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Sustainable Construction through Tradition: Inventory of Cob Buildings in the Guérande Peninsula (France)

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Abstract: This paper delves into the investigation and inventory of cob buildings within the Guérande Peninsula, employing an interdisciplinary framework merging academic inquiry, fieldwork, and digital cartographic methodologies. Against the backdrop of escalating environmental concerns within the construction sector, raw earth construction emerges as a compelling avenue for sustainable building practices due to its low embodied energy and reversible characteristics. Despite historical prevalence in regions such as northwest France, traditional earth-building techniques have experienced waning prominence with the advent of industrial materials. However, the resurgence of interest in raw earth's minimal carbon footprint has catalyzed renewed attention towards earth-building methods. Through a meticulous investigation methodology, this study identifies and analyzes 802 potentially old cob buildings, with 46 structures confirmed as cob constructions. Employing statistical analyses of building characteristics, including wall and lift heights, preservation states, and geographical distributions, this research sheds light on the significance of preserving cob heritage amidst rapid urbanization. The findings underscore the imperative for ongoing research and awareness efforts to safeguard these vernacular architectural traditions. By illuminating centuries-old building practices, this research contributes to the scholarly discourse on sustainable construction methodologies and local cultural preservation. Moreover, it underscores the necessity of integrating traditional knowledge systems with contemporary sustainability initiatives to foster resilience and longevity within the built environment.

Keywords: heritage; earth construction; cob; Guérande peninsula

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1. Introduction

Of all human activities, construction is one of the largest consumers of global energy. It consumes more than 40% of all energy used in the economy [1–3]. It also consumes 40% of the world's production of natural aggregates, 25% of the world's primary forests, and 16% of the world's water annually [2–4]. The European Commission estimates that the sector is responsible for 50% of the raw materials extracted in Europe [5]. It is also one of the main producers of waste [6].

About 75% of building sector waste is made up of mineral soil, the raw material used in raw earth construction [7]. Raw earth is a local resource with low embodied energy [1] and possesses reversible characteristics [8]. For these reasons, raw earth stands out as a key building material in addressing the climate crisis.

In many higher-income countries, the emergence of industrial materials in the early 20th century led to the abandoning of traditional materials and skills, including raw earth and associated expertise [9,10]. However, over the past few decades, raw earth has attracted renewed interest, due to its low carbon footprint. This can be seen in the growing number of building projects and studies involving raw earth [11].

Traditionally, raw earth was used extensively in buildings in the northwest of France. In Brittany, cob dwellings have been built since the sixteenth century and represent 20% of the built heritage in this territory [12]. The cob technique is also found in the Vendée marshes, where squat dwellings known as *bourrines*, dating back to the fourteenth century, bore witness to the use of local, natural resources [13,14], when possible. Indeed, as demonstrated by Hamard et al. [8], not all soils are suitable for building with cob. This is also true for various earth construction techniques when no binder is used by the builders. The use of earth in construction is therefore highly dependent on the quality of the soil, which may be modified by adding a mineral or vegetable filler, and on the expertise of local craftsmen. Between these two well-documented earth-building territories lies the Guérande Peninsula, where earthen heritage (see Figure 1), which until recently has been little-known and neglected, has become the object of mapping and inventory studies.

Figure 1. A cob outbuilding at Kerhebé, dating from the mid-19th century [15].

The vernacular practice of cob building is inherently sustainable due to the excellent carbon footprint of raw earth [1,8]. This traditional method has become a significant source of inspiration for contemporary sustainability initiatives. As stakeholders seek authentic solutions to the global climate crisis, these rediscovered architectural practices are providing valuable insights and fostering a renewed interest in earth building at the local level.

Given that practical knowledge of earth building has nearly vanished in many regions, each extant cob structure serves as an exemplar from which contemporary builders can derive important lessons. These structures inform best practices in the renovation and construction of earth buildings. Both local professionals and students have derived substantial understanding of the properties and behavior of local earth materials through the study of existing cob buildings' siting, conception, and implementation [15–17].

In the report by Hilton [15], the author indicates that "While comprehensive texts specifically addressing earth as a building material in the region (Guérande peninsula) are scarce, several sources provide valuable insights". The *Atlas des Paysages de Loire-Atlantique* [18] mentions the typical *Brière* house, characterized by *adobe* walls with white rendering and a steeply pitched thatched roof. Additionally, in *Vivre et habiter sa chaumière* [19], the authors describe the use of earth in construction, highlighting its prevalence due to the lack of quarries. They describe how the walls of thatched cottages, often made of earth or cob, rest on a stone base and are protected by rendering. Similarly, *L'architecture Briéronne et rurale* [20], an appendix to the local urban planing of Saint Nazaire, discusses the mixed construction of stone and earth walls in houses, typically with stone plinths and lime rendering added for protection in the mid-nineteenth century.

Further insight comes from Yves Labbé's article *La chaumière briéronne* [21], which explores the existence of numerous earth-built dwellings and annexes in the *Brière region*. Labbé notes that the last remaining buildings reveal the use of earth mixed with straw, built up from a stone base using the *bauge* (cob) technique. However, identifying these earthen constructions can be challenging due to the rendering covering them.

Jacques Fréal [20] emphasizes the scarcity of stone in the marshy landscape of the Brière region, leading to the predominant use of sun-dried clay blocks known as *pisé* (rammed earth) for construction. Fréal's mention of clay blocks and *pisé*, alongside references to *torchis* (wattle and daub) and *bauge* (cob), highlights the varying terminology used to describe earth construction techniques in the region. Despite the confusion in terminology, regarding the modern classification, these sources collectively underscore the importance of earth as a building material in the region and the challenges in identifying and preserving earthen constructions.

A synthesis of the available texts reveals a consensus on several points. These include the use of a stone base, lime rendering for protection, and the dwindling number of surviving earthen buildings. However, discrepancies in terminology and construction techniques underscore the need for further research and clarification. Although the authors cause some confusion in using the wrong terms to describe earth construction techniques, it should be noted that the field of earth construction has well defined the different earth construction techniques. Hilton's work [15] has shown that where the terms *torchis* or *pisé* were used to describe building techniques on the Guérande peninsula, they were in fact *bauge*, i.e., cob (see the article by Hamard et al. and [22] for a detailed description of the cob technique).

In particular, the disappearance of this earthen heritage is a consequence of the need for space to build new buildings in a region of intense housing need. This justifies the proposition that a comprehensive inventory of the earthen heritage on the Guérande peninsula would be beneficial in order to more accurately identify the buildings, the construction techniques, and the building typologies and to preserve this heritage before it is lost forever.

Recent inventory efforts and the resultant professional expertise are already informing local development projects. The new Maison Neuve eco-neighborhood in Guérande exemplifies this application [23]. This flagship project intends to reuse several thousand tonnes of site-excavated earth for its construction activities in the coming years. Insights gained from the Brière inventory enabled the Guérande town council and the project's main developer, LAD SELA, to recognize that site-excavated mineral earth is not merely a waste product but a valuable building material. Its reuse on-site represents an effective circular solution to the issue of waste.

Additionally, leveraging knowledge of vernacular practices acquired during the inventories, local earth-building experts have been able to advise the initiative on appropriate building techniques that align with the characteristics of the site-excavated earth [24].

The inventory work has also led Guérande's School of Art and Heritage and the Brière Natural Regional Park to develop new educational and awareness-raising activities around local earth-built heritage plus, as in the case of the Brière Park, to take several steps toward greater dissemination of best practice in earth building and renovation [25].

The aim of this paper is to present the methods and findings of recent inventories of cob buildings on the peninsula, conducted by an interdisciplinary team comprising academics, researchers, university students, earth masons, and a key regional partner, the Brière Natural Regional Park. This article contributes to the broader effort of documenting earth-based constructions, much like the studies previously presented by Aras-Gaudry et al. [26] or Ford et al. [27] or those included in the WHEAP inventory [28]. This article first describes the methodologies employed during the inventory process, including the use of a geographical information system (GIS) for analysis by comparing ancient and modern maps. The following section details the key findings and insights derived from the study: first, a statistical analysis of cob building types, states of preservation, and geometric analysis; second, an examination of the types of earth used and surface analysis; and third, a collection of photographs depicting cob buildings representing different typologies.

Additionally, a comparison with geology and pedology maps aids in better interpreting the distribution of cob buildings in the Guérande peninsula.

2. Investigation Zones and Methods

2.1. Investigated Region

The region investigated in this work is a part of the Guérande Peninsula, located in the west of France, close to Brittany (see Figure 2). The area is known for its salt marshes, in the south-west of the peninsula, and, to the east, the Brière inland marshes. It is an attractive, touristic region, and the peninsula is densely populated. The investigated area corresponds to the east part of the peninsula as shown on Figure 3.

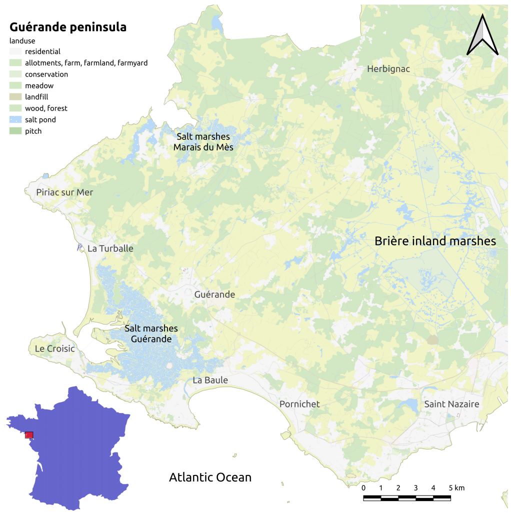

Figure 2. Guérande Peninsula landuse and main towns [29].

Covered with wetlands and famous for its many *chaumières* (thatched cottages—see Figure 1), this territory also bears witness to significant use of earth in traditional construction. As well as many examples of wattle and daub elements in both vernacular and noble buildings, the peninsula is home to an as yet unknown number of cob buildings.

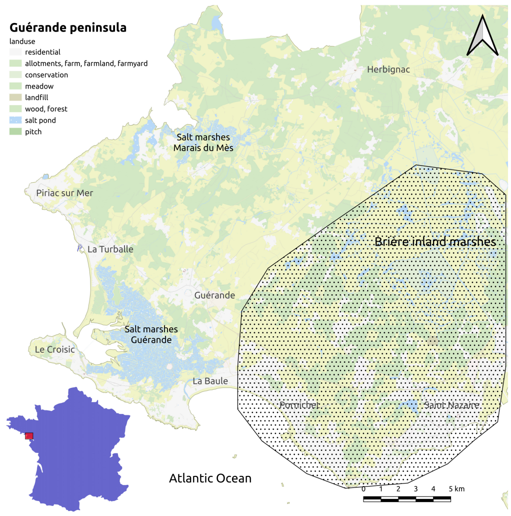

Figure 3. Investigated area [29].

The region is part of the Saint Nazaire urban unit, which has a population of 189,875 over an area of 472.2 km^2 (population density of 402 inhabitants/km^2). It includes major towns such as Saint Nazaire, Pornichet, La Baule, and Guérande. The main economic activities on the peninsula are tourism, fishing and shellfish farming, water sports, salt farming, and heavy industry, particularly shipbuilding. It is a dynamic region from an industrial point of view, with steady population growth (average annual growth of 0.8% calculated over the period 2014–2020) and a growing demand for new housing.

As can be seen from Figure 4, the Guérande peninsula has undergone rapid urbanization since the Second World War. The map shows the proportion of buildings constructed before 1945. The majority of urban areas in Saint Nazaire (the main town in the area) contain between 0 and 10% of old buildings. The proportion of older buildings is higher in the following:

- In the coastal areas of La Baule and Pornichet, where seaside-style buildings predominate. This area was protected from bombing during the war because of its distance from the German submarine base at Saint Nazaire.
- In the rural areas north of Saint Nazaire and bordering the Brière marshes. Until recently, these areas were not very attractive to the new inhabitants of the peninsula, but they are gradually becoming urbanized as a result of demographic and building pressure.
- In the rural areas to the north of the peninsula, in the countryside between Guérande and Herbignac.
- In the areas bordering the salt marshes of Guérande and Le Mès, where typical salt worker villages are still preserved, or the buildings of the fishing port of Le Croisic.

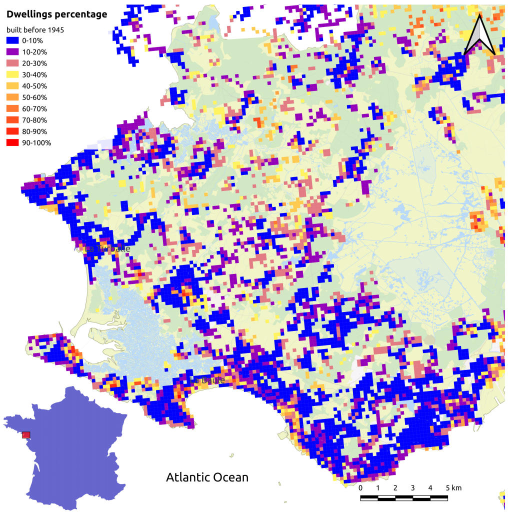

Figure 4. Percentage of dwellings built before 1945 [29,30].

2.2. Cob Buildings

There are many different techniques for building with raw earth, generally developed according to the qualities of the earth available in a particular region and to the know-how of local craftsmen. Cob, rammed earth, adobe, compressed earth blocks, and wattle and daub [31] are all examples of earth building techniques used in France (see Figure 5). The cob technique is widespread in the north-west of France, particularly in Brittany, Normandy, and Pays-de-la-Loire [12–14]. The Guérande peninsula is located in the latter region, where the cob areas are predominantly found in Maine-et-Loire, Vendée, and Mayenne. However, the Guérande peninsula is rarely identified as cob territory on the available maps, although it is well known to local architects and craftsmen that there is an earthen heritage in this region.

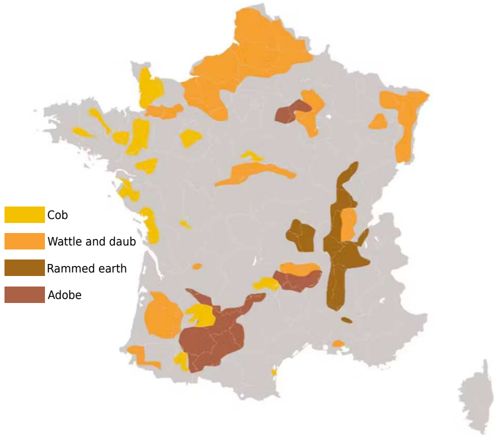

Figure 5. Different construction techniques using earth in France, adapted from [32].

According to Hamard et al. [8], the cob technique consists of stacking clods, or cakes, of a wet raw earth mixture of fairly stiff consistency to form a monolithic, load-bearing, or free-standing wall (see Figure 6). The earth is excavated on site or nearby and may be mixed with natural fiber additives such as straw, reed, or hay. A cob wall is built in layers, known as 'lifts', because each layer of fresh, wet material must dry sufficiently to support the mechanical load of the upper layers before another lift can be applied. A cob building also usually has a stone foundation plinth to protect the walls and floors from water damage caused by capillary rise and splashing from rain hitting the ground [8].

Figure 6. A cob wall in modern construction [33].

2.3. Investigation Method

In order to identify the cob buildings on the Guérande Peninsula, we combined several sources of information and open-source digital tools. The first step was to demarcate sub-zones for investigation. To do so, we imported the digital map of the region from Géoportail [34], a government website, into the geographic information system software QGIS 3.34.10-Prizren [35]. Each place (such as hamlet, village, district, and so forth) is already assigned a location and a name on the Geoportail map. These locations were used as nodes to perform a Delaunay triangulation, from which we obtained Voronoi cells. The Delaunay triangulation is an optimized method for joining the nearest nodes and creating a triangular mesh (see Figure 7). The Voronoi tessellation method allows for the generation of a tiled partition of the surface, wherein each vertex of a given polygonal Voronoi cell is positioned at the same distance from the vertices of the Delaunay triangle to which it belongs. Each Voronoi cell on the map is considered an investigation sub-zone. As this method is based on location names, and as the number of dots on location maps is greater in denser zones, it allows us to delimit the investigation zones according to building density. This is the reason why the investigation zones (Voronoi cells) are larger in the countryside than in the towns (Figure 8).

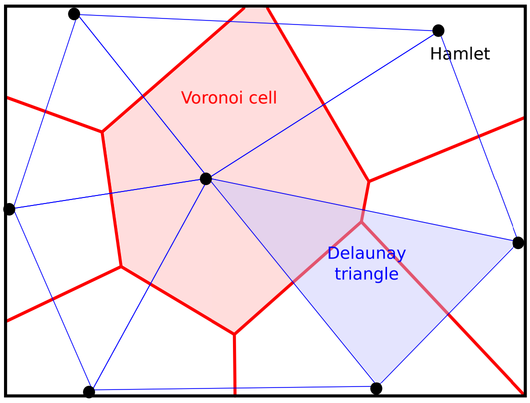

Figure 7. Delaunay triangulation and Voronoi diagram used to define the investigation zones.

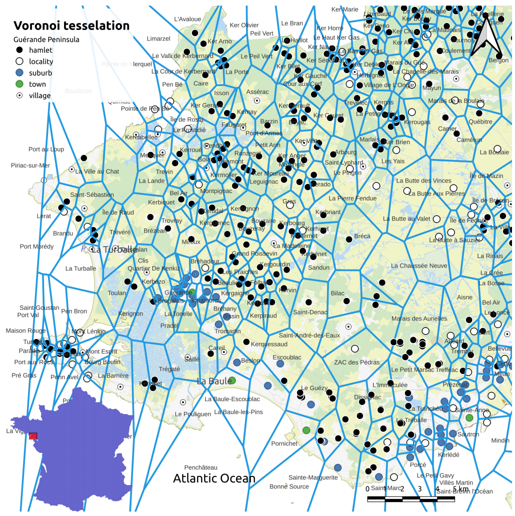

Figure 8. Voronoi tesselation of the Guérande peninsula [29].

It is important to note that the area of study, situated to the northwest of the port town of St Nazaire, suffered extensive destruction as a result of bombing during the Second World War. The surviving old buildings are scattered amongst the numerous post-war, modern buildings. In order to assess the importance of the cob heritage, which we assume to have been constructed before the Second World War, we had to consult general maps dating from 1850 [36]. This identification method therefore involves some uncertainty since it is based on the comparison of maps drawn up until the mid-19th century. If earth buildings were constructed between that period and today, they might not be present on these old maps. However, these maps do allow for the identification of historical settlement areas on the peninsula that are most likely to reflect local construction methods.

The maps in question have been established throughout the first part of the 19th century over a period of approximately fifty years, with the duration varying depending on the region. They are available for free on the IGN website [36] and can be imported into QGIS as georeferenced raster layers.

The superimposition with modern maps is particularly accurate, allowing for the identification of remarkable land reliefs and points of interest, including roads, wells, large buildings, and rivers. On the maps, existing buildings are represented by red rectangles.

To highlight these buildings and remove unnecessary pieces of information, the maps were each treated using Fiji 1.54 [37].

A threshold procedure was applied to the images in the HSV space (Hue, Saturation, Value), with the aim of creating binary images. HSV space thresholding is known as the best way to select entities based on their color. These images were then subjected to a Fiji *close* procedure, which allowed for the improvement of the delimitation of buildings and the removal of isolated dots. Figure 9 illustrates this process.

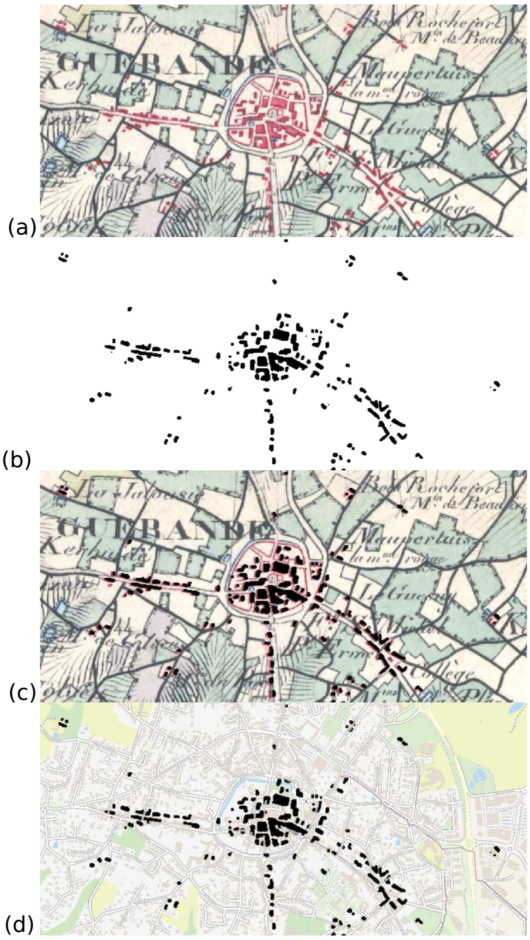

Figure 9. (**a**) Original map; (**b**) thresholded map to highlight the buildings; (**c**) checking for the procedure; (**d**) superimposition on modern map [29,36].

The next step was to import these pictures into QGIS, and to georeference them. The *raster* layers obtained were then vectorized and saved as vectorized georeferenced layers. The remaining parasite structures were then removed by hand by selecting the vectorized entity. Finally, the ancient building layers were superimposed with the modern map. This allowed us to identify matching constructions. Then, using Google Maps and Google StreetView, we carried out virtual visits to the different locations identified, which allowed us to ascertain whether the constructions were old or recent. These visits enabled us, firstly, to eliminate certain locations where old buildings had been razed and, secondly, to note if matching buildings were old or recent. Once identified, matching old buildings were inspected closely via Google StreetView to try to detect the construction materials used (stone, cob, or both). However, this research can only be applied to buildings located near the road or that can be seen from the road. As soon as a building is hidden by vegetation or another building, it is not possible to identify the construction method used. This method, therefore, allows for the exclusion of buildings that are obviously new or whose construction method is clearly visible in the photographs (concrete, wood, sheet metal, exposed stone, etc.). This preliminary screening stage was followed up by field visits to confirm whether the buildings identified as being potentially built of cob were indeed so. Site visits also made it possible to resolve uncertainty, when the buildings were accessible, regarding the construction method of buildings not visible on Google StreetView.

Once a cob building was identified, we took photographs and noted certain data:

- Type of building (dwelling, outbuilding, etc.);
- State of preservation (based on pre-established parameters);
- Building dimensions: height of the stone foundation plinth; height of the cob lifts.

These data were finally keyed into QGIS to complete the database.

The results presented in this paper concern buildings located on the eastern part of the peninsula around the towns of Saint Nazaire, Pornichet, Saint André-des-Eaux, l'Immaculée, and La Baule (blue zone on Figure 3). Other buildings outside the investigation sub-zones were also found by talking with inhabitants during field visits, by Hilton's work [15], and, during heritage events, local festivals and other awareness-raising activities.

2.4. Statistical Analysis

In order to obtain quantified criteria for statistically describing the results of investigations for the different numerical parameters measured on accessible buildings, we determined the normalized distribution $f_X(x)$, i.e., the percentage of buildings for which the value of a parameter X (wall height, lift height) is lower than a given value x.

$$f_X(x) = P(X <= x) \quad (1)$$

To do so, we discretized the interval of variation of the parameter, and we counted the number of buildings fulfilling the condition described by Equation (1). Then, we divided this number by the total number of buildings. We then derived the 25%, 50%, and 75% percentiles that give a statistical description of the value distribution inside their range of variation. We also calculated the average and standard deviation for each parameter.

3. Results

3.1. The Cob Buildings, in Numbers

Using the method described, we identified, in the investigation area, 802 buildings that we suspected to be old and potentially built from cob (see Table 1). For the moment, we have visited only 50% of the buildings identified. Among these, we identified 46 cob buildings, representing 6% of the total number of buildings. However, 149 of the buildings visited have been classified as "suspected cob" because it was not possible during the field visit to determine whether they were definitely made of earth or not. This is because certain buildings were located on inaccessible private properties, the owners of which were not present at the time of the visit or did not allow us to enter their property. Nevertheless, the remote observation of these buildings led us to believe that they were potentially made of cob. It is therefore important to be aware that biases are introduced in the analyses due to factors such as the following:

- The inaccessibility of certain buildings;
- The difficulty of taking samples;
- The challenge of removing interior and exterior coatings to clarify the status of 'suspected cob' buildings;
- Other factors that may prevent a more detailed analysis.

The 26% remaining buildings are either old buildings made of stone or wood, or new modern buildings. So, up to half of the buildings visited are potentially made of cob, which is a finding that validates our searching method.

However, the buildings identified do not always correspond to the locations of older buildings shown on the 1850 map. This method is therefore more suitable for identifying the locations of old villages with cob buildings than the buildings themselves, and although the method used is interesting and valid, it is more sensitive to old villages than buildings.

This proves that fieldwork is needed to accurately locate cob buildings and add them to our maps, as well as information about the construction technology.

Table 1. The cob buildings in the investigation area.

Category	Number	Percentage
Total	802	100%
Still to visit	400	50%
Cob buildings	46	6%
Suspects	149	19%
Other buildings	207	26%

Recently, a large cob farmhouse, discovered during a previous identification campaign in Saint Sébastien, was completely destroyed. A new building was built in its place. This is a new incentive to better identify the cob houses and their architectural interest, as they are an example of vernacular building techniques of the Guérande Peninsula.

3.2. Cob Building Location

In order to better understand where the cob buildings are located, we used the automatic algorithm HeatMap implemented in QGIS. It creates a color map corresponding to the number of entities in the investigation zone. The result is presented in Figure 10. We can see that most of the buildings are located to the north-east of the zone (22 in Marais des Aurielles and Le Petit Marsac), on the edge of the Brière marshes. This should be seen in relation to the map in the figure above, which shows that these two Voronoi cells have the highest local proportion of buildings constructed before 1945 (20% in Marais des Aurielles and up to 36% in Le Petit Marsac).

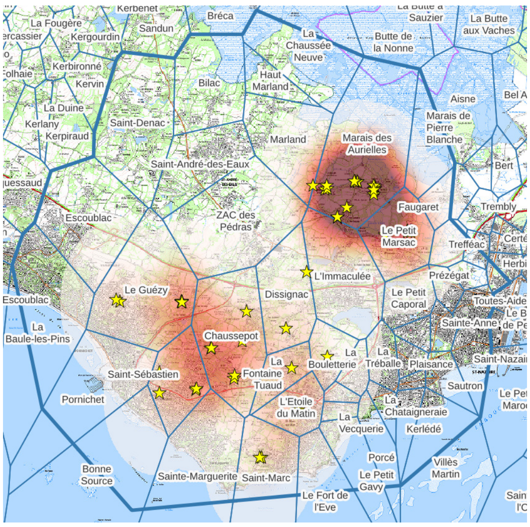

Figure 10. Location of cob buildings in the investigation zone—the red color represents a higher density of cob buildings discovered (asterisks).

A secondary group is located to the south-west (16 in Saint Sébastien, Chaussepot, and Le Guézy). Both of these zones are poorly populated rural areas, which could go toward explaining the significant number of cob buildings remaining there. The proportion of buildings built before 1945 can be as high as 27% in Chaussepot and Saint Sébastien, and 57% in Le Guézy. Pressure on real estate is lower in these areas compared to the towns of Saint Nazaire, La Baule, and Pornichet, where the increasing need for accommodation forces the municipalities to incentivize the construction of residential buildings, leading to the destruction of old ones. Even so, certain buildings are located in the old quarters of sea-side resort towns such as Pornichet.

3.3. State of Preservation

We classified the 46 cob buildings identified according to one of four states of preservation (examples on Figures 11 and 12):

- Destroyed: present on old photographs collected from local inhabitants but not present on site;
- Ruin: not usable, no roof, only the walls or part of the walls;
- Good: usable as an outbuilding, existing roof;
- Habitable: the building is still used as a permanent dwelling.

Table 2 presents the results of the classification. We can observe that most of the cob buildings in the investigation region are still in a good state of preservation (63%), and two of them are occupied.

Table 2. The cob buildings in the investigation area.

Category	Number	Percentage
Total of investigated buildings	46	100%
Destroyed	3	7%
Ruin	14	30%
Good	24	52%
Habitable	5	11%

Among the identified outbuildings, which are in a relatively good state of preservation, different techniques have been employed to maintain them in such a good state (see Figure 11). In general, the roofs of the buildings, which may have been covered with reed thatch in the past, have been replaced with brick tiles or corrugated sheets (galvanized steel or fiber cement). In some cases, we observed that parts of the upper walls had been partially destroyed and replaced by concrete or concrete blocks, indicating a desire to preserve the cob parts. The reason for this choice is not immediately apparent, but it may be influenced more by economic than by architectural considerations.

Additionally, one building was identified in which an attempt was made to rebuild the gable using local material. However, as can be observed in the accompanying image, Figure 11d, this was carried out using a different type of soil, likely Brière blue clay, which is different from the material used for the lower part of the wall. This attempt to rebuild the gable was carried out without recourse to earth builders. This appeared to be an ill-considered attempt to maintain the building in its original state.

Figure 12 shows some examples of habitable buildings. The houses shown in Figure 12a,c,d are for residential use. These buildings have one or more walls made of bauge as well as parts renovated with modern materials, mainly concrete blocks. Parts of the walls are visible in some places, including the following:

- In electrical switchboards or service ducts, where no plaster or lining has been applied;
- On walls overlooking external storerooms, which have not been rendered.

They are main residences or public buildings renovated during the last thirty years. Houses c and d are two-story houses (ground floor and converted attic). From an architectural point of view, this elevation is keeping with what can be seen on most of the region's cob buildings. Some parts of the building have been renovated and rendered with a type of plaster that we have not been given. They also include new parts or extensions built using more modern materials. It is also worth noting that the owners have chosen to replace the existing roof, probably made of reed thatch, with slate or even zinc in some areas. House a also has two levels, but in this case, the second level is an extension built from a different material. It would appear that only the main facade visible in the photo has been raised, as the height of the rear section is in line with the heights generally observed on local cob buildings. We were not given any information about the materials used for the extension, the way in which the interface between the cob part and modern materials is managed, or any structural calculations carried out on the building to demonstrate that the lower cob section has sufficient load-bearing capacity. These various examples show that cob buildings can be renovated to suit modern lifestyles. However, some residents have reported problems with capillary rise or damp walls in certain parts of the building. Some also have indicated that regular maintenance was required on certain parts of the building.

The building in Figure 12b is a local house located in a residential area of Saint Nazaire with a high concentration of new buildings. It is a building open to the public. It is interesting to note that despite the fact that this district is undergoing major urban restructuring linked to the demographic development of the town of Saint Nazaire, this building has been preserved and renovated. The town of Saint Nazaire did not decide to demolish it and replace it with a new building.

Figures 11 and 13 present overall or close-up views of walls illustrating the state of surface preservation. These photos correspond to easily accessible areas in sheds. The walls generally do not have any coating, allowing us to observe some changes from an assumed initial state, which can be defined based on the ICOMOS glossary for stone deterioration forms [38] and which can be extended to earth constructions. The main degradation types observed include material loss, due to erosion or mechanical damage, and cracking, and they are outlined as follows:

- Cracking: Microcracks can be seen in Figure 13b, and larger cracks in Figure 13c. These cracks do not appear to compromise the overall mechanical stability of the structure.
- Mechanical damage by perforation: Figure 13b shows perforations across the surface caused by wasps or mason bees, with added material used to complete their nests.
- Mechanical damage by abrasion: This can be observed near the gable window, likely caused by the repeated passage of domestic cats (this was observed during the visit).
- Erosion: Localized erosion is visible on certain parts, particularly at the lower section of the building in Figure 11a, which does not appear to have a waterproof barrier to prevent capillary rise, unlike the buildings in Figure 11b,c. The eroded material has formed a mound of earth at the base of the structure. Material loss can also be seen in Figure 11c, on the right side of the door and above the stone base (bottom left).

There does not appear to be any biological colonization, even though the climate is humid, whereas moss and lichen colonization can be observed on the roofs of nearby buildings.

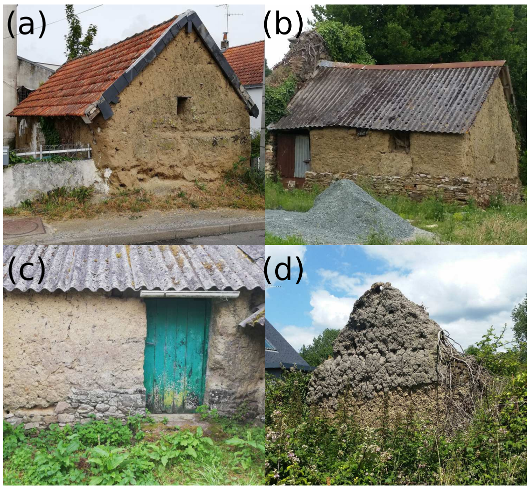

Figure 11. Examples of outbuildings, the roofs of which have been replaced with brick tiles or corrugated sheets (**a**–**c**), and an attempt to rebuild a gable with clayey material (**d**).

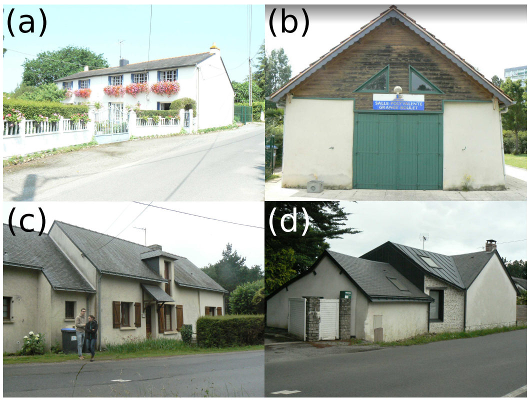

Figure 12. Examples of refurbished houses: (**a**) Chaussepot; (**b**) La Bouletterie; (**c**) Dissignac; (**d**) La Fontainte Tuaud.

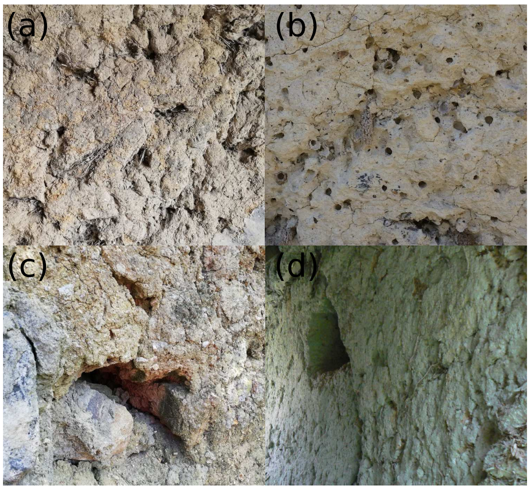

Figure 13. Close views of typical examples of earth wall surface composition. (**a**) Haut Marland; (**b**) Kervoilan; (**c**) Le Guézy; (**d**) L'Etoile du Matin.

3.4. Statistical Analysis

For each of the accessible buildings, we measured different characteristic lengths. Statistical analysis results relative to the cob buildings' wall heights (for 28 buildings) and lift heights (for 20 buildings) are presented below. The distribution functions are given in Figure 14, and the statistical parameters, in Table 3.

We can see that some of the buildings have walls as high as 600 cm. These are the habitable houses that are in a good state of preservation. However, some of the high values belong to ruins. The lower heights were all measured from ruins; 50% of the buildings have a wall height between 140 and 350 cm.

Table 3. Statistical parameters of lengths.

Parameter	Wall Height [cm]	Lift Height [cm]
Average	262	61
Standard deviation	160	10
Q1	140	50
Q2	200	56
Q3	350	62

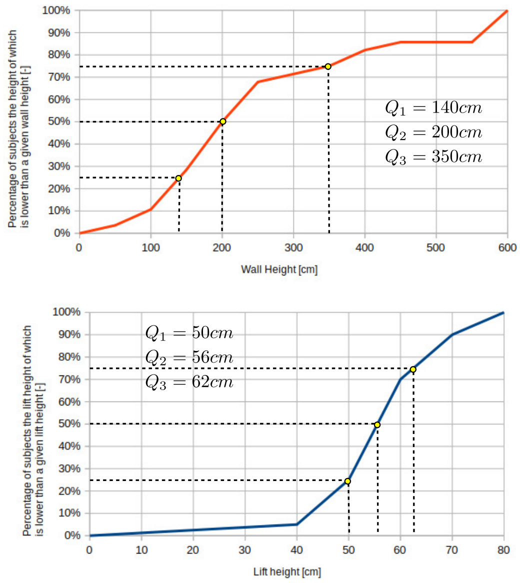

Figure 14. Statistical analysis of wall height and lift height for the different cob buildings.

The lift height varies from 40 to 80 cm, with an average value of 61 cm, which is in accordance with values available in the literature [8]. In total, 50% of the buildings present a lift height between 50 and 62 cm. The lift height can generally be correlated with the properties of the fresh earth during construction and possibly also to wall thickness. This latter parameter is not presented in this study as only a few buildings were accessible for such measurement. It would nevertheless be interesting to correlate these different pieces of information to develop knowledge around the local technical specificities of cob construction.

3.5. Correlation with Geology and Soil

The geological map of the Guérande Peninsula, depicted in Figure 15, delineates seven primary geological units, some of which encompass the following subgroups:

- Dune formations: These formations are prevalent around the Bay of La Baule, extending toward Pornichet and along the shores of La Turballe.
- Peat, clay zones, and silty sands: These geological features are situated beneath the Brière marshes and the Guérande salt marshes. Notably, the Mès marshes are distinct from this geological unit, characterized by recent alluvial deposits primarily from the Mès, the coastal river of the peninsula.
- Guérande Granite: This granite bedrock predominantly surrounds the town of Guérande. Its northern boundary spans from the Marais de Brière in the east to Piriac sur Mer in the west, while its southern border runs along the Guérande salt marshes. The Guérande Granite comprises laminated mylonitic granite in the northern region and muscovite and biotite leucogranite in the southern region.
- Vilaine formation: Positioned in the northern part of the peninsula, this formation consists of muscovite- and chlorite-bearing micaschists, potentially containing biotite, garnet, and secondary staurotide in specific sections. It is characterized by scattered quartz veins.
- Muzillac formation: Occupying the eastern part of the peninsula, this formation comprises Saint Nazaire migmatites and metatectic gneisses with biotite and sillimanite. It is situated between the Brière marshes, the granite bedrock of Guérande, the Loire estuary, and the dune formations of the Bay of La Baule.
- Saint Père en Retz massif: Predominantly composed of biotite anatexis granite, this formation is sporadically distributed on the peninsula, primarily concentrated on the

Croisic peninsula. However, it resurfaces between Pornichet and Saint Nazaire as metatexites, with occasional resurgences observed in the Muzillac formation.

- Residual Pliocene formations: Scattered in the northern region of the peninsula and interspersed within the Vilaine formations, these formations are remnants from the Pliocene epoch.

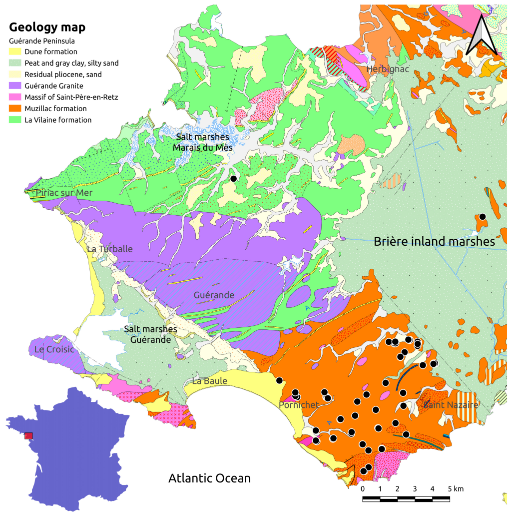

Figure 15. Geology map of the Guérande Peninsula [39].

For the moment, only the eastern part of the peninsula has been exhaustively studied. The conclusions in this section therefore relate solely to this geographical area. Further investigations will be required over the whole of the Guérande peninsula to confirm them. However, previous non-quantitative work has already pointed to a low representation of cob buildings in the eastern part, except in the northern part where we have recorded several specimens that have not been included in this study.

The prevalence of cob buildings on the Guérande Peninsula, particularly on the Muzillac formation, can be attributed to several geological and historical factors. The Muzillac formation, characterized by Saint Nazaire migmatites and metatectic gneisses, occupies the eastern part of the peninsula. This geological composition seems to play a significant role in shaping the architectural landscape of the region.

One plausible explanation for the predominance of cob buildings on the Muzillac formation is the scarcity of suitable building materials, particularly good quality stone, in this area. As highlighted in [19], the traditional construction materials available on this area of the Guérande Peninsula were often limited due to geological constraints. The lack of abundant stone resources, essential for durable and stable construction, would have prompted local builders to turn to alternative building methods utilizing readily available materials.

Furthermore, the soil depth map (Figure 16) shows that the soil depth in the area under investigation is between 30 and 50 cm. This means that the bedrock is located at a shallow depth and is therefore easily accessible. In contrast, in the area around Guérande, the soil depth is between 50 and 100 cm. In this area, however, granite stone has been used extensively for construction. It would therefore seem that the depth of the stone resource has not been an obstacle to its use. The preferential use of earth, which seems to have been common in the eastern part of the peninsula, could therefore be due to factors other than the difficulty of extracting the building material. The reason for this could be the poor quality of the building material.

Cob emerged as a practical solution in regions where stone was scarce. Its use allowed for the construction of sturdy and weather-resistant structures using locally sourced materials. Given the geological composition of the Muzillac formation, which may not have been conducive to widespread quarrying or natural stone deposits, cob construction likely became the preferred method for erecting buildings.

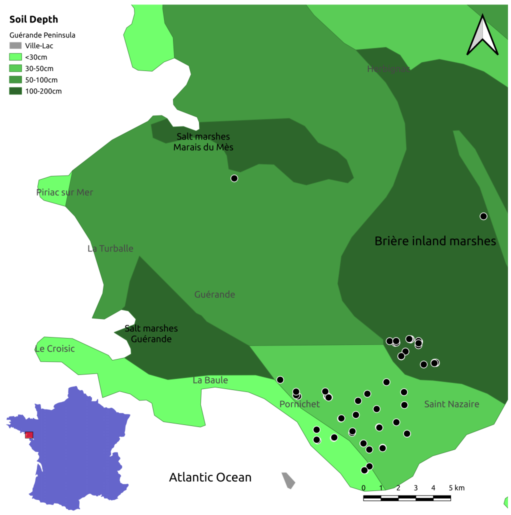

Figure 16. Soil depth of the Guérande Peninsula [40].

Furthermore, historical and cultural factors may have also influenced the prevalence of cob buildings in this region. Traditional building practices often endure due to cultural heritage and historical precedent. The presence of cob buildings on the Guérande Peninsula may reflect a long-standing tradition of earth-based construction methods, passed down through generations in response to the local geological and environmental conditions.

During our field visits, a notable encounter with a local retired farmer shed light on the geological characteristics of the area. The farmer, who had spent decades cultivating the land, shared his firsthand observations regarding the quality of the stone found in the region.

Engaged in traditional farming practices, the farmer recounted his experiences plowing the fields with a horse-drawn plow. Through years of working the land, he observed that the stone encountered during plowing was of subpar quality.

His intimate connection to the land enabled him to surmise that the stone he came across was unsuitable for construction. This firsthand narrative underscores the obstacles posed by the attributes of the Muzillac formation, which lacked the requisite quality of stone essential for construction endeavors, especially in close proximity to the surface.

Conversely, in the western part of the Guérande Peninsula, particularly in the area characterized by the Guérande Granite, a stark contrast in construction materials emerges. Here, the abundant presence of granite has facilitated the extensive utilization of this material for the construction of houses and large buildings.

The Guérande Granite, a prominent geological feature extending primarily around the town of Guérande, offers a durable and readily accessible building material.

Unlike the Muzillac formation, where cob construction prevails due to the scarcity of suitable stone resources, the abundance of granite in the western part of the peninsula has encouraged its widespread use in building' projects.

4. Discussions

The findings of this study provide valuable insights into the distribution, state of preservation, and characteristics of cob buildings in the Guérande Peninsula, and offer a broader understanding of the region's vernacular architecture and its relationship with local geology. The implications of these findings are multifaceted, touching upon cultural heritage preservation, architectural history, and regional planning.

4.1. Cob Buildings as Cultural Heritage

The identification of 46 confirmed cob buildings within the investigation area highlights the importance of this traditional construction method in the region's architectural heritage. Cob buildings are an integral part of the local cultural landscape, representing a building tradition that has been largely overlooked in historical surveys of the area. The fact that these structures are predominantly found in less urbanized zones, such as the northeast (Marais des Aurielles and Le Petit Marsac) and southwest (Saint Sébastien, Chaussepot, and Le Guézy), suggests that rural areas have served as refuges for these older, vernacular buildings. This spatial distribution underscores the need for targeted conservation efforts in rural regions, where the pressure from urban development is less intense, but where cultural heritage is equally vulnerable due to neglect or lack of awareness.

Until now, there has been a lack of quantitative studies focusing on earth buildings, which represent a distinctive architectural feature in certain areas of the peninsula. This architectural signature has been largely overshadowed by conservation efforts that have primarily focused on preserving reed-thatched buildings. As a result, earth construction, an important yet underappreciated aspect of the region's architectural heritage, has remained relatively unknown and undervalued.

This study addresses this gap by providing a systematic analysis of earth buildings, thus shedding light on a significant but neglected aspect of vernacular construction. By highlighting the historical and architectural importance of these structures, the research aims to enhance their recognition and appreciation, ultimately contributing to a more comprehensive understanding of the region's architectural heritage.

4.2. Challenges in Identification and Preservation

The methodology employed to identify hamlets likely containing earth buildings involves several key steps. Initially, historical maps from 1850 were used to locate hamlets that existed during that period. These data were then cross-referenced with information on land use and traditional construction materials in the region.

However, this methodology has notable limitations. Firstly, it identifies hamlets where earth buildings might potentially be found, but it does not allow for the specific identification of earth buildings themselves. The hamlets identified on the 1850 maps encompass various types of constructions without providing explicit information about the building materials, whether they are made of earth or otherwise. It is also possible that earth buildings were constructed after 1850 and therefore would not be reflected in the historical maps used for this study. Such more recent constructions would not be identified by our methodology based on historical maps.

Furthermore, the 1850 maps represent a snapshot of that time and do not ensure that the buildings present then still exist today. Some buildings may have disappeared since, and there is no indication that the structures shown on these maps were necessarily built with earth. It is important to note that the quantitative analyses conducted during this survey are inherently biased, as they are based only on buildings that are both still existing and accessible. The statistics reflect only those earth buildings that remain standing and have been reachable for inspection, potentially overlooking structures that have already disappeared or are inaccessible. Consequently, the findings may not fully represent the historical prevalence and distribution of earth construction in the investigated region.

Moreover, as previously mentioned, identifying earth buildings can be challenging, particularly when it is conducted without invasive probing or sampling techniques. This difficulty arises because earth construction may be obscured by later modifications, such as plaster or other surface treatments. For example, Figure 17 illustrates a case where earth materials were discovered during the renovation of a stone building. Specifically, after removing part of the façade, earth elements were revealed beneath the outer layer.

This underscores the fact that earth construction can be hidden beneath external coatings, making it nearly impossible to identify through visual inspection alone. This particular instance is noteworthy as it reveals that the earth component appears to have been introduced during a previous renovation of a building originally constructed from stone. Such findings not only highlight the challenge of detecting earth construction but also offer insights into historical building practices and modifications over time.

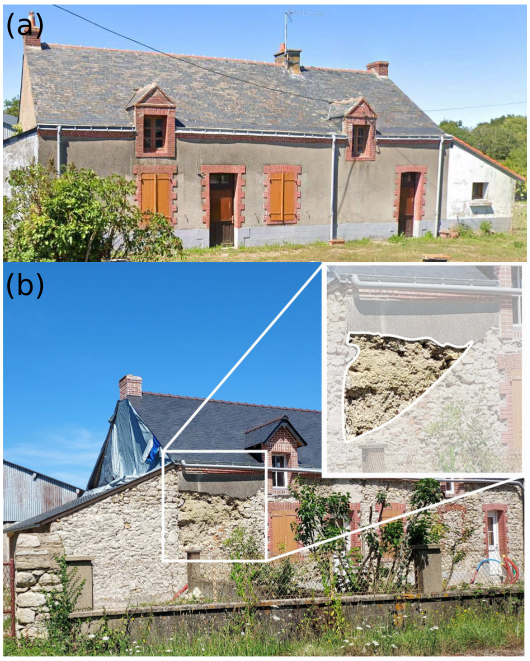

Figure 17. Example of a house before (**a**) and during (**b**) the renovation of the external coating showing an unexpected cob part.

4.3. State of Preservation and Maintenance Practices

The state of the preservation of the identified cob buildings varies widely, from ruins to habitable dwellings. The fact that 63% of the identified buildings are in a good state of preservation, with 11% still in use as permanent residences, is encouraging. However, this study notes that many of these buildings have undergone alterations, such as roof replacements and partial reconstruction using modern materials like concrete blocks. While these modifications may have been necessary for the continued use of the buildings, they also raise questions about the long-term impact on the structural integrity and authenticity of the cob structures. The examples of attempted repairs using unsuitable materials, such as the use of Brière blue clay for gable reconstruction, highlight the importance of using appropriate materials and techniques in the conservation of cob buildings.

Especially, it is important to note that there can be significant incompatibility between the original materials used in earth buildings and the modern materials employed during renovations. This incompatibility often stems from differences in the hygroscopic and thermal behavior of the materials within a given climatic environment. For instance, the application of inappropriate coatings or renders can create issues such as the development of a dew point within the wall assembly. This can lead to condensation, which, when interacting with unbound earth materials, results in increased moisture content.

The consequence of this moisture accumulation can be severe. Excessive dampness can compromise the structural integrity of the earth components, leading to a loss of load-bearing capacity and, eventually, the potential collapse of the structure. The proper understanding and consideration of the material properties and environmental conditions are essential to ensure that renovations do not inadvertently exacerbate the degradation of historic earth buildings. It is crucial to select renovation materials and techniques that are compatible with the original construction to preserve the building's structural integrity and historical value.

Additionally, structural issues can arise in earth buildings even when no direct intervention has been carried out on the building itself, but rather in its vicinity. For instance, urban renovation cycles, particularly those involving roads and sidewalks, can lead to an elevation of the ground level, which may alter the effectiveness of the building's lower protection against capillary rise or water splashing. These renovations can also change the properties of the surface coating, potentially creating a barrier that prevents water infiltration or the evaporation of ground moisture. Such changes in the boundary conditions of the earthen wall can impact the movement and diffusion of water near or beneath the wall.

4.4. Correlation with Geology and Soil

The correlation between the location of cob buildings and the geological map of the Guérande Peninsula offers interesting insights into the historical relationship between local building practices and the natural environment. The presence of cob buildings in areas with specific geological features, such as the peat and clay zones of the Brière marshes, suggests that the availability of suitable earth materials played a significant role in the development of cob construction in these regions. This finding aligns with the broader understanding that vernacular architecture is often closely tied to the local environment, both in terms of available materials and the adaptation of building techniques to local climatic and soil conditions.

However, an extensive study covering the entire Guérande Peninsula would be valuable in determining whether the distribution of earth buildings is indeed correlated with local geological conditions. While preliminary observations suggest that geological factors might play a role, it is clear that they are not the sole determinants. Within the study area, one can find both historic earth buildings and structures constructed from stone.

The reasons behind the choice of earth as a construction material remain unclear and are likely influenced by a combination of factors. Historical, economic, and cultural considerations may have all contributed to the decision to use earth in certain contexts. Therefore, it is challenging to fully elucidate the specific motivations behind the use of this material without a more comprehensive investigation.

4.5. Implications for Future Research and Conservation

This study contributes to the broader effort to rediscover and promote earth construction at a regional level. It has led to the creation of an inventory identifying potential locations for earth buildings and analyzing historical data. This work aids in the renovation and preservation of these traditional structures and supports the integration of earth materials into modern construction practices.

This research has also been valuable in educating students from various disciplines about earth construction. This engagement helps students understand the relevance and potential of these techniques in contemporary architecture.

Participation in this research has enhanced the knowledge and skills of local builders, especially the two co-authors of this article, who are now key experts in earth construction in the Guérande Peninsula. While difficult to measure scientifically, the increase in their expertise has likely led to more renovation and new construction projects in the region.

Institutional support for earth building has been strengthened by this research. The *Parc Naturel Régional (PNR) de Brière* has played a significant role in promoting earth construction through its involvement in the *Adème's* Local and Circular Economy Action Plan, titled *"Valorisation des filières biosourcées et du patrimoine bâti, 2023–2025"* (Promotion of Bio-based Sectors and Built Heritage, 2023–2025). This initiative includes creating an inventory of qualified local craftspeople, including earth builders, to assist self-builders and renovators.

In this context, *Terre Crue Presqu'île* (https://www.facebook.com/profile.php?id=100057401712986, accessed on 15 August 2024) is an important grassroots collective that has been active since 2017. Supported by the findings of this research, this collective has helped local artisans with tangible building projects and increased awareness of earth construction in the community. The collaboration between academic research and initiatives like *Terre Crue Presqu'île* demonstrates the practical applications of traditional building techniques.

Additionally, awareness-raising activities have been launched to promote local, natural materials, particularly earth, to both the local community and professionals. Proposals for future actions based on these findings will be published in the final quarter of 2024.

Despite these advances, challenges remain, particularly regarding regulatory recognition. Currently, regulations limit earth materials to non-load-bearing elements, restricting their use in structural components. Addressing these regulatory barriers is necessary to fully utilize earth construction and encourage its broader adoption in modern building practices.

This work advances the understanding of earth construction and sets the stage for future efforts to integrate these materials into contemporary architecture and overcome existing regulatory constraints.

5. Conclusions

The cob heritage in the Guerande Peninsula is still present but disappearing, and could vanish rapidly if people are not aware of the interest in this vernacular architecture. As a result of this research, the cartography of a centuries-old architectural culture is beginning to emerge. In recent decades, local institutions have carried out important work to protect the thatched cottages in the peninsula, as these vernacular buildings bear witness to local skills and ways of life. A similar approach could help to protect local cob heritage, and, in doing so, also highlight its many lessons for sustainable building practices today.

The prevalence of cob architecture in the Guérande Peninsula, particularly within the confines of the Muzillac formation, can be attributed to its geological composition, characterized by Saint Nazaire migmatites and metatectic gneisses in the eastern region. Cob construction emerged as a pragmatic solution in locales where premium-grade stone resources were scarce, propelled by the limited availability of conventional construction materials, particularly quality stone, due to geological constraints. Socio-cultural factors, including historical precedents and indigenous building practices, played a pivotal role in perpetuating cob construction as a favored architectural modality in the eastern part of the Guérande Peninsula.

In terms of methodology and statistical analysis, this study employed a comprehensive approach combining fieldwork, geographical information system (GIS) analysis, and statistical techniques to elucidate the distribution and characteristics of cob buildings in the Guérande Peninsula. The field investigation allowed us to confirm the validity of the technique and to gather complementary pieces of information relative to the buildings (type, state of preservation, wall height, lift height, etc). The analysis of the results using the software QGIS allowed us to show that the cob buildings are located in poorly populated rural areas where the real estate pressure is low compared to the neighboring towns. The buildings identified are mainly in a good state of preservation and used as outbuildings and, in some cases, dwellings. To date, we have also identified cob buildings in other parts of the peninsula, via different approaches. In future research, we intend to apply the technique described in this article to analyze the other parts of the peninsula and verify whether the areas around the medieval city of Guérande contain cob buildings.

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