Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 44 (2020) 92–99

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

1st International Conference on Optimization-Driven Architectural Design (OPTARCH 2019)

Fujian Tulou Rammed Earth Structures: Optimizing Restoration Techniques Through Participatory Design and Collective Practices

Evangelia Frangedaki[1]*, Xihong Gao[2], Nikos D. Lagaros[3], Bruno Briseghella[4], Giuseppe Carlo Marano[4,5], G.-Fivos Sargentis[3], Nikiforos Meimaroglou[3]

[1]*School of Architecture, National Technical University of Athens, 42 Patision street, 10682 Athens,Greece*
[2]*Department of Architecture, Fuzhou University, Fuzhou, China*
[3]*School of Civil Engineering, National Technical University of Athens, 9, Heroon Polytechniou,15780, Zografou, Greece*
[4]*College of Civil Engineering, Fuzhou University, Fuzhou 350108, Fujian, China*
[5]*Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy*

Abstract

Fujian Tulou is a significant part of the international built heritage. Renovation and strengthening of existing Haka Tulou's earth constructions can ensure a better quality of life for their residents, as well as contribute to a long-lasting prominence of China's heritage. Previous studies of Fujian Tulou mainly cover habitation patterns, construction features and architectural details. In this research a layout has been summarized of causes of deterioration, pathology of structure, focused on the buildings' conservation value and restoration, in terms of history, culture and construction technologies. Out of Fujian's more than 3,000 Tulou, only a few dozen have been awarded the status of World Heritage Sites by UNESCO. Along with that status, the 46 buildings chosen for the award. The buildings which belong to UNESCO's heritage are on list of possible restoration while the rest remain in disintegration and the villages are getting vacant through years. The answer for the restoration could be found through participation and team work of experts and habitants. A Tulou is usually inhabited by one family clan for several generations, and the enclosed structure allows to the members of the community to work together and participate in a common goal.Therefore, it is necessary to find new intervention techniques for these earthen buildings, or to adapt those already existing —and proved— to the specific characteristics of the material. This is the context in which the present research aims at contributing to the development of grouting and stitching the cracks by means of earthen mortar in rammed earth walls, as collective restoration techniques.

*Keywords:*rammed earth, earth mortars, mud grouts, renovation with locals,renovation with natural materials,Fujian Tulou

* Corresponding author. Tel.: +30 6947 830840
E-mail address: evif@central.ntua.gr

10.1016/j.promfg.2020.02.209

1. Introduction

1.1. The earth as a building material

Earth is the most abundant, locally available, cheapest and lowest energy input impact materials it is possible to build with.The energy required to dig up and treat sufficient earth for a house, was all provided by humans and animals. Nowadays, mechanical extraction and mixing is the more likely method, but assuming the earth is sourced fairly locally to the site, it is still a common and very low-energy way of construction. Currently it is estimated that one half of the world's population – approximately three billion people lives or works in buildings made of earth. Earth buildings have been created since ancient times, but the use of modern materials with standardization and better mechanical strength has placed this technique on the sidelines of construction.

1.2. Earth as Commons and its Social dimension

The soil, through the various earthen building techniques, has been a principal building material, as part of the load-bearing system of a structure (rammed earth or adobe masonry), as a filler element (three-leaf masonry) or as the final layer of the construction (roughcast and render). Its abundance in nature and its ecological context have provoked the interest of people in recent years in its use in modern architecture. In addition structures made of earth are healthy for humans and can play a crucial role in sustainability in construction. The availability, the economic price of the material means it bears great potential to contribute to poverty alleviation and sustainable development even in period of crisis (economic crisis, emergency need for shelter e.x. refugee camps) [1]. It is not always easy to produce building material out of a clayey soil, and experience is required, but it's a procedure that can be taught and shared between people with a common tradition. Building with mud brick or block in particular, requires little or no specialist skills. The process is labor-intensive and the work is often heavy, but it can be phased to suit both the weather and the availability of helpers. The right preparation depends on the type of earth, its consistency and its expected application. Moist crumbled earth with less clay and more sand content can be used immediately to build a rammed earth wall even as it is dug out [2].

Earthen architecture is well-nigh ubiquitous.We found earthen building techniques in both modern and traditional architecture in a variety of structures ranging from mosques, palaces and temples to dwellings, huts and granaries. Its cultural importance throughout the world is evident and has led to its consideration as a common heritage of humankind, therefore deserving protection and conservation by the international community. In 2011, over 10% of the World Heritage properties incorporated earthen structures and deserve particular attention in terms of conservation and maintenance; about ¼ of the sites inscribed on the World Heritage List in Danger are earthen sites [3]. History shows us that 'commoning' is the principle by which human beings have organized their existence for thousands of years [4].

In this research we examine how to enable networks to emerge and to sustain processes of commoning restoration techniques. Techniques which are common heritage based on a common resource [5]. The sharing of knowledge could benefit the local practices, both on an individual and on a collective level. On the one hand, it could enhance the sustainability of local initiatives. On the other hand it could enable them to scale up and generate new restoration techniques and improvement of hakka dwellings.

In addition an open-source process is proposed, which acknowledges the collective ownership of the knowledge produced and the means for knowledge production [6]. The produced knowledge could be circulated back into the communities from where it emerged, while at the same time remaining open to allow others to adopt them and continue the process of co-restoration producing knowledge beyond the specific building project.

1.3. Architecture of Hakka Tulou

The case study of this research is the Haka Tulou in Fujian province in China. Built between the 13th and 20th centuries out of rammed earth, in fertile mountain valleys; these buildings are an extraordinary reflection of a communal response to settlement which persisted over time. They have an outstanding universal value because of their enormous size, the technical ingenuity and the remarkable earthen defensive characteristics as buildings; they met both their communities' physical and spiritual needs, almost all folk dwellings keep the traditional form of courtyard. And courtyard building is the most stable system in the Han culture, which is determined by traditional Chinese "vigor" view and the special aesthetic taste of the Han people based on such a view [7].

They are several storeys high, built along an inward-looking, circular or square floor plan and housing up to 800 people each. Furthermore, the building itself, has many facilities such as water wells, ceremonial hall, bathrooms, wash rooms, and weaponry, all of which were shared property. Even the surrounding land and farmland, fruit trees etc. were shared since they were farmed communally. The layout of Fujian Tulou follows the Chinese dwelling tradition of "closed outside, open inside" concept. Usually, the plan can be described as an enclosure wall with living quarters around the peripheral and a common courtyard at the center. Ground floor plan includes circle, semicircle, oval, square, rectangle, and irregular pentagon, see Fig. 1.

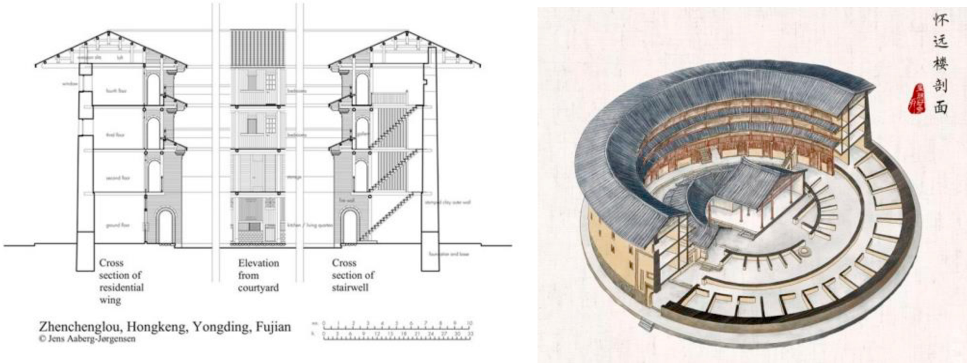

Fig. 1. (a) Tulou design; section [8] (b) Tulou axonometric design [9].

The more authoritative definition of Tulouis "Multi-layered large residential buildings which are jointly supported by rammed earth walls and wooden beams and columns [10].The foundation of tulouwas built with paved stones on top of compacted earth ground, in two to three tiers. There is a circular drain around the top tier foundation to prevent rainwater from damaging the tulou wall. Tulous earth architecture represents a valuable source of human cultural heritage [11].

1.4. Importance of Tulou and objectives of this research

Following the global cultural governance regime of UNESCO, China ratified the 1972 World Heritage Convention, a little later, in 1985. China is now home to 43 UNESCO World Heritage sites. Dozens more sites are on China's Tentative List awaiting nomination to the World Heritage Committee, which determines the World Heritage List. Nevertheless, many of the earthen buildings are in such a vulnerable situation that makes the permanent loss of this heritage only a matter of time. It takes dozens or even hundreds of people, generally a large family of the same surname, to build a Tulou, which lasts for several years or even decades. Carpenters and mason are employed during the construction process. For example, Chengqi Tulou was built in the Ming Dynasty, but it was completed in the 48th year of Qing Emperor Kangxi (1709). It experienced 3 generations and took 81 years to finish the construction. There are 400 rooms in Chengqi Tulou, and once 800 people lived there at the same time [12]. All households are closely related, showing strong public and social features.

However, in the case of rammed earth structures, there is still an important lack of research for the development of new techniques that could be easy implemented by local people. Despite their significance, many of these structures suffer from luck of maintenance, accelerated the last decades by the unprecedented movement of many of their inhabitants to urban centers in search of work. So, severe vertical cracking, particularly between the rammed earth blocks, is nowadays typical, hindering their structural performance. In addition cracks constitute paths for rainwater which can dramatically reduce the compressive strength andthe stiffness [13].

Therefore this research has three main aims:

a) Assessing the efficiency and comparing the two most widely used restoration techniques in reestablishing the continuity of a cracked earthen element. These techniques are grouting, applied to small to medium cracks, and filling the crack with earth mortar, which is usually applied in medium to large cracks.

b) Optimizing the role of water. The objective was to mitigate the water sorption phenomenon, caused by the dry cracked building element when an intervention is taking place. In order to do so, water was added inside the crack, which was left wet for different time intervals. This way, the recovery of the initial strength was assessed and the essential time of water inside the crack, before grout or mortar is added to repair it, was optimized.
c) Suggesting restoration techniques easily adaptable and with the potential to be evolved by the local community. Techniques which can be implemented in a collaborative way, as the tulos were built, with the materials for the restoration locally available.

2. Building's characteristics and Pathology

2.1. Constructions Techniques of Rammed earth

It is difficult to clearly define the origins of this technique, since it could be linked to early human settlements in Northern Africa, Middle East, Far East, Europe, and Central and South America. In any case, it is reasonable to state that rammed earth structures may have been developed independently and being mutually influenced and transferred along different periods [14]. Rammed earth structures are based on the compaction of moistened soil with a granulometry from clay to gravel. Earth is compacted layer by layer between temporary timber formworks, which its dimensions extensively vary depending on the region. Considering for instance the Maghreb region, side formworks are 265 x 90 cm, with a standard thickness that varies between 50 and 60 cm. Rammed earth structures, have in general very low tensile strength that makes them vulnerable to severe vertical cracking, especially between the distinct sections created by the formwork. This type of cracking reduces the overall stiffness and strength and has a deep impact on the seismic behavior [15]. Furthermore it promotes water penetration which can result in complete loss of the load-bearing capacity and collapse of the building.

2.2. Rammed earth Constructions Techniques at Hakka Tulou

The construction process of Tulou is very complicated. Firstly, before the construction, the site of Tulou needs to be chosen according to fengshui. The ideal location is at the foot of the mountain which faces a river. After the site is chosen, the foundation is excavated, to a depth ranging from about 0.6 to 2 meters [12]. Then a wall base should be built with stones taken from nearby rivers and streams. The larger sides of stones must face down and the gaps should be filled with pebbles. After the Qing Dynasty, the Tulou were built with stone dados, which played a waterproof role. The heights of the stone dados are different, usually ranging from 0.6 to1 meter high [16]. In addition, the stone dados should be built above the highest flood level to avoid flooding the soil wall. The construction of the Tulou in Fujian is carried out in layers, see Fig. 2.

Fig. 2. Construction and pathology of Tulou (a) Source: Fujian Tulou (b) Source: Ramming Technology of Hakka Tulou

Generally, loess soil with high sand and aggregate content is used. If the clay content is not enough, it is added what is called "field mud" (also known as "field bottom mud", which is the clay that has not been cultivated in the lower layer of the paddy field). The materials used in the south of Fujian Province are different. What is used is the so called "three-in-one soil", that is, loess, lime and sand, mixed with concrete. Despite their significance, many of these structures suffer from luck of maintenance; a situation which accelerated the last decades by the unprecedented movement of many of their inhabitants to urban centers in search of work.

3. Materials and methods

3.1. Soil and rammed earth specimens

The soil for the preparation of the specimens was taken from the same field from where soil was recently excavated for a successful rammed earth construction in Greece. Atterberg limits were assessed according to ASTM D4318 and the particle size distribution was assessed with Bouyoucos hydrometer method. Among the results, presented in table1 one of particular importance is the clay content and the Plasticity Index, which are correlated with the compressive strength and the linear shrinkage of the dried building material [17]. As it can be seen in table 1 the properties of the soil c mply with the criteria of modern standards and literature for rammed earth construction.

Table1: Properties of the soil used in the preparation of rammed earth specimens.

Soil Properties	Clay (%)	Silt (%)	Sand (%)	Liquid Limit	Plastic Limit	Plasticity Index
Soil used	16	17	67	21	13	8

The methodology followed to assess the strength recovery ratio, was the one proposed by R.A. Silva in his PhD thesis [18]. At first the soil was dried and sieved with a 6 mm sieve and then, the water content for the rammed earth specimens was defined according to the ball-drop test at 11 %. With this soil, 40*40*160 mm prisms were fabricated after compaction in three layers. A manual rammer was used to compact specimens. The specimens were tested under flexural loading when constant mass was obtained, according to EN 1015-11.

3.2. Restoration mortars and grouts

Both restoration mortars and grouts were fabricated with the use of the same soils as the rammed earth specimens, without incorporating additional binders, as lime and cement. On the one hand compatibility and sustainability reasons led to the decision to use unstabilized soil. On the other hand, this choice was based on previous researches, which indicated that for grouts, this way a better adhesion and a better strength recovery of the damaged material is achieved [19] [20]. Notwithstanding, recovery of flexural, compressive or shear strength is in all cases more or less distant from initial strength [21] [22]. Also, in the case of repair mortars for rammed earth, it has been shown that unstabilized earth mortars are more suitable [23].

Therefore, the unstabilized grout derived after sieving the same soil with a 0.2 sieve, adding limestone powder (soil to limestone powder 1:1) with a maximum grain of 80μm, to reduce the clay content and thus the volume change, and mixing with water with a w/s ratio of 0.35. To improve fluidity and reduce the water/soil ratio, 1% sodiumhexametaphosphate (HMP) was added. For the production of the repair mortar, soil was sieved with a 2 mm sieve and left to dry. The water content was defined with the flow table test according to EN 1015-3 and the selected flow table value was 14 cm as suggested in [24]. The grout had a flexural strength of 0.72 N/mm^2, apparent density of 1.69 g/cm^2 and linear shrinkage of 7.2 %, while the repair mortar had a flexural strength of 1.01 N/mm^2, apparent density 1.84 $g/cm^2$and 4.4 % linear shrinkage.

3.3. Repair procedure

After the flexural testing of the rammed earth specimens, the two broken parts of the prisms were aligned, so as the two broken edges of the crack had a distance of approximately 0.5-1 cm in the case of earth grout repair and of 0.8-1.5 cm, in the case of earth mortar repair. Mortar was applied with a trowel and grout with a syringe and an adjusted tube. The two sides of the crack were sealed and five scenarios were applied: first, the grout and the mortar were applied directly on the dry crack surfaces; second, water remained in the crack for 15 minutes before mortar and grout were applied; third, water remained in the crack for 2 hours before mortar and grout were applied;

fourth,water remained in the crack for 3 hours before mortar and grout were applied and finally, water remained in the crack for 24 hours before mortar and grout were applied. After the restoration of the crack, the specimens were tested under flexural loading when constant mass was obtained, according to EN 1015-11, to evaluate the intervention and assess the strength recovery ratio.

4. Results and discussion

The results obtained are presented in table 2, table 3 and Fig. 3. In these two tables, it can be observed that the results regarding the rammed earth specimens are quite consistent. Their density is high, ranging from 2.01 g/cm^2 to 2.12 g/cm^2, as well as their flexural strength which ranges from 1.07 N/mm^2 to 1.37 N/mm^2. The linear shrinkage assessed, is also relative low, ranging from 0.5 % to 1.9%, lower than the 5% limit that is proposed by P.Walker [25].

Table2: Rammed earth repaired with grouts

Grout applied in different intervals	ρd (g/cm^2)	Linear shrinkage (%)	Fb (N/mm^2) initial	Fb (N/mm^2) after	Strength recovery ratio (%)
RG0 (0 hours)	2.03	1.3	1.13	0.13	11.5
RG1 (0.25 hours)	2.06	1.4	1.26	0.33	26.2
RG2 (2 hours)	2.07	1.5	1.15	0.37	32.2
RG3 (3 hours)	2.09	0.5	1.36	0.64	47.1
RG24 (24 hours)	2.01	1.1	1.07	0.13	12.1

Table3: Rammed earth repaired with earth mortars

Mortar applied in different intervals	ρd (g/cm^2)	Linear shrinkage (%)	Fb (N/mm^2) initial	Fb (N/mm^2) after	Strength recovery ratio (%)
RM0 (0 hours)	2.11	0.90	1.25	0.38	30.4
RM1 (0.25 hours)	2.05	1.20	1.18	0.42	35.6
RM2 (2 hours)	2.12	1.90	1.24	0.64	51.6
RM3 (3 hours)	2.08	0.8	1.37	1.15	83.9
RM24 (24 hours)	2.1	1.10	1.17	1.06	90.6

Table 2 represents the average values obtained for the rammed earth specimens, which, after they were tested in flexural loading (Fb initial), they were repaired by means of earth grout. The repair took place in different time intervals, during which the edges of the cracks remained wet. As it can be seen in this table, the flexural strength after the repair (Fb after in the table) is distant from the initial strength and the strength recovery ranges from 11.5 % to 47.1 %. It is worth noting, that the lowest strength recovery occurs when the edges of the crack are dry before the grout is applied (RGO in table 2). Then, an increase is observed in the cases of RG1, RG2 and RG3, in which the edges of the crack remain wet for 15 minutes, 2 hours and 3 hours respectively before the intervention, but when the broken edges of the specimens remain wet for 24 hours, there is a sudden drop in the recovery ratio. The low recovery ratio in the case of RGO, can be explained by the water sorption of the cracked dry element. Then, when the broken edges are wet, ion-electrostatic bonds between the clay particles of the broken edge and the clay particles of the grout can manifest, leading to better adhesion capacity and to an increased recovery ratio. But when there is a prolonged exposure of the broken edges to water, as in the case of RG24, capillary forces make the whole specimens wet. So, upon drying, volumetric shrinkage reoccurs, separating the grout from the rammed earth specimens.

In table 3, regarding the results obtained when the rammed earth specimens were repaired with earth mortar, more or less the same sequence as for the grouts applies. For the reasons mentioned above, the recovery ratio is relatively low, 30.4% when the broken surfaces of the rammed earth specimen are dry, and increases proportionally with the time these surfaces remain wet before the mortar is applied. There is a big difference though, evident in Fig. 3. The sudden drop of the strength recovery ratio, which appeared in the case of the grouts after the surfaces of the crack remained wet for 24 hours, didn't occur the same with the repair of earth mortars. On the contrary, the adhesion capacity and the strength recovery ratio continued to increase, reaching 90.6%. The reason for this differentiation is that the earth mortar was from the same soil with the rammed earth, with slightly different granularity (sand up to 2 mm). So, a similar behaviour towards water between the mortar and the rammed earth can be assumed. When, after 24 hours the whole specimen was wet, instead of a separation as in the case of grouts, whose composition also derived from the same soil, but with the addition of limestone powder and most importantly, a much different granularity (maximum grain size 0.2 mm), mortar and rammed earth were homogenized. So, the subsequent volumetric shrinkage occurred on an almost homogenized material. This could be seen with a naked eye on the RM24 samples, at which it couldn't be distinguished the repair mortar from the rammed earth. Furthermore, it should also be noted, that the strength recovery ratio is for all time intervals significantly higher for earth mortars than for grouts.

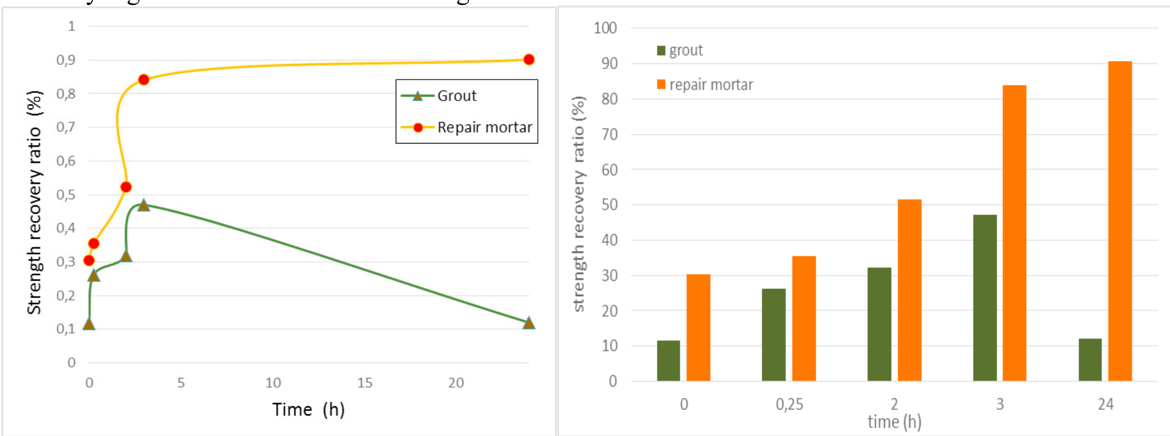

Fig. 3: Bending strength recovery ratio versus the time the surfaces of the broken rammed earth specimens remained wet.

5. Conclusions

The main results of this research, regarding the performance of mud grouts and earth mortars for the restoration of rammed earth, are the following:

- Water has a crucial role in the effectiveness of both techniques. Before an intervention on a cracked rammed earth wall, either by mortar or by grout, it is important to keep wet the cracked surfaces for a significant amount of time. Not only to mitigate the water sorption by the dry material, but also to activate the binding force, the interaction between the clays of the repair material and the clays of the damaged material. When earth mortars and grouts were applied on the dry surfaces of the cracks of the rammed earth specimens, the adhesion capacity and the strength recovery ratio were very low. Only 11.5% of the initial strength was recovered with grouts and 30.4 % with earth mortars.
- For the repair with earth mortars: The longer the surfaces of the crack of the rammed earth specimens remained wet, the better the adhesion and the strength recovery ratio were. The best strength recovery, 90.6% of the initial strength, was achieved when the earth mortar was applied after the surfaces of the crack had remained wet for 24 hours.
- For the repair with mud grouts: The strength recovery ratio when grouts were applied was found lower than when earth mortars were applied. As in the case of earth mortars, the cracked surfaces must be wet before the grout is applied. Nonetheless, an optimization of the time the surfaces remain wet is required, since it was found that after a prolonged exposure of the surfaces to water before the grouting, the adhesion capacity was hindered.

The use of unstabilized grouts and earth mortars in repairing cracked rammed earth walls was found to be efficient. These interventions could also be easily adopted and improved by the local community and the residents of the Tulou structures.

To realize the long-term success of a restoration project, it must be adopted a collaborative network model in partnership of the Government, the Chinese cultural heritage officials and locals. The model can be organised with community empowerment, based on the work of Global Heritage Fund, a non-profit organization empowering communities through historic conservation and heritage-driven local development [9]. Historic preservation guidelines can be produced by collaboration of local communities, builders and scientists, establishing a scientific planning and restoration design process according to regulations on construction and building codes. This can lead to the formation of a comunity with an advisory team and also a team of workers to restoration. By this collaboration it can be produced a common-pool resource of knowledge which can be transmitted to the whole community and also useful to all Haka comunity. The methodology for the partnership is an aim of our future research directions.

Acknowledgments

This research has been supported by the OptArch project: “Optimization Driven Architectural Design of Structures” (No: 689983) belonging to the Marie Skłodowska-Curie Actions (MSCA) Research and Innovation Staff Exchange (RISE) H2020-MSCA-RISE-2015.

References

[1]. M. Townsend, School built for Syrian refugee children wins top architecture prize, Independent Digital News & Media Ltd, Independent, (2018).
[2]. G. Minke, Building with Earth, Birkhäuser – Publishers for Architecture, (2006).
[3]. J.Hosagrahar, https://whc.unesco.org/en/earthen-architecture/, https://whc.unesco.org, visited 2016,Cited: 15 September (2019).
[4]. S. Federici, P. Linebaugh, Re-enchanting the world : feminism and the politics of the commons. Oakland, CA, PM Press, 2019.
[5]. E. Frangedaki, Optimizing engineering aspects of earth constructions. The earth as"common" material, Vienna, Geophysical Research AbstractsVol. 21, EGU2019-11412-1, EGU General Assembly (2019).
[6]. C. Baibarac, D. Petrescu, Co-design and urban resilience: visioning tools for commoning resilience practices, CoDesignInternational Journal of CoCreation in Design and the Arts, UK, (2017).
[7]. H. Zhou, S. Dong, Impact of Ethnic Migration on the Form of Settlement: A Case Study of Tulou of South Fujian and the Hakkas, Journal of Landscape Research, (2015).
[8]. J. Aaberg-Jørgensen, Clan Homes in Fujian. Arkitekten. Arkitekten, November 2000, Vol. no. 28, pp, 2–9, (2000).
[9]. Global Heritage Fund Mission, available at: http://globalheritagefund.org/what_we_do/updates/current_projects/fujian_tulou, visited (2019).
[10]. H. Huang,, Fujian Tulou, Beijing: SDX Joint Publishing, (2017).
[11]. H.Ma, S. Li, and C.-S. Chan, Analytic Hierarchy Process (AHP)-based assessment of the value of non-World Heritage Tulou: A case study of Pinghe County, Fujian Province Tourism Management Perspectives, p.26, 67-77,(2018).
[12]. J.Hong, Ramming Technology of Hakka Tulou, Employment and Security, p.39-44, (2018).
[13]. J. Warren, Conservation of Earth Structures. Bath, UK, Butterworth Heinemann, (1999).
[14]. H. Houben, H. Guillard, Earth Construction, A Comprehensive Guide, London, Practical Action, (1994).
[15]. B. Briseghella, V. Colasanti, L. Fenu, C. Nuti, E. Spacone, H. Varum, Seismic Analysis by Macroelements of Fujian Hakka Tulous, Chinese Circular Earth Constructions Listed in the UNESCO World Heritage List, International Journal of Architectural Heritage, (2019).
[16]. H. Huang, Fujian's Tulou-A Treasure of Chinese Traditional Civilian Residence, Springer, (2020).
[17]. N. Meimaroglou, H. Mouzakis, Cation Exchange Capacity (CEC), texture, consistency and organic matter in soil assessment for earth construction: The case of earth mortars. Costruction and Building Materials, Vol. 221, pp. 27-39, (2019).
[18]. R. A. Silva, PhD thesis, Repair of Earth Constructions by Means of Grout Injection. University of Minho, Portugal,(2013).
[19]. R. A. Silva, D. V. Oliveira, L. Schueremans, T. Miranda, J. Machado, Effectiveness of the repair of unstabilised rammed earth with injection of mud grouts. Construction and Building Materials, Vol. 127, pp. 861-871, (2016).
[20]. J. Vargas, M. Blondet, C. Cancino, F. Ginocchio, C. Iwaki, K.Morales, Experimental results on the use of mud-based grouts to repair seismic cracks on adobe walls, Proceedings of the VI International Conference on Structural Analysis of Historic Constructions. pp. 1095-1099, (2008).
[21]. R. Illampas, R. A. Silva, D. C. Charmpis, P. B. Lourenço, I. Ioannou. Validation of the repair effectiveness of clay-based grout injections by lateral load testing of an adobe model building. Construction and Building Materials, Vol. 153, pp. 174-184, (2017).
[22]. R. A. Silva, O. Domínguez-Martínez, D. V. Oliveira, E. B. Pereira. Comparison of the performance of hydraulic lime- and clay-based grouts in the repair of rammed earth, Construction and Building Materials, Vol. 193, pp. 384-394,(2018).
[23]. M. I. Gomes, P. Faria, T. Diaz Gonçalve, Rammed earth walls repair by earth-based mortars: The adequacy to assess effectiveness. Construction and Building Materials, Vol. 205, pp. 213-231, (2019).
[24]. N. Meimaroglou, H. Mouzakis, Mechanical properties of three-leaf masonry walls constructed with natural stones and mud mortar, Engineering Structures, Vol. 172, pp. 869-876, (2018).
[25]. P.Walker, R. Keable , J.Martin, V.Maniatidis, Rammed earth: design and construction guidelines, United Kingdom, BRE bookshop, (2005).