

LASER SCANNING FOR HISTORICAL AND GEOTECHNICAL STUDIES AT POINTE DU HOC

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ABSTRACT:

The Pointe du Hoc Historic Site, in Normandy, France was host to one of the most important battles of D-Day. Its importance is marked by the bravery of the men of the 2nd Ranger Battalion who scaled its 30 m cliffs to challenge one of the strongest German defense positions on the Atlantic Wall. That effort and its subsequent aid to the overall Allied success on D-Day has resulted in Pointe du Hoc becoming one of the most popular tourist sites in Normandy. Yet, Pointe du Hoc is at risk. The site, a sharp protrusion into the English Channel, is particularly vulnerable to erosive forces of rain, wind, and sea which for 60 years have taken their toll on the cliffs and the 20+ concrete structures they hold. The Center for Heritage Conservation was selected by the American Battle Monuments Commission (ABMC) to undertake an interdisciplinary study of the failure mechanisms of the cliffs at Pointe du Hoc. To determine the failure mechanisms for the cliff, subsurface mapping must be tied to surface maps. By integrating surface maps of the current conditions of the site and its buildings with subsurface geotechnical data a comprehensive understanding of cliff failure mechanisms and their inceptions can be created. This paper will review laser scanning of the cliffs and its use as the central tool in bringing together historical, geotechnical, and geophysical data to create recommendations for its preservation.

1.1 Introduction

The Pointe du Hoc Historic Site, in Normandy, France was host to one of the most important battles of D-Day. Its importance is marked by the bravery of the men of the 2nd Ranger Battalion who scaled its 30 m cliffs to challenge one of the strongest German defense positions on the Atlantic Wall. That effort and its subsequent aid to the overall Allied success on D-Day has resulted in Pointe du Hoc becoming one of the most popular tourist sites in Normandy.

Situated on the Normandy coast between Utah and Omaha



Figure 1: Observation Post and Cliff

beaches, Pointe du Hoc was the perfect location for observation and control of sites critical to the allied plan of attack on D-Day. The Germans, aware of its significance in protecting the Atlantic Wall, relied on its location high above the English Channel for protection from allied attack by sea. Their observations and firepower were directed seaward but their endeavours for protecting the site were directed inland.

Whether this philosophy led to the American decision to attack Pointe du Hoc by scaling the cliffs is unclear, but the results of that decision and the subsequent unfolding of events from June 6 to June 9, 1944 changed Pointe du Hoc from “just another” German defense to one of the most highly visited WWII sites in Normandy.

The symbol of that popularity, the building that represents the tragic events of D-Day is the Observation Post (O.P.). From its perch on the northern most position on the point this building represents the strength of the German resolve to block out the world and the American resolve to penetrate its barrier. The symbolic power of the O.P. was embraced and enlarged in 1979 when a memorial to the rangers was placed on top of its domed observation room. The memorial pylon is flanked by two granite tablets that tell the ranger story of D-Day in English and French.

For most tourists the memorial and the O.P. are the most significant objects of Pointe du Hoc. In 2001 the O.P., with its close proximity to the cliff edge, was closed to tourists because of concerns emanating from various collapses of the cliffs. This decision separated the most symbolic elements of the site from the public, but more importantly it created a debate over what, if anything should or could be done, to save the signature building and its Ranger Memorial from falling victim to a future cliff collapse.

The debate is complex because of the fusion of scientific questions with historical, international, and national significance. From these considerations, the American Battle Monuments Commission (ABMC) issued a call for a two-part study of Pointe du Hoc consisting of a study of the failure mechanisms of the cliffs with suggested remediation measures

and a survey of the important historical features on site. The Center for Heritage Conservation at Texas A&M was chosen to perform this study.

2.1 Geotechnical Study

The English Channel is the part of the Atlantic Ocean that separates the island of Great Britain from northern France and joins the North Sea to the Atlantic. Duperret *et al.* (2004) reported nine different chalk units along the coastline of NW France (120 km from upper Normandy to Picardy). According to Rodet (1992) and Crampon *et al.* (1993), karst systems are better developed in Upper-Normandy than in Picardy and may extend along pre-existing fractures of the chalk. The chalk sea cliffs retreat along the Normandy coast of France over decadal time scales, is ranging from effectively stable to landward retreat between 0.1 to 0.5 m/yr with mean value of 0.23 m/yr (Duperret *et al.* 2004). The retreat usually takes place by successive local collapse. Many authors (e.g. Emery & Kuhn 1982; Sunamura 1992) propose that marine parameters acting at the toe of rock cliffs are responsible for under cutting the cliff, which leads to rock failures. The coastal monitoring program at the Sandown Bay, UK, which is about 140 km north of Pointe du Hoc, gives a range of maximum wave height, H_{max} , between 5 and 6m during the storm season as shown on Fig. 1. Benumof and Griggs (1999) also state that waves are one of the leading forcing mechanisms of sea-cliff erosion, secondary only to the material properties of the rock itself. The geology of the Pointe du Hoc area consists of: a top layer of sediments, which have been deposited in the Bajocien - Bathonien period. Below is a limestone layer of "Calcaire de St Pierre du Mont" also called "Calcaires du Bessin". This limestone layer is based on a marl layer of "Marnes de Port en Bessin". This marl is apparent in the nearby small harbour of Port en Bessin under the form of slopes created by the erosion on both sides of a small river that reaches the sea at this location.

The site reconnaissance revealed the following observations: The O.P. which is nearest to the cliff edge appears to be intact; however, some cracks in the O.P. walkway and entrance stairs were identified. Massive rock failures (Figure 2) were observed along the beach, all of them had a vertical plane of failure. The West side of the cliff head was found to be more concaved than the East side; this may indicate that the predominant wave and wind direction is from the west. The rock bedding is nearly horizontal, dipping down towards the north with an approximate angle of 5°. Fresh water seepage from the cliff face was noticed in several places at a level of approximately 2-3 m above the base of the cliff and sometimes higher. The predominant conjugate perpendicular joints on the West side of the Pointe appeared at an orientation of Azimuth angles 30° and 120°, yet on the East side, another set of conjugate perpendicular joints appeared at an orientation of Azimuth angles 0° and 90°. The observed joints' spacing ranged between 1 and 2 m. On the East side of the Pointe, just under the O.P., two extended joints appeared at the cliff face with the possibility that they coincide with the O.P. walkway cracks. Some large size undercutting and caverns were found to have heights up to 3.5 m and depth (i.e. perpendicular to the cliff face) from 3 to 4 m (Figure 3). The high tide level may reach up to 3 m from the cliff base at some locations and the waves may add another 6 m of water attack above that. Calculations of the erosion rate over the years from aerial photos indicate that at the most aggressive locations, the Pointe Du Hoc site experienced about 10 m of erosion due

to collapse over the last 56 years (from 1944 to 2000), or an average erosion rate of 0.18 m/year. This erosion rate is consistent with the numbers found in the literature.



Figure 2: Massive collapse about 300m west of the O.P.



Figure 3: Caverns near the Observation Post (West side)

2.2. Geotechnical Borings

The reconnaissance work included the drilling of six bore holes numbered from B1 to B6 to a depth of 30 meters. B1 and B3 were equipped with piezometers and B4 was equipped with a settlement benchmark. B1 and B5 were core drilling boreholes, and the rest of the boreholes were destructive drilling. In the destructive boreholes, the following drilling parameters were recorded during the drilling: instantaneous penetration speed, pressure on tool, rotation torque pressure, and drilling fluid injection pressure. One part (12 samples) of the intact samples taken during soundings B1, B1', and B5 was sent to the FUGRO Geotechnical Laboratory in France. The second part (10 samples) was sent to Texas A&M University, College Station, Texas, USA. The boring logs lead to the stratigraphy shown in Figure 4.

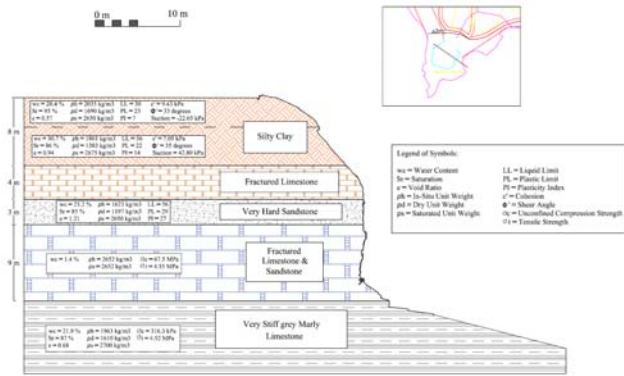


Figure 4: Stratigraphy and soil/rock properties at boring B1

3.1 Geophysical Study

The geophysical fieldwork, data analysis and interpretation for the Pointe du Hoc geological stability project have been completed. We used the electromagnetic induction (EMI) method for siting potential borehole drilling hazards and multi-electrode (MER) resistivity tomography for evaluating cliff stability and the present condition of the observation-post foundations.

The borehole drilling was performed safely. We identified several hazards within the proposed drilling areas. The drillers were alerted to avoid these locations.

A grid of ten top-side and six cliff-side multi-resistivity (MER) profiles were acquired (Figure 5). Two-dimensional resistivity fence diagrams have been assembled, from which suggested routes of groundwater infiltration into the fractured chalk are identified. We provide final 2D geological interpretations of the individual MER profiles and a quasi-3D synoptic interpretation based on the fence diagrams. We also present a fully 3D resistivity tomogram constructed from the entire data set, along with an interpretation of the tomogram in terms of the geostability hazard.

There were two main objectives associated with the summer—2006 resistivity tomography investigation at Pointe du Hoc. The first was to map major subsurface fracture zones that could indicate possible pathways of groundwater through the cliff. The ingress of acidic groundwater through carbonate formations enlarges pre-existing fractures via limestone dissolution and weakens the overall structural integrity of the cliff. The second geophysical objective was to ascertain the geometry and general condition of the concrete foundations of the observation post. Both geophysical objectives bear on the overall project goals which are to provide a detailed site stability assessment with special attention to the at-risk, cliff-side buildings and to recommend geotechnical remediation options for stabilizing the site.

The large amount of steel, concrete and void spaces (due to cratering, etc.) at the site, in addition to the presence of the extreme cliff topography, renders the 2D and 3D interpretation of resistivity data challenging but not intractable. A few trends emerge based on our analysis of the entire data set. The cliff face appears to be relatively intact and well-drained at the base, but possible groundwater accumulation may occur near the cliff top. Several important routes taken by groundwater into fractures within the limestone are identified; these occur mainly

on the western side of the site, but there may be an important flow of groundwater directly behind the observation post with an egress point on the eastern side of the site between the observation post and the anti-aircraft east building.

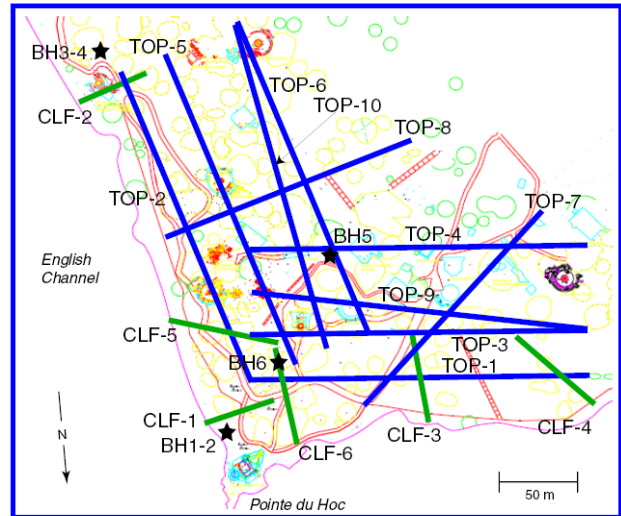


Figure 5. Pointe du Hoc 2006 Geophysical Site Map

The MER data also indicate that the observation post foundations are most likely to be “floating” on the soil rather than securely anchored to the bedrock. The geotechnical information and resistivity data, taken together, suggest that the bottom of the foundation is about 2 m above the top of the chalk bedrock.

MER tomography is the most appropriate geophysical technique to study geological stability of the cliffs at Pointe du Hoc. The electrical data responds sensitively to the occurrence of subsurface clay- or alluvium-filled fractures and groundwater infiltration into the fractured, karstic limestone formation. We have assembled 2D resistivity inversions into 3D fence diagrams to provide a better overall perspective of the subsurface hydrogeology.

We have also constructed a 3D resistivity tomogram of the entire survey area which includes the effects of the extreme cliff topography on the resistivity measurements. Our interpretation of the geophysical images in terms of the site geostability hazard is included in this report. The essential result is that the surficial zones (less than 5—10 m depths) are assemblages of small-scale resistive and conductive features that reflect the cultural noise and hydrogeological complexity of the karstic subsurface formations. At greater depths (more than 10—20 m) broader, resistive zones are observed which indicate the likely presence of large but dry void spaces originating from acidic groundwater dissolution of limestone. These dry areas may constitute a stability geohazard if they become significant drainage routes during and after periods of heavy rainfall. A good correlation is found between a void space found in the borehole—1 core and a resistive zone found in the 20—m tomographic depth slice.

4.1 Scanning and Survey

The geotechnical and resistivity work was performed first to discover general failure mechanisms for the cliff around the entire site but secondly to use this information to analyse the local failure mechanisms around the O.P. For general information about the site, location of resistivity lines within a

few meters was good enough to make general conclusions. However, to say anything definitive about specific conditions round the O.P. more careful measurements were needed. For this we used a combination of laser scanning, aerial photographs, photogrammetry, and hand measurements.

One of the central questions we needed to answer about cliff erosion was how much cliff had been lost since WWII and how much of that loss was natural versus loss resulting from the war. Clearly, we needed a very tight profile of the current cliff to compare with any historical profiles we may generate from archival information. Laser scanning was the central tool used to establish this fact. To check the validity of the scans we would overlay them with current satellite photographs and total station measurements.

Laser scanning at the site was difficult and we were very fortunate to be aided by ATM-3D in France for dealing with the realities of the 30m cliffs and the tides. Each day of scanning had to be choreographed with the tidal schedule giving us 4 hours of available time at the cliff base during low tide.

We used a Riegl Z 420i terrestrial scanner with 10cm cylindrical targets on the top of the cliffs and 10cm flat targets at the base. Nine panorama scans and 6 high resolution scans were taken on the east and west beaches. These were connected to 5 scans taken at the top of the cliff to give an overall context. All scans were registered to the same coordinate system used to measure the historical structures and bomb craters enabling all data to be merged together.

Through an established point-cloud, information about the current state of the cliff could be used to determine the risk state of the O.P. Sections through the cliff immediately in front and adjacent to the O.P. were used by the geotechnical engineering team to identify the exact location of the basal caverns of concern. Horizontal sections were also taken to render contours of the cliff face enabling a comparison of the current cliff profile to profiles created from WWII reconnaissance photographs. Finally, the 3D resistivity tomogram was overlaid on the point- cloud to pinpoint the location of highly resistive and conductive zones. This information was especially important for determining remediation schemes for the cliff and restoration plans for the O.P.

Discussion

Observation from the west beach shows large debris formations, indicating that cliff failures occur apparently in a sudden or catastrophic manner as a sudden collapse. Evidence of large-scale collapse features exists in more than one location on the west beach suggesting that catastrophic failure is the primary agent of mass movement at the site.

Cliff retreat inferred by the physical evidence has been corroborated through study of historical aerial photographs. By marking cliff edges on photographs taken prior to German construction and allied bombing and comparing those lines with current edges marked through 3D laser scanning we discovered those portions of the cliff edge that have registered the greatest retreat. It is clear from photographic study that failures occur sporadically with some portions of the current edge matching closely with historical edges while other portions show a retreat in some areas up to 7–10 m over the last 60 years. Clear photographs are difficult to obtain in every decade but we were

able to verify that failures in two key areas were not significant until after 1966.

The two areas are indicated in Figure 6. The area marked “A” near the Observation Post (O.P.) is on the east side of the point stack. The area marked “B” is on the west side of the stack about 85 m east of the O.P. The cyan line marks the outline of the cliff-top in 1942. The white line marks the current outline of the cliff-top as given by laser scanning while the magenta line marks the cliff-base from the laser scans. On the east side at “A” we see a significant loss of cliff-top (difference between white and cyan).



Figure 6: Cliff Line Comparison

Figure 7 details some dimensions in this area. We see the distance from the front of the O.P. walkway to the 1942 line is about 12.9 m. The distance from the same walkway to the current cliff line is 3.8 m, thus demonstrating a 10 m loss of cliff over 64 years. However this loss is not the full height of the cliff. We see a 3m difference from the 1942 line and the current cliff-base line suggesting that that most of the 10 m loss was in the softer soils above the base.

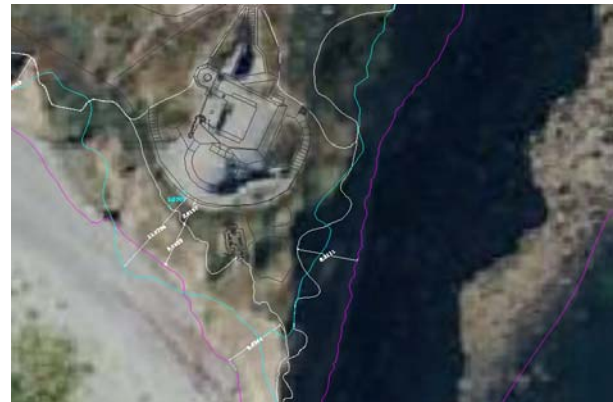


Figure 7: Cliff Edge Dimensions

Figure 8 shows that on the west side at “B” we see about a 15m loss since 1942 in the upper 11m of cliff with about a 5m difference between the current cliff-base line and the 1942 cliff-top. In both cases we see about a 3m-5m difference between 1942 cliff-line and the current cliff base in most places along the cliff, though the west side shows an area at “C” in Figure 9 with about a 10m difference. This suggests that basal erosion on the west side is greater than on the east.

Differences in historical cliff lines between the east and west sides of the point stack are significant because the west-side cliff base shows evidence of basal notching (Figure 10) and deep cavern formation which is absent on the east side (Figure 11). This observation, taken alone, suggests that any failure from basal cavern formation should occur only on the west. The lack of observable cavern formation on the east side of the

stack doesn't necessarily reflect the extent of the cliff stability geohazard. Due to the



Figure 8: Cliff Dimensions at 'B'



Figure 9: Cliff Dimension at 'C'

significant westerly direction of the tide, the sea action on the leeward east side of the stack has much less erosive power than it does on the exposed, windward west. This difference has caused a gravel spit of significant thickness to accumulate on the east. The spit, or shingle, has raised the apparent level of the cliff base by 3 m above that of the west. It is possible that caverns similar to those found on the west occur on the east but they evade observation due to the elevation of the gravel. Nevertheless, putative east-side caverns are effectively shielded from sea attack by the gravel and, should they exist, are not likely to be enlarged at an appreciable rate that would threaten the historic buildings at the cliff edge.



Figure 10: Scan Showing Basal Caverns West



Figure 11: East Scan with Pointe Stack

Measurements of previous cliff-base failures on the west indicate that when a cavern reaches an unsupported depth of about 4 m a failure is likely to occur. Observation and measurement of caverns on the west with depths approaching 4 m raises a caution about the future stability of the cliff in those areas. Cavern formation is a complicated process that involves the long-term dissolution of the limestone by acidic groundwater circulating within and enlarging the pre-existing cracks and voids of primary tectonic genesis. These avenues for continued groundwater action create a wide network for possible groundwater flow within the vadose, or unsaturated, zone to the cliff face. As fissures at the cliff base widen, large blocks of stone become vulnerable to significant mechanical action of the sea eventually causing their removal.

This is not the only way that groundwater contributes to cliff retreat. Multiple lines of evidence suggest that throughout the Normandy coast, cliff-top failures have occurred in association with periods of heavy rains. Large-scale collapses can occur as increased moisture levels in the Pleistocene and Quaternary silts and clays (upper 8 m) that overlay the Jurassic limestone formations weakens the tensional strength of the soil. Wedge failure occurs in portions of the cliff tops where geometry in conjunction with reduced strength leads to mass movement. This mechanism accounts for the irregular profile of the upper cliff in comparison with the relatively smooth profile marking the edge of the lower cliff. Not only is the upper cliff profile highly irregular but it is also set back from the lower cliff by about 10 m.

In our preliminary report we noted the potential for failures on the west side to be of greatest concern. The west side contains physical evidence of past failures and evidence of cavern formation. What was puzzling was the lack of mass movement scars on the east side. After completion of the aerial photography study and further analysis of the geophysical resistivity data, it has become clear that the mass movement hazard on the east side is just as significant as the west despite the lack of evident scars. Our analysis indicates that cliff-top wedge failures have occurred on the east side. The soil and debris comprising the wedge are carried away by tidal action leaving no visible trace on the beach.

Wedge failure of the upper cliff at "A" represented by the 1942 line is suggested by the 3D resistivity tomogram overlaid on the

site survey (Figure 12). A significant, likely persistent, source of ground water is apparent in the upper layers of the cliff near the O.P. The 3D tomogram also suggests possible

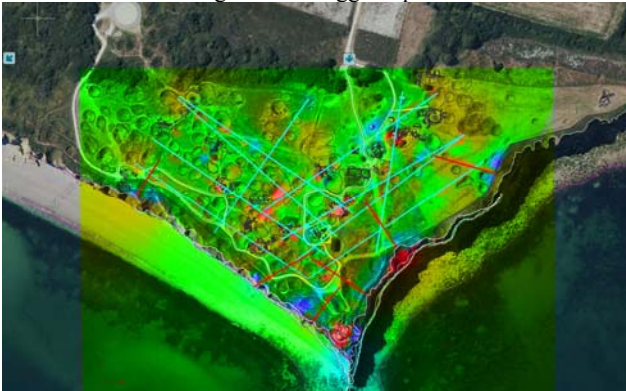


Figure 12: 3D Resistivity Tomogram with Site

karstic action in the form of enlarged voids on the lower east side near and beneath the O.P. The tomographic evidence is consistent with observation of groundwater seepage from beach gravel at low tide. It is also consistent with drilling logs in boreholes near the O.P. that show a 2 m drop in the bit indicative of a subterranean void, at about 20 m depth. It is possible that caverns or voids would be visible on the east face of the cliff if the beach gravel were removed. The top of the voids on the west cliff face lie at -23.8m with respect to our established benchmark while the gravel intersection with the cliff on the east occurs at -24.1 m from the same benchmark. Still, it is unlikely that any void formations on the east would be as significant as those on the west because of protection afforded against tidal action by the gravel and the reduced force of wave action on the east side of the point stack.

Summary

Observation studies were performed in the past at Pointe du Hoc leading to the decision to close the O.P. to the public. Opinions from these studies were insightful and in their concern for public safety chose to err on the side of caution. Still, these decisions were made without much data to support their decisions.

The importance of this site to the public is demonstrated through the nearly one million visitors per year and the blow to public morale caused by the decision to close the O.P. was tremendous. Laser Scanning and photogrammetry enabled us to gather data to support the original decision for closure but also to carefully recommend remediation schemes that will ultimately lead to reopening the O.P. The importance of continued develop of these tools cannot be overstated in their connection to our cultural heritage. Without their use at Pointe du Hoc the its story might have collapsed with the cliffs.

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