THE USE OF EARTH AS A RECONSTRUCTION MATERIAL: A CASE STUDY IN ITALY.

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ABSTRACT

Even if earthen buildings are not widely diffused in Italy, they represent an important heritage characterizing some rural regions and sites, in particular in the South. Since World War II, technical knowledge about these constructions has been progressively forgotten. The main reasons for this are the introduction of new materials (mainly reinforced concrete) and a cultural resistance to a kind of architecture judged as poor and worthless. However, in the last decades, the research community has become more and more interested in this ancient technique.

The object of the this present paper is the use of earth as a material for the reconstruction and the integration of ancient existing historical centres. In particular, the study is concentrated on Balestrino (SV), a small village made of stone masonry, currently being subjected to a rehabilitation project as it has been abandoned and in ruin. The choice of earth is motivated by different reasons: the easiness in shaping this material, in particular the connection with existing structures, its physical and mechanical compatibility and its ability to blend in with the environment. In fact, its colour and material matches perfectly the environment, since the earth is excavated directly in the construction area. It is worth noting that this solution allows us to exploit the natural resources of the site.

The paper presents a study of the structural behaviour of the earthen constructions, analysing both the interaction between the existing and new structures and their seismic performance. Finally, a mechanical characterization of the material through experimental tests is presented.

1. BALESTRINO: CONSTRUCTION HISTORY AND DAMAGE CONDITION

Balestrino (SV- Italia) is a medieval village (Figure1), presently abandoned. Its building heritage is characterized by a complex history. Today, it presents heavy and diffused structural damages.

Figure 1: The village of Balestrino (SV-ITALY)

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The long-time static precariousness of the village is exemplified not only by a number of ancient written documents which report the collapse risk of buildings, but also by the existence of ancient retrofitting interventions, such as spurs (Figure 2, on the left) and wall thickenings (Figure 2, on the right). Such precariousness depends on different causes.
In the first place, the intrinsic building characteristics of the village are to be considered. The structures, usually of poor quality, are completely made of stone masonry jointed with large quantities of mortar. The floors are constituted by vaults, which can be seen even at the top of the construction. This feature is derived by the shortage of building wood, which, for centuries, has been exclusively owned by the Lords of the village.

Figure 2: Spurs (on the left) and wall thickenings (on the right).

In the second place, the village suffered from the earthquakes that hit the North-West coast of Italy during XIX century. In particular, the earthquake of 1887 (magnitude 6.7) destroyed some villages of the area. Although there are not historical damage surveys of Balestrino, some documents report that some repairing interventions were made after this seismic event.
Finally, the area where the village was built has for a long time been subjected to hydro geological problems. These were the reasons for the abandonment in 1953. In that year, in fact, the Civil Engineers declared the structural unsafety of the village and ordered the inhabitants to move out and destroy their houses. The houses, luckily, were not demolished, but from then on the village has suffered a progressive degradation.
Today, the abandonment is probably the main cause of the static precariousness of the buildings.
The lack of maintenance of the constructions, in particular of the roofs, has led to immense degradation of masonry structures. Deprived of the standard water protection systems, the masonry has been subjected to a continuous wash out of the rain-water; this phenomenon has produced a diffused shattering of the mortar joints and, in multi-leaf walls, of the inside filling (Figure3, left). The imbibition of the walls has been increased by the low quality of the materials and of the masonry pattern.
The degradation of the walls has also been also favoured by the growth of vegetation (Figure 3, right), in particular on the terraces where the rain-water stagnates. The penetration of the roots produces, in some case, the shattering of the underlying vaults.

Figure 3: Masonry shattering (on the left) and internal collapses with vegetation growth (on the right).

The presence of thrusting structures even at the top floors, on one side, and the progressive loss of the floors, on the other side, has caused the walls to be visibly inclined (Figure 4, on the left). In some case, it is possible to find broken or unanchored tie-rods.
An instability phenomenon can be observed, in particular, in the church of S.Andrea. Its back is subjected to a strong settlement; nearly vertical cracks, some centimetres large, run from the bottom upwards on the lateral walls.
Finally, in the fronts of the buildings, many buckling phenomena are present. Shear cracks in the lintels, associated to a loss of squareness of the windows, can be noticed (Figure 4, on the right).
The structural damages involve, actually, more than 30% of the constructions. In some cases the buildings suffered internal collapses, until the complete emptying of the building volume. In other cases, the degradation is almost irreversible and the complete collapse has been reached.

Figure 4: Inclination of the external walls (on the left); local buckling of the lintels (on the right).

The reasons for the abandonment in 1953, today, appear partially unjustified (the strong building rush of the post-war period played a decisive role). On the one side, the abandonment created the degradation of the buildings, while on the other side it guaranteed the preservation of the original features of the constructions, which have not been subjected to the typical transformations of many Italian historical centres. This feature is particularly meaningful for the history of the village.
Now, Balestrino is the object of a complex restoration plan. A strong interest for the conservation of the historic centre and landscapes originated in Italy in the 1980's, this was punctuated by the revocation of the decree of the Civil Engineers in 1989. The village will be considered 'safe' if adequate retrofitting interventions and reconstructions will be realized.

2. RECONSTRUCTION PLAN AND USE OF THE RAW EARTH

The recovery design of Balestrino village is expected to resemble the pre-existent urban buildings from the year of abandonment in 1953; it will be obtained through the consolidation of structures, the integration of the collapsing parts and the reconstruction of the lost buildings. In particular, the recoverable volumetric entity is 44000 m^3 and the area needs to be reconstructed is 1800 m^2. The possibility of the reconstruction of pre-existent parts of village arises from the historical papers, and also from large photographical and cadastral the documents. It is observable from these papers that the buildings' collapse started in 1980. Moreover, a wide research about constructive technologies permits us to known the principal characteristic of the buildings.

The chosen material for the reconstruction is the raw earth, through the *pisè* technique. Both the material and the constructive technology are not traditional for this geographical area [Bertagnin, 1999], which is instead characterized by stone masonry with or without mortar. The reasons for this preference are various [Bertagnin et al., 2002; Morel et al., 2001].

In the first place, there is a methodological reason. Frequently the choice of the material for reconstruction and reintegration is critical, because its use must be suitable with existent structures. In general, there can be two ways: one, is the blending of the new structures with the existent ones, using historical materials and constructive techniques; while the other distinguishes between existent and new constructions, using different materials belonging to the modern architecture. In the first case, the irreversible loss of the original constructive culture frequently conducts to a mere simulation of the original material and techniques. In rare cases, even if the imitation is successful, there is still doubt that the reconstruction is historically inaccurate. In the second case, the type of intervention is implicit; however, the risk is the incompatibility between existent and new structures, both from the environmental, visual, chemical–physical and mechanical point of view. The choice about the *pisè*, a non traditional technique for the area, follows this second point. However, for different reasons, it assures optimal compatibility.

If the earth is excavated in the reconstruction area, it is a material that harmonizes with the landscape, because it reproduces its colour and aspect. Moreover, it is a natural material, that has a good physical-chemical compatibility with the stones of the existent buildings. From the mechanical point of view, its compatibility still needs to be verified, even if, from the first evaluations, it appears good. In general, preliminary tests have permitted us to verify that the earth present in Balestrino is fit for the reconstruction by the pisè technique.

The pisè is a material extremely simple to mould, able to adapt to irregular forms. This feature is fundamental in the recovery plan. Besides the ex-novo reconstruction of the collapsed buildings, it also previews the rebuilding and integration of the buildings' parts. It is useful to have a material that can be adaptable to irregular forms of the buildings in ruin; in Figure 5 can be seen a simulation of the earth integration (on the left of building).

Finally, the raw earth is a ecological material, because it does not undergo the transformation processes and its extraction in the reconstruction area and transport have a low environmental impact. Besides these advantages, it is clear that there are different problems about the use of earth for reconstruction and integration. In the first place, it is necessary to verify its mechanical compatibility with existent structures, not only for a short time, but also for a long period. In fact, it is necessary to consider that the existent masonry elements have been subjected to deformation and tensional history, while the pisè is a new material that must still subjected to this process.

Figure 5: Example of integration with existent structure.

In the second place, the constructive technique of the pisè previews the beating of the earth through manual and mechanical tools. It is necessary to verify that the beating does not produce damages or excessive vibrations to the existent masonry. In particular these actions can be dangerous because the original masonry is multi-leaf (in general two external leaf are made of stone, while the internal is constituted with incoherent material) and it is greatly degraded. If the two external leaves are not well connected, the risk is that it could create a degradation of the walls and collapse due to instability. Finally, it is necessary to verify the seismic behaviour of the buildings that will be subjected to integration. In fact, the interaction between two constructive systems (stone masonry and pisè) is not clear. Besides the evaluation of the relative stiffness between the two systems, the constructive point of view of the connections must be studied.

3. DEFINITION OF THE MATERIAL

The preliminary tests are carried out with the composition of the earth, the geotechnical and mechanical properties, which will be used for the reconstruction of the village. The material has been excavated directly from the reconstruction area, 30 cm deep, in order to avoid the use of a material containing organic substances or which have a low mechanical resistance [Narici et al., 2001]. In this particular case study there are two layers considered on different depths: the first is situated at 1.5 m (earth A); the second is situated at 3 m (earth B).

3.1 Identification of the earth

The parameters that allow has to understand the behaviour of the earth are: the amount and quality of the contained clay in the earth sample [Briccoli et al., 2002, CRATerre, 2000; Narici et al., 2001; Raviolo,1993; Storelli, 1994].

The granulometry analysis for sifting and the sedimentation have been carried out to identify the first parameter [Raviolo, 1993]. The first step is limited to a coarse fraction of earth, that is the percentage withheld from the sieve number 200 (the dimensions of the grains is greater than 0.074 mm). The sedimentation analysis is used to check the remaining part of material (aerometry). The results of the analysis are represented on the diagram, where on the *x* axis there is the size of grains passing through the sieve (logarithmic scale), and, on the *y* axis, there is the percentage of the quantity of grains passing through the sieve. It is observable that the more the granulometry curve is next to the vertical, the more the composition is homogeneous and less graduated. This feature is described through the evaluation of the uniformity coefficient C_{60} (ratio between the diameter correspondent to passing 60% and the diameter correspondent to passing 10%)[Lancellotta, 1993].

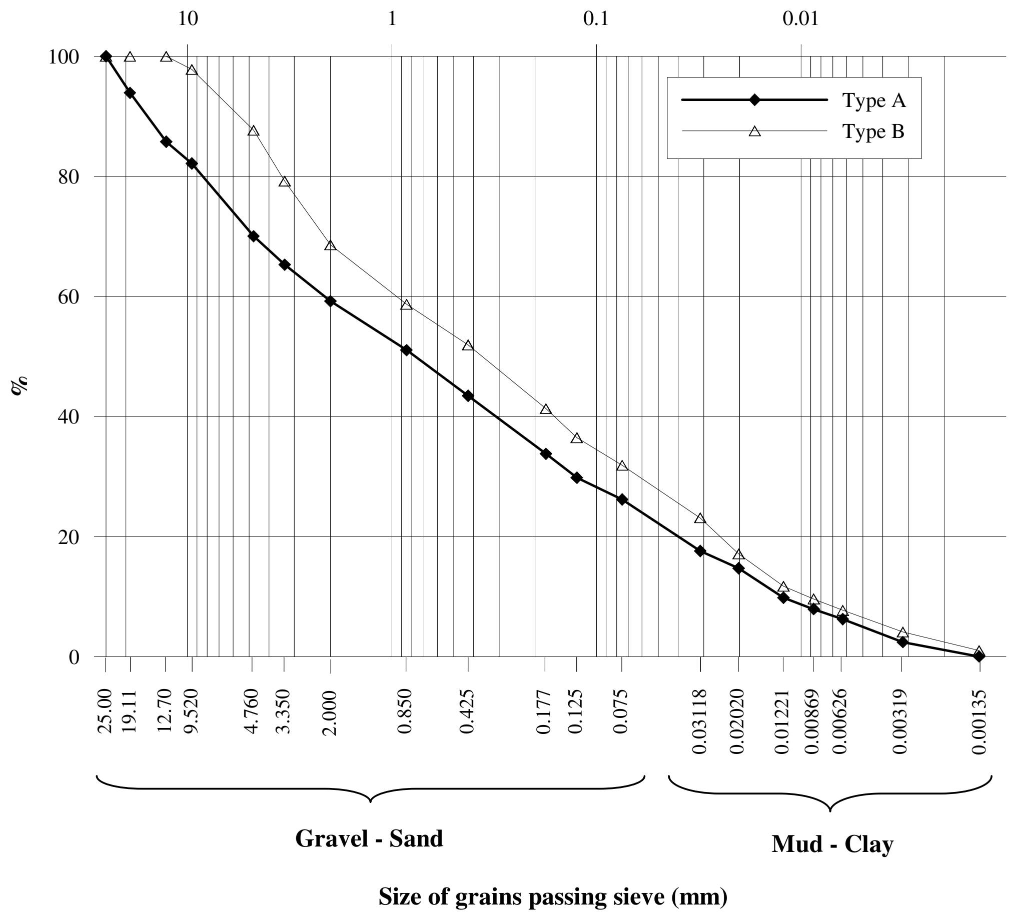

Figure 6: Grain size of earth used in this study.

From the diagram in Figure 6, which is relative to the obtained granulometry curve found by sifting, it is observable that the percentage of the quantity of grains passing through sieve ASTM 200 is similar for A and B; it is equal to 30% of the overall weight. Therefore, the evaluation of the sedimentation curve is justified. The earth A presents larger grains than B. They have a higher clay amount. The sedimentation curve underlines the fact that the earth used has a high mud amount; for this reason, in the paste of the pisè, it will be necessary to add 5% of lime, to improve the quality of the material.

In order to recognize the quality of the clay and the behaviour of the earth in presence of water, there are various tests available. These include: the diffraction analysis of X-rays; the test by the methylene blue [CRATerre, 2000; Chiappone et al., 1987], used in France and included in the standard tests for the selection of the inert destined for the road construction and the determination of the index of plasticity (I_P) and of the Skempton's index of activity, (I_s) through the determination of the Atterberg's limits [ASTM, 1984; CNR, 1964; Raviolo, 1993]. These limits are based on the concept that the clay can exist in one of the four states (solid, semi – solid, plastic, liquid) depending on the water quantity. Table 1 shows, for the two types of earth (A and B), the values of Atterberg's limits obtained through lab tests and the uniformity coefficient (C_{60}) obtained from granulometry curve.

Table 1: Geotechnical characteristics of the tests of earth.

Sample	γ_s (kg/m^3)	γ (kg/m^3)	Liquid Limit	Plastic Limit	I_p	C_{60}
Earth A	2750	1824	35.9	26.6	9.3	163.8 (No Uniform)
Earth B	2770	1912	37.6	27.9	9.8	96.1 (No Uniform)

It is observable that the two earth samples have similar geotechnical characteristics; in fact, both are clayey earths, not much plastic (the plasticity index is in a range from 5 to 15), active (the Skempton's index of activity is higher than 1.25) and extremely heterogeneous.
In conclusion, the density of the solid part of the earth and the one relative to the overall volume have been estimated and they have presented similar values.

3.2 Eevaluation of mechanical propreties

The evaluation of mechanical properties of the construction material has been carried out on a set of samples of raw earth, stabilized with 5% of lime [Narici et al., 2001] and cured for four months. Their dimensions are: 12 cm x 12 cm x 40 cm. These samples have been subjected to a test of bending in control of forces on three points, with various loading and unloading cycles. The force has been applied perpendicular to the beating surface.
Subsequently, from the bending tests, cubic samples have been obtained (the dimensions are: 12 cm x 12 cm x 12 cm); on such cubic samples monoaxial compression tests have been conducted in control of force, applying also in this case loading and unloading cycles. In Table 2, the results of the experimental tests are shown.

Table 2: Mechanical characteristic of earth samples.

Sample	σ_f (kg/cm^2)	σ_c (kg/cm^2)	σ_c / σ_f
1A	1.94	11.25	5.8
2A	2.19	9.03	4.1
		8.75	4.0
3A	2.72	8.61	3.2
2B	3.92	16.67	4.3
		18.75	4.8
3B	2.25	13.40	6.0
4B	3.83	15.56	4.1

From the results obtained, it is observable that Balestrino's earth is suitable for the reconstruction through the technique of pisè. The ratio between the compressive and bending strengths is comparable with these present in literature [Narici et al., 2001]. The compressive strength is only slightly below average. The reason for this discrepancy can be attributed to various factors, such as: the different water quantity, the present humidity and the different beating energy of the earth. Moreover, it has to be considered that the resistances are relative to disturbed samples, obtained from the bending tests.
However, the compressive strength could have been influenced from a confinement effect, as a consequence of the compact samples. In the future, other tests will be executed on undisturbed samples with the correct slenderness (1:2). Comparing the obtained results for the earths A and B, it is observed that earth B presents better characteristics in terms of resistance. The reason could be attributed to the different water entity amount in the mixtures. In Figures 7 and 8, the diagrams about the compression and bending tests are shown respectively, in terms of tension –

deformation and loading – displacement. In particular, it is observable that the bending graphic presents a hardening phenomenon, due to the sample's compaction.

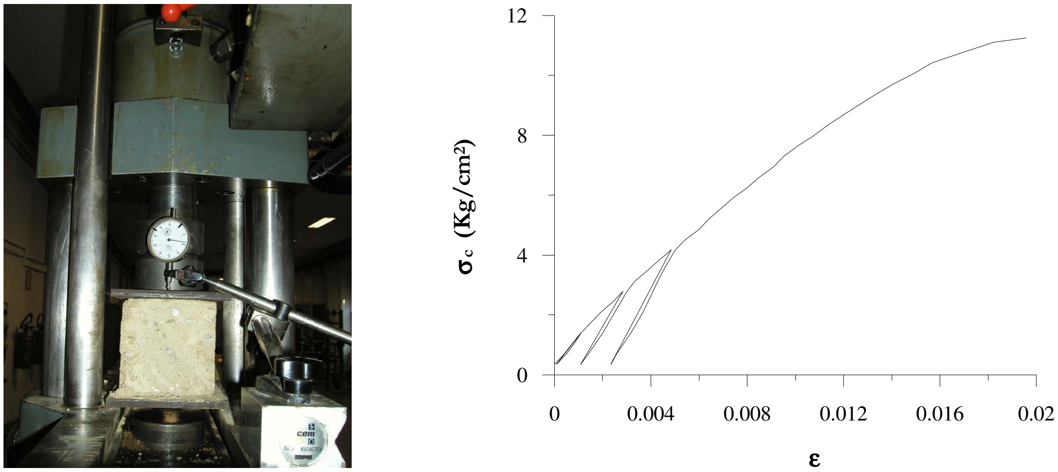

Figure 7: Test of compression (on the left); Diagram of tension – deformation of the earth A (on the right).

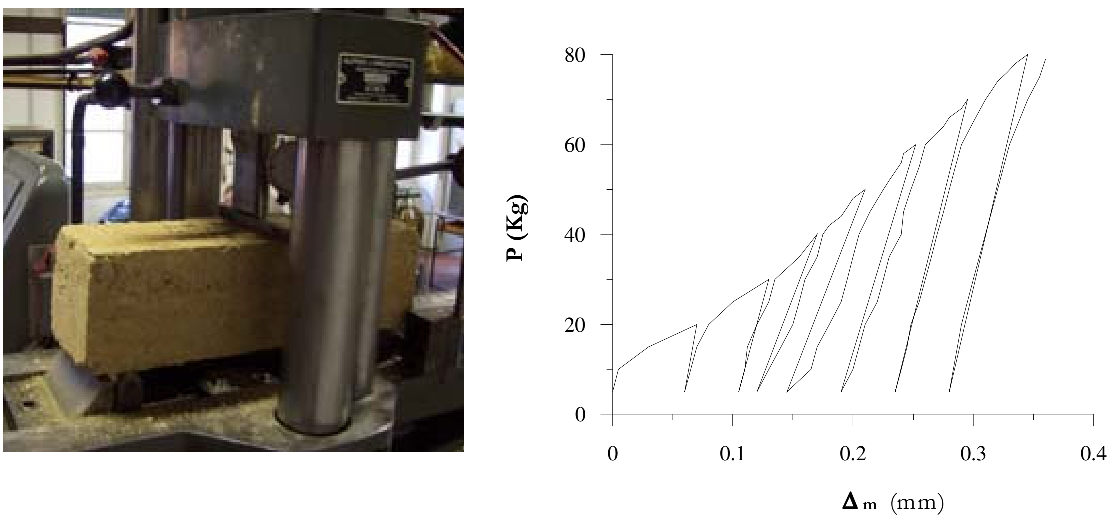

Figure 8: Bending test (on the left); Diagram loaded – displacement of the earth A (on the right).

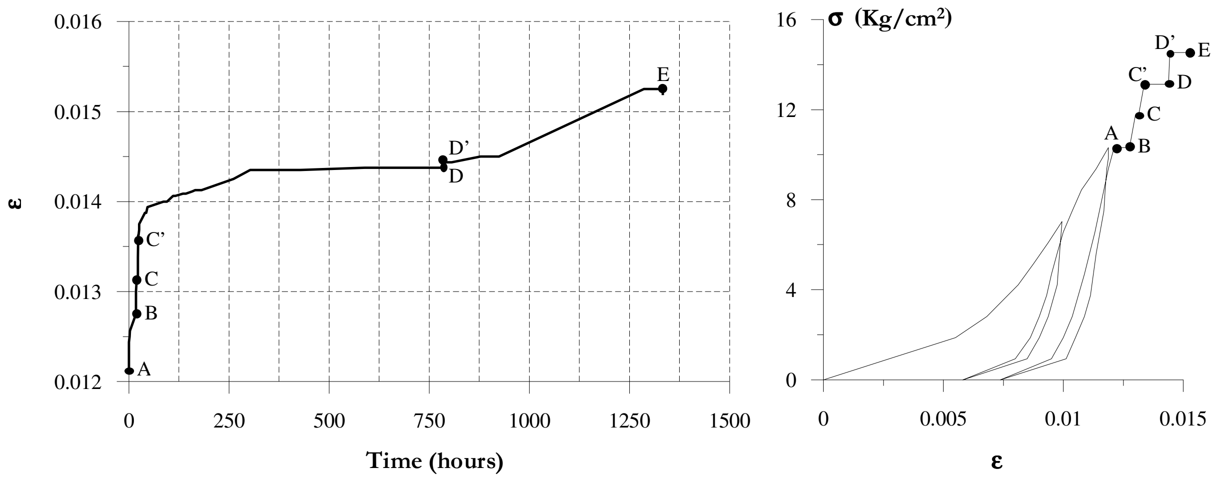

Figure 9: Evaluation of deformation in the time(on the left); diagram tension - deformation (on the right).

To discover the mechanical compatibility of pisè with the existent masonry, a creep test was perform on a cubical sample; its dimensions were 8 cm x 8 cm x 8 cm. The scope is to evaluate the deformation of the earth subjected to load constant in time. Two contributes of deformation are to be considered: the instantaneous one (ε_i) and the long period one (ε_t).

The variation in time of the deformation (on the left) and the relative curve of tension – deformation (on the right), are represented in Figure 9. Initially, the sample was subjected to instantaneous loading and unloading cycles; when the load reached the 70% of the compressive strength (point A), it began the creep test. In the first line of diagram it can e observed that line A-B is constant and the deformation had a modest increase in time. When the deformation reached a constant value, the load was increased (in the point B and C). After the application of the load in C, there was a instantaneous deformation ε_i (line C-C') and then, an evident increase of the deformation ε_t (line C'-D). After another increase of the applied load (point D), there was a small instantaneous deformation (line D-D'); after many hours, the sample had an important long term deformation until it arrived at E point. It is observable that the increase of the applied load was constant.

4. INTERVENTIONS PROPOSAL

The recovery of Balestrino is a complex and difficult due to the fact that there is not a clear normative design. The recovery plan previews different degrees of interventions, including the strengthening of the existing masonry structures, the reconstruction, and the integration through the technique of the pisè. This ambivalence of the intervention means the combined use of different codes, for example, the ones for the retrofitting of masonry structures and the ones for the raw earth constructions.

The first is recognizable partially in the recently issued Code 3274/2003 *"Criteri per la classificazione sismica del territorio nazionale"*. For the earth buildings the national code does not yet exist, even if there is a bill code: n°2374/2002: "*Modifiche alla legge n° 64 del 2 Febbraio 1974, recante i provvedimenti con particolari prescrizioni per le zone sismiche"* .

The complexity of the recovery plan requires the presentation of a special code to the Ministry of Public Works; in particular, the type of interventions and the correct techniques of reconstruction have to be presented, in observance with the seismic code. This proposal could be the basis for the national code that would considers the use of the earth as a material for the reconstruction in small masonry villages.

From the technical and structural point of view, the problems are of various nature. It is necessary to consider the reconstruction of existing masonry buildings [Mastrodicasa, 1993], the definition of connection systems between masonry structures and pisè construction, and the new pisè buildings. In particular, the reconstruction of existent structures do not have to applied only to still functional buildings, but also to those ruined. The latter, will support the new pisè structures. On first analysis, on the basis of the specific type of damages of the village, it will be necessary to define suitable interventions appropriate to the local environment. As it has been showed previously, the principal type of structural disease is the inflexion masonry leaves, associated with the washing away of inside filling. The possible solution could be the insertion of transversal element made of conglomerate reinforced with metallic or FRP bars (*diatoni artificiali*) in log holes. This technique would ensure the effective transversal connection between the two external leaves of masonry. This solution, moreover, prevents instability phenomena and would give a monolithic behaviour to the wall regarding to the orthogonal forces. The masonry structures would be reinforced and its structural original behaviour wouldn't change. This technique can be used also on low quality masonry, because it does not produce damages during the execution (Figure 10, on the left). This solution represents a technical system functional to the following introduction of the earth structure. In fact, the intervention guarantees a monolithic behaviour of the masonry walls and prevents instability.

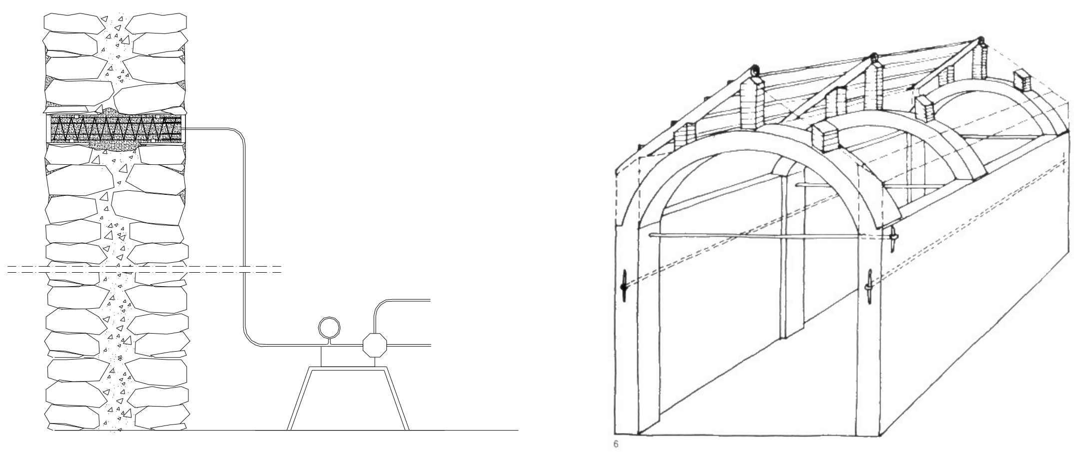

Figure 10: Insert of the *diatono artificiale* in the masonry width (on the left); insert of the tie-rod down the arch (on the right).

Another type of instability is the overturning of vertical elements, due to the presence of thrusting structures or to a scarce connection of orthogonal walls. To contrast the first phenomenon it's possible to use tie-rods (Figure 10, on the right). As a rule, tie-rods will be situated on arches' reins. If it couldn't be possible this disposition, tie-rods could be placed on different levels, on condition that it could be demonstrated the effectiveness of that remedy in containing the thrust. These structural elements must have a suitable stiffness (if possible, big diameter and limited length bars are favourites); tie-rods must be pre-stressed by suitable forces, avoiding extreme values that could create local damages.
As far as scarce wall connections are concerned, a possible solution could be the insertion of metallic tie-rods. It has to be considered that sometimes, the building perimeter is not complete, and therefore, an earth structure has to be inserted. In this case, it is necessary that the tie-rod is placed within the masonry and earthen structures, in order to guarantee a monolithic box behaviour of the construction, useful in case of a seismic action. Finally, the tensile force of the tie-rod has to be suitable with the admissible stress of the raw earth structure.

CONCLUSION

In this paper the use of earth as a possible reconstruction material in small masonry villages typical of Ligurian architecture is discussed. In particular, the ancient village of Balestrino, which has already subjected to a municipal recovery plan, is considered. The objective of this plan is to reconstruct the collapsed parts of the village and to retrofit the remaining buildings. In order to use the local earth for the reconstruction interventions, preliminary tests for the identification of the geotechnical and mechanical properties of the material were done. Tests revealed a suitable structural behaviour of the earth in terms of compressive and bending strength. The obtained values are consistent with those present in literature. It has to be pointed out that the tests were not standard [CRATerre, 2000; Narici et al., 2001]. Considering the integration of the earth structure with the masonry, the creep test is presented, as it defines the sample's deformation over time. Finally, possible consolidation involvements in the case of the recovery of a masonry village, situated in seismic zone, through pisè technique are presented.

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