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Analysis and Preservation of Lime-Kilns in Corsica

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Abstract**—**The aim of this paper is the analysis and preservation of lime kilns, focusing on the structure, construction, and functionality of vertical shaft lime kilns of the Cap Corse in Corsica. Plans and sections of two lime kilns are presented in detail, providing an overall picture of this specific industrial heritage. The potential damage areas are identified performing structural analysis of a lime kiln using the finite element method. A restoration and strengthening technique that satisfies the directions of the Charter of Venice is presented using post-tensioning tendons. Recommendations are given to preserve and promote these important historical structures integrating them into the custom footpath.

Keywords**—**industrial heritage, lime kilns, post-tensioning, preservation

I. Introduction

LIME kilns are structures used to produce quicklime through the thermal treatment (calcination) of limestones. These kilns are usually located close to the limestones' quarries. The early lime kilns were constructed from brick or stone having a cylindrical burning chamber. Several of these structures are left without maintenance resulting in extensive damage and destruction. Lime kilns are part of the architectural heritage of almost every country and their preservation is necessary. Thus, it is important to locate these particular structures, to examine how they are constructed and sustain their loads, to identify their present condition and to find ways to restore and strengthen them.

The lime kiln related research is mainly focused on the improvement of existing processes to increase production of lime [1,2] and not on the preservation of old and historical lime kilns. Specific lime kilns have been restored and preserved by societies and committees such as the Kendal Civic Society preserving the Greenside lime kiln [3], the Polo Historical Society preserving the Buffalo Grove lime kiln [4] etc.

There are many historical lime kilns located at the Cap Corse in Corsica. Several are in poor shape, covered with vegetation (mostly maquis) and are in danger of collapsing. This study presents the history of these lime kilns in Corsica including important architectural and construction aspects, similarities that may exist between them, and their present condition. Structural analysis is performed on a lime kiln with representative dimensions and shape to identify the most stressed areas that need to be strengthened. Recommendations are given to restore and preserve these historical structures.

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II. Lime Production

A. General Aspects

Limestone or chalk has been produced at least since the Roman era. On Corsica Island limestone is acquired from sedimentary calcareous rocks. These formations are composed mainly of mineral calcite (calcium carbonate $CaCO_3$) originating from accumulation of marine organisms, e.g. shells of sea creatures and coral deposits, at the bottom of former seas dating back to the second era. The grey-white limestone at the Pointe of the Cap Corse forms a geological curiosity, since the region consists mainly of schist and serpentinite rocks [5].

In former times, the production of lime was obtained through calcination at about 800-1300^o C. First, the stone blocks were perforated and cracked, in order to obtain a fairly uniform shape of lump stones that fitted inside the kiln shaft. The use of round and fine stones was avoided because they behave badly during burning [6]. An arch of limestones was constructed inside the kiln shaft. Then the kiln was filled from bottom to top, positioning the bigger stones first and later the smaller ones, in order to facilitate air circulation during firing [7]. This loading procedure would last approximately one day.

At the bottom of the kiln the fire was kindled with local straw and faggots of wood for ten to twelve hours to moderately heat the rocks and to evaporate all water, avoiding the collapse of the arch. The fire would gradually spread raising the temperature. The process lasted three to four days removing the carbon dioxide (CO_2) [8]. New wood faggots had to be added into the kiln to maintain the flame as heat escaped. Usually after another three days the calcination process was completed and firing was stopped. At this point the stones had turned into a characteristic rose-white color and the flame was colorless [9].

The end product consisted of white quicklime (calcium oxide, CaO) in the form of blocks. The kiln had to cool down for two days. Afterwards the arch was destroyed using an iron rod and the kiln was unloaded. While the shaft was raked out either through the base or the top, attention was given not to remove the ashes, as only burned lump stone was of use. Unloading the shaft took another day – so in total the production of quicklime was a week-long process [6].

Water had to be added for the hydration process (slaking) in order to turn quicklime into a stable and usable product. During this process, the stones expanded releasing heat simultaneously. Then the lumps were disintegrated to a fine powder or paste. Depending on the amount of water used, the final product could have different consistencies [6]. The final paste called slaked lime (calcium hydroxide, $Ca(OH)_2$) is an important basic material which can be used in many ways.

B. Lime Production in Corsica

In Corsica quicklime was produced in vertical shaft kilns using mostly two methods. In the first method, an arch of

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limestones was constructed at the bottom of the lime kiln's shaft (discontinuous kiln) and it was filled up to the top with limestones. Wood and fuel were placed in the foyer and were lit, burning the limestones for four days and producing quicklime [8]. In the second method, according to locals, the limestones were positioned in a cylindrical way parallel to the kiln shaft's walls leaving an empty chimney in the centre, where straw and wood were placed. The fire was maintained for four days till the remaining small stones were ready for quenching.

Different methods were used for the extinction of quicklime. In the first method quicklime, was placed in a closed cavity, was exposed to air and sprinkled to start the hydration process. In the second method, quicklime blocks were soaked in water and then stapled to drain and get exposed to air. In the last and most common method water was added to quicklime till it was saturated and a viscous paste was obtained [6].

At the end of the nineteenth century three basic types of lime were known in Corsica according to Gauthier [5]:

- Fat lime, as a result of burning limestone without impurities, hardening at air, doubling its volume when mixed with water, and providing a paste that sticks well.
- Thin lime, as a result of burning limestone with divers impurities, forming a granular paste.
- Hydraulic lime, as a result of burning a mixture of limestone with clay, and hardening in water.

The perishable nature of the end product made reliable transport necessary. In Corsica, little boats were loaded with lime next to kilns and then transported it around the island or exported it to the "terra ferma" (Italian mainland) [7]. A boat was the only means of transport which could carry this heavy cargo all year around, as carts, for example, got stuck in the mud during winter time.

C. Use of Lime in Corsica

Historically, lime was an important product for Corsican economy. Lime has been produced and used at the Pointe of the Cap Corse since the roman era. During the Genovese epoch significant amounts of lime were used to bind and render stonework of new citadels. Lime was also used to reinforce dry masonry walls in simple housing [5].

During the last centuries, lime was sold in the form of blocks. In order to avoid deterioration, it was stocked in barrels or under a layer of sand. The lime was mixed with water and sand to create a mortar or coating ready for use. At the Pointe of the Cap Corse, a long-lasting mortar and whitewash was produced, which was preserved up to one-hundred-fifty years [5].

Lime was also used as dynamite due to its explosive qualities when water is added. Moreover, in the nineteenth and twentieth century lime was used in agriculture as a fertilizer especially in vineyards. In addition, lime was necessary for the production of paper, soap and more. Thus, lime was playing an important part of the island's economy, providing work in the two main fields of housing and pelt tanning.

The abundance of limestone resulted in the construction of numerous lime kilns. However, during the nineteenth century, the use of local lime was reduced rapidly on Corsica Island. Most of the existing lime kilns were only used sporadically for a few burnings per year (four to six). According to locals, the last lime kilns in use at the Pointe of the Cap Corse were those at the entrance of the village of Macinaggio that stopped their production in 1946. At that point, Portland cement replaced quicklime all over the island.

III. Lime Kilns At The Pointe Of The Cap Corse

A. Construction Details of Vertical Shaft Lime Kilns

A lime kiln may have various forms. In Corsica most of them were built as cylindrical shafts. These kilns were ovoid or ellipsoidal, probably due to the facilitation in their construction [7]. A lime kiln is a massive round chimney with an inside diameter at its bottom of about 3-4.5 m. In most cases at the Cap Corse, the cylinder narrowed gradually a little up to its top. The chimney's height varied from kiln to kiln usually between 3-5.5 m. The Corsican kilns' volume was between 20 to 60 m^3.

Corsica's lime kilns at the Cap Corse are partly embedded into a natural sinking or built next to a hillside. The position of each kiln was chosen so that it could easily be filled from the top. In most cases, one part was sculptured into the existing hillside or built next to it. The walls of the other part of the chimney were built from local stones with or without mortar [9]. The wall thickness varied between 1-3 m, depending on the total height of the kiln shaft. The gross mass was chosen to limit leakages and heat losses. According to locals, in order to avoid or limit heat losses, the construction originally was wrapped up both inside and outside with coverings of clay plaster. Today, none of the covering material persists [7].

The lime kiln's wall was at some point interrupted by an arched opening with a trapezoid doorway (Fig. 1). Three wooden beams still exist in this example and are the only evidence of a gate. This gate together with a small foyer constituted the entrance to the chimney for the fire feeding. In some cases one or more niches were found in the sidewalls of the foyer.

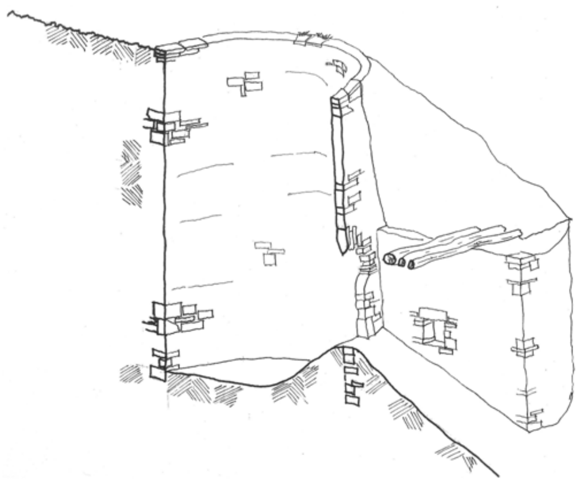


Fig. 1 Sketch of a section through a typical Corsican lime kiln at the Pointe of the Cap Corse

B. Suitable Site for Vertical Shaft Lime Kilns

The site for the erection of a lime kiln was chosen carefully. The construction site was always built close to the transportation and utilization areas. In the case of the Pointe of the Cap Corse this was next to the Genovese towers, citadels, villages, and docks. In addition, local wood and straw for firing should be easily acquired.

A lime kiln was always located next to the limestone quarry at a lower level in order to facilitate the rolling of the extracted rocks from the quarry down into the chimney. The construction site was built next to a road or near the sea front, to facilitate the loading, transportation, and distribution of lime either locally or regionally. In some cases, remains of orthogonal buildings (probably used for lime storage) as well as relics of docks or little quays can still be found close to the Corsican lime kilns.

A lime kiln was erected wherever raw limestone was available close to the burning material. The end product was distributed either by land or by sea, depending on the distance from the construction site. Thus, many of the lime kilns at the Cap Corse are close to still existing docks.

C. Geographic Location of Lime Kilns

The locations of lime kilns can be found on numerous historic maps of the region. The map of Fig. 2 indicates, with dark circles, the lime kilns that still exist today (some of them heavily damaged). The reference numbering in the following corresponds to the one used on this map. Broken line circles indicate the position of a lime kiln shown on ancient or more recent maps of the region that did not coincide with the position of remains of a limekiln. In total eleven limekilns were located during this research, half of them being in bad shape.

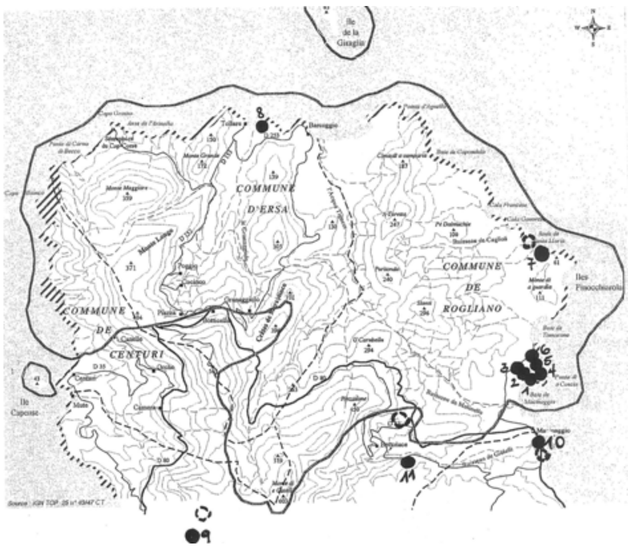


Fig. 2 Map extract of the Pointe of the Cap Corse showing the location of the lime

On an ancient Genovese map of the region (1600-1668) from Santa Maria di a Chjapella [10] two lime kilns (1 and 3, Fig. 2) can be spotted next to the sea front, near the village of Macinaggio, as well as the location of a construction which resembles to a dock. On another Genovese map from the same period [10], two more lime kilns are shown. One is located next to the chapel of Santa Maria near the sea and the other next to the Tower of Santa Maria near the sea as well. Again, a small dock is positioned nearby.

On the Napoleonian cadastre (1862) both Genovese lime kilns of Macinaggio reappear (number 1 and 3 in Fig. 2). However, on this map, the Genovese dock is not shown, which leads to the conclusion, that it probably remained a Genovese project that was not realized or was destroyed in the meantime. On another Napoleonian map three new lime kilns are shown next to the sea front (corresponding to 4, 5 and 6 of Fig. 2). Probably they were built sometime during the eighteenth and nineteenth century. Next to these lime kilns, another building is depicted probably used for quicklime storage. The two Genovese lime kilns next to the chapel of Santa Maria are not shown in any Napoleonian map; they probably were not any more in use during the nineteenth century. Finally, on the cadastre from 1973, the first two Genovese lime kilns reappear. Furthermore, a new lime kiln is drawn (corresponding to lime kiln 2 of Fig. 2). However, during this research many more lime kilns were spotted, as can be seen on Fig. 2 (dark circles). Since these kilns are not shown in any of the previous historic maps, their date of construction, the period of use or their connection to the region can not be reliably estimated. Most lime kilns at the Pointe of the Cap Corse seem to have been field kilns, erected close to the places where the end product was needed or from where it could easily be transported. The lime kilns that are next to Macinaggio and to Santa Maria della Chiapella (1, 2 and 3) are close to a still visible quarry and remains of a probable historic dock. The quarry and the dock are located approximately 50 m from these lime kilns. No quarry could be found next to lime kilns 4, 5 and 6. However, a dune of aeolianite located at a higher level and a rock which probably served as a landing dock for boats at sea level are visible. Since the openings of these three lime kilns are oriented towards the sea, it seems probable that all lime was transported through the sea.

IV. Presentation Of Two Lime Kilns At The Point Of Cap Corse

During the survey problems were encountered due to harsh vegetation, which made it impossible in many cases to enter into the lime kiln's chimney or take sufficient measurements. Two of the most accessible and best-preserved lime kilns are presented in detail. Their shape and construction principles are representative of lime kilns in Corsica.

A. Lime Kiln 1

Lime kiln 1 (Fig. 3) belongs to the Community of Rogliano and is located in the Western part of the Pointe of the Cap Corse, beneath two historic mills. This kiln is located at the beginning of the custom footpath and can either be accessed by car, using the D80 until Macinaggio and then via a small path towards the beach of Tamarone, or on foot via the trail that starts at the Northern end of Macinaggio a small distance after the marsh.

Fig. 3 Lime Kiln 1 as seen from the access path

This kiln has been partly built adherent to the hillside (almost two thirds of it). The rest of the kiln is constructed of stone walls with mortar. The thickness of the walls varies from 1.4 up to 3.6 m close to the entrance. The inside diameter of the chimney is around 5 m at the bottom (Fig. 4), narrowing gradually and reaching 4.5 m at the top. The entrance foyer of this lime kiln is almost 4 m long. The gate for entering the foyer is also almost 4 m wide, narrowing gradually until the door where the firing occurred. This firing door is today around 0.85 m wide. In this foyer, three 0.5 x 0.5 m niches still exist.

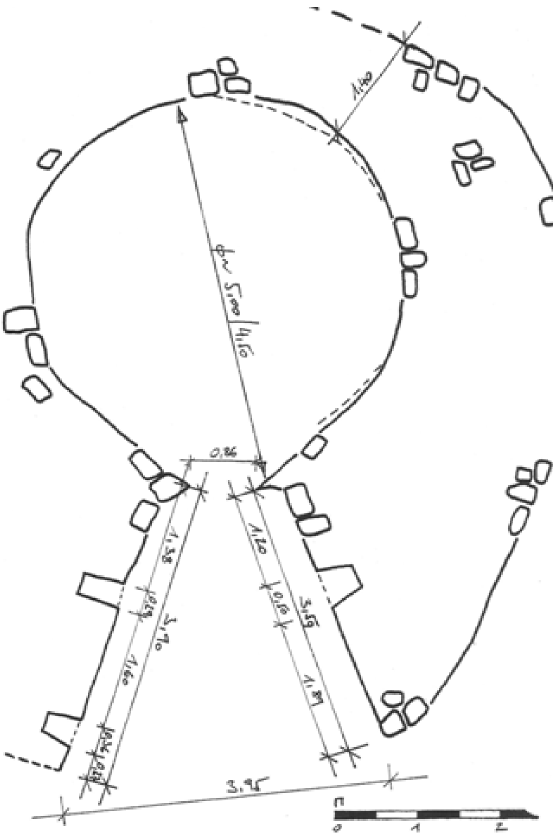


Fig. 4 Ground plan of Lime Kiln 1

Fig. 3 shows the condition of the kiln today. While the shaft's cylinder subsists completely at the bottom, large parts have collapsed over time from its top. The remaining kiln's height today measures 5.35 m at its highest point (Fig. 5). Its real height, when in use, cannot be estimated. The firing door opening is 1.65 m tall today. At the same height three wooden beams remain, where probably the foyer's roof was constructed on.

There are still visible lime spots inside and outside the chimney. It was also possible to find the quarry which is located near the kiln. However, no stock house could be found nearby, which leads to the assumption that this lime kiln was used for the construction of the two mills or the expansion of the village of Macinaggio located in a short distance. The lime kiln is visible and easily reachable from the custom footpath. Unfortunately, a fig tree that has grown inside the kiln has started to destroy the masonry, while the outside is covered to a large extent by maquis.

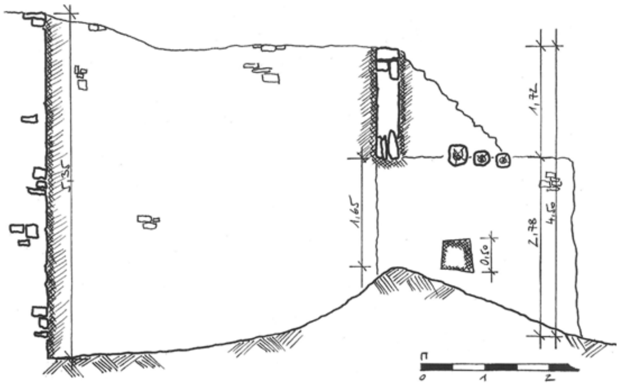


Fig. 5 Section of Lime Kiln 1

B. Lime Kiln 2

Lime kiln 2 (Fig. 6) also belongs to the Community of Rogliano and is located next to lime kiln 1. This lime kiln is much smaller than lime kiln 1. The inside diameter of the kiln's shaft measures only 3.6 m, and is constant from bottom to top (Fig. 7). This structure has also been partly built into the hillside. The rest of the kiln form walls built with mortar of 1.15 m wide. An entrance foyer is still visible, but not so well maintained. The entrance width is about 3 m and the distance from the corridor to the firing door almost 4.5 m. The firing door is 0.72 m wide and 1.60 m tall and is better preserved than the previous one (Fig. 8). The firing door dimensions of these two lime kilns are similar, although the shaft's dimensions vary considerably. The shaft of this kiln is in good condition in contrast to the outside part of the foyer. The kiln's height is today approximately 5 m. Two wooden beams still exist at the firing door opening. Lime kiln 2 was probably using the same quarry as lime kiln 1. This kiln is also visible and easily reachable from the custom footpath although its outside part is completely covered by maquis.

Fig. 6 Lime Kiln 2 as seen from the access path

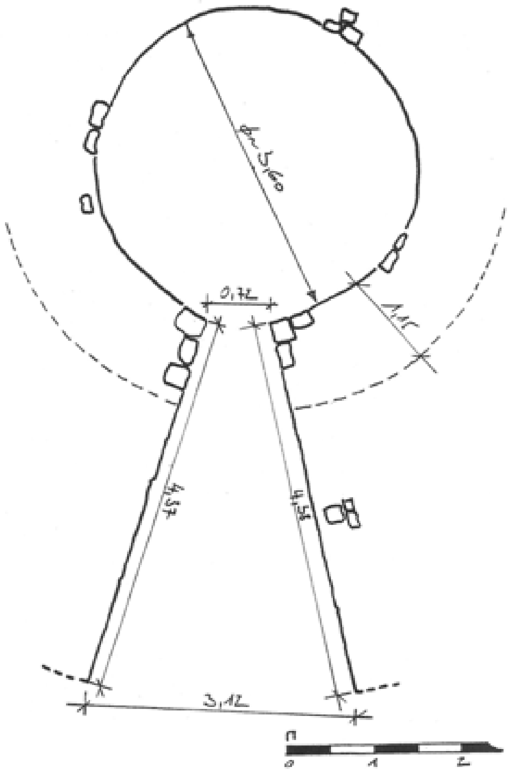


Fig. 7 Ground plan of Lime Kiln 2

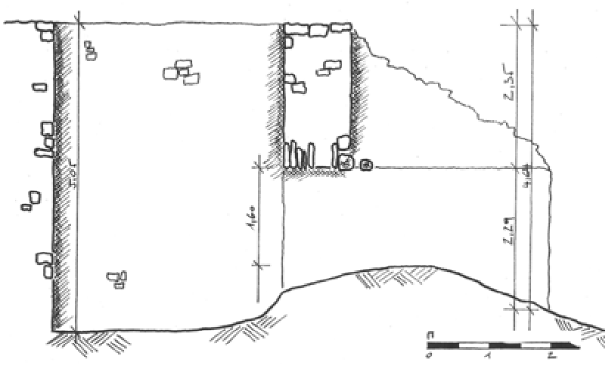


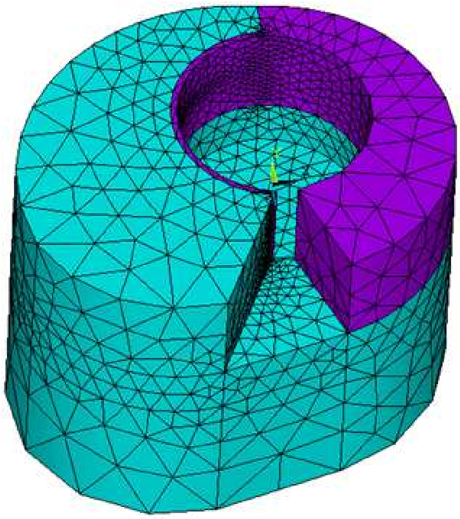
Fig. 8 Section of Lime Kiln 2

V. Lime kiln structural analysis

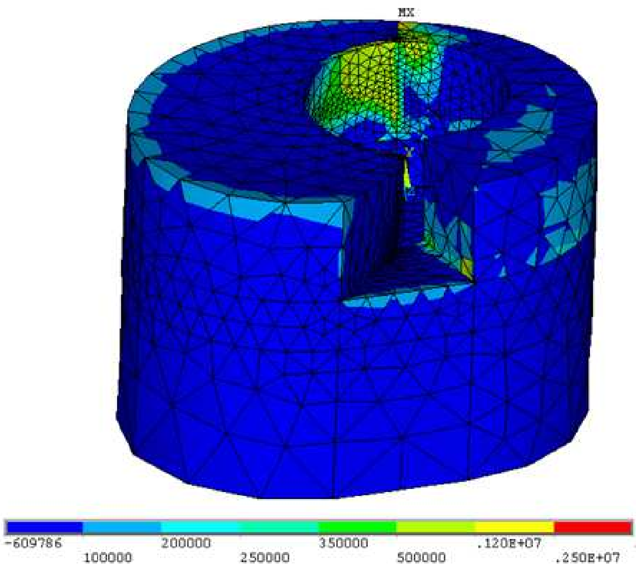
Structural analysis was performed on a typical limn kiln using the finite element method. The dimensions used for the model are representative of the dimensions of the lime kilns of Corsica and are based on the dimensions of lime kiln 1. In the finite element model the soil underneath the kiln was considered to extend up to 4 m. The thickness of the soil was 1.5 m at the junction of the thick stone wall with the soil, 10 m in the middle and 4 m next to the entrance (Fig. 9(a)). Extended dimensions of the soil were considered so that the kiln's existence had small influence on the soil at the end of the model where the boundary was considered fixed. A masonry wall of 0.20 m thickness was attached to the soil inside the shaft. Based on observations of the soil and masonry walls of the lime kilns in Corsica, the following properties were used to represent appropriately the materials that compose the lime kilns: the soil's density was 1800 kg/m^3, the modulus of elasticity 35 MPa, and the Poisson's ratio 0.24. The masonry's wall density was 2100 kg/m^3, the modulus of elasticity 2500 MPa, the Poisson's ratio 0.24, the compressive strength 2.5 MPa, and the tensile strength 0.25 MPa. The materials were considered homogeneous and isotropic. Only dead load was considered. Static analysis was performed using the structural analysis software Ansys. The masonry and the soil were modeled using a 10 node, 3-D solid element. The results are presented in the form of contour plots of the first principal stress (in Pa). Fig. 9(b) shows that the masonry walls are the most stressed parts of the lime kiln. Most of these high stresses are due to the pressure that the existing soil exerts on the masonry structure. In particular, the most stressed areas are the area around the junction of the thick wall with the soil (extended to the thin wall inside the shaft), and the lower part of the thick masonry wall at the entrance. At these areas the stresses exceed the tensile strength of the wall. These results explain the damages appearing on the lime kilns not only in Corsica but elsewhere also (Fig. 6) where the stones have fallen inside the shaft and the entrance wall has been destroyed.

VI. Restoration and preservation of lime kilns

Lime kilns are historical structures of every country's industrial heritage and an effort must be made for their restoration and preservation. This can be accomplished by removing any vegetation that has grown, replacing the mortar and stones that have been fallen or are in poor condition, and strengthening the areas of high stress. Several methods can be considered for increasing the strength of this structure and reducing the danger of future damage. One of these methods is the post-tensioning that has been used to strengthen several historical structures in the past [11]. A significant advantage of this method is its reversibility, keeping the structure in its original form something highly desirable for historical structures according to the directions of the Charter of Venice [12]. In this method stainless steel tendons are placed in any direction needed and are tensed with an initial stress that can tie the structure and reduce the danger of failure. The tendons not only stabilize the structure but also apply compressive stresses to the walls they are tied on, reducing the tensile stresses that may exist. The post-tensioning system must be designed for the case in hand, selecting appropriately not only the properties of the tendons but also their location and the anchoring technique.



(a)



(b)

Fig. 9 (a) Finite element model of the lime kiln and the surrounding soil examined (light blue colour represents the soil and dark purple the masonry) (b) First principal stress (in Pa) of the lime kiln and the surrounding soil

Post-tensioning can be applied to all the high stressed areas of the lime kiln considered, especially around the junction of the thick masonry wall with the soil. The usefulness of this method in reducing the high stresses was examined by performing finite element analysis on the same lime kiln model considered earlier. A few tendons were applied inside the shaft to tie the thin wall with the soil. The steel tendons used were modeled in Ansys using link elements and had the following properties: modulus of elasticity of 180 GPa, Poisson's ratio of 0.3, total area of 800 mm^2, and initial strain of 0.00028. Fig. 10 shows the principal tensile stresses at the junction of the stone wall with the soil with the steel tendons. The existence of the tendons reduces drastically the stresses at the area around the tendons. All high tensile stresses will be reduced as more tendons will be applied to tie the stone wall to the soil securely.

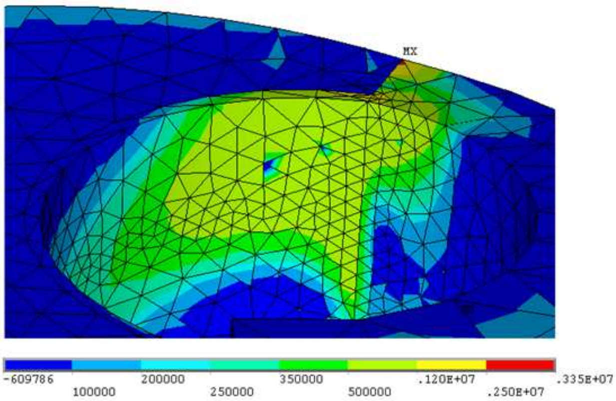


Fig. 10 Close-up of the first principal stress (in Pa) around the junction of the thick stone wall with the soil after using post-tensioning at certain locations inside the shaft

VII. CONCLUSIONS

The architecture, construction and functionality of the lime kilns in Corsica were examined. Their current condition was presented giving detailed analysis with plans and sections of two vertical shafts lime kilns that are better preserved than the rest. Structural analysis was performed on a representative lime kiln based on the finite element method. This analysis indicated the higher stressed areas that are prone to experience damage.

The abandonment of the kilns and their exposure to weather conditions deteriorated the materials they consist of reducing their strength. The mortar from the stone walls dusted away over the years. Moreover, the weight of the stones, the pressure of the soil, and the intruding vegetation created large cracks and produced destruction to some degree.

The vertical shaft lime kilns on Corsica Island are a significant reminder of local history and an important industrial heritage for the whole world and need to be named, restored and preserved. The vegetation that has been grown on the kilns needs to be removed, the stones and mortar need to be replaced and the high stressed areas need to be strengthened with a technique like post-tensioning that is reversible and satisfies the directions of the Charter of Venice [12]. Besides the lime kilns' restoration, the path to these important historical industrial structures needs to be cleaned and be visible from the main path. It is obvious that these lime kilns could easily be integrated in the custom footpath with explicative boards indicating the existence of these valued historical structures.

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