model (above standard depth of investigation DOI (~40m), total residual 0.55%). View from the NW.*

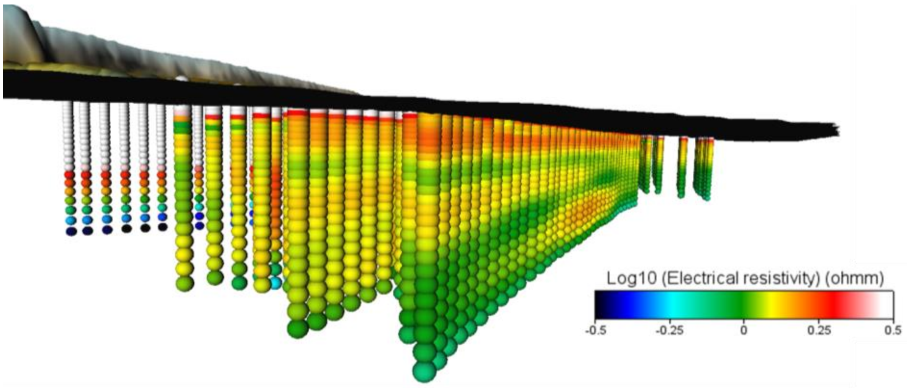

Figure 4 *3D resistivity model obtained above the pebbles beaches (above standard depth of investigation DOI (~20m) total residual 0.76%). View from the NE.*

Conclusions

The various geophysical measurements have revealed a saline intrusion at the base of the cliff to the southwest. To the northeast, a rise in the underlying waters has been observed at various places on the platform. Resistivity mapping using tTEM reveal the complexity of marine intrusion phenomenon and its ability to map quickly such objects and locate sensitive areas. The TIR spectroscopy has identified areas vulnerable to collapse at the top of the cliff. To follow the evolution and confirm the geological and hydrogeological observations, six new ERI profiles were carried out at the end of winter 2023. This data will now be integrated to further understand the different mechanisms and their relations.

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