A holistic approach to enhance the seismic resilience of the Hakka Tulou

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INTRODUCTION

Hakka Tulou (Figure 1) are well known massive traditional earth constructions located in the Fujian Province (China) and part of the UNESCO list of World Heritage buildings. There are more than 23,000 Tulou in the provinces of South-Western China and date back to being built 1300 years ago. Recently, the seismic response of these structures has been partially investigated as well as other research into the building's resilience to the natural environment. The buildings are of particular interest in understanding the resilience of these sustainably built dwellings. The buildings have withstood many earthquakes which include a strong earthquake (Richter scale 7.0) in 1918 [1]. This earthquake is reported to have caused a significant three meter crack to the Huanji Tulou. This crack has reportedly self-healed in size since. The seismic protection of such structures is of paramount importance for their heritage value. As rammed earth is a material which is sensitive to temperature and humidity levels a holistic multi-hazard approach therefore will be addressed in this study to enhance the resilience of the Hakka Tulou to environmental actions while preserving the artistic value of heritage buildings. This study investigates, through a combined approach, using experimental models and complex numerical finite elements models in order to reduce the impact of various earthquakes on the structure.

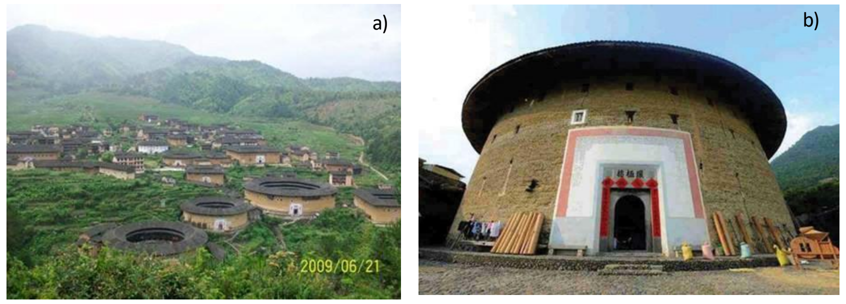

Figure 1: a) A cluster of Hakka Tulou [1] b) Huanji Tulou

AIMS AND OBJECTIVES

The aim of the study is to provide a holistic approach to improving the seismic resilience of the Tulou, to this aim the following objectives are:

- Investigate the seismic behaviour of the Tulou through advanced finite element models, at reduced scale.
- Design a bespoke non-invasive ViBa (Vibrating Barrier) seismic protection device.
- Build a reduced scale prototype to validate the effectiveness of the proposed vibration control strategy in different climate conditions.

SHAKE TABLE TESTS

Two reduced scale models of the Tulou were created at a 1:100 scale. The geometry and mechanical properties of the Tulou have been taken from the prototype Tulou described in [2]. Hence the prototype has a height of 20 m with three equally spaced floors and a diameter of 43.2 m and the rammed earth considered to have an elastic modulus of 1000 MPa at 1600 Kg/m^3. For the purpose of the shake table tests, the properties of the Tulou material were scaled using the similitude table [3] and hence the Tulou's walls are constructed from RTV silicone (Figure 2b).

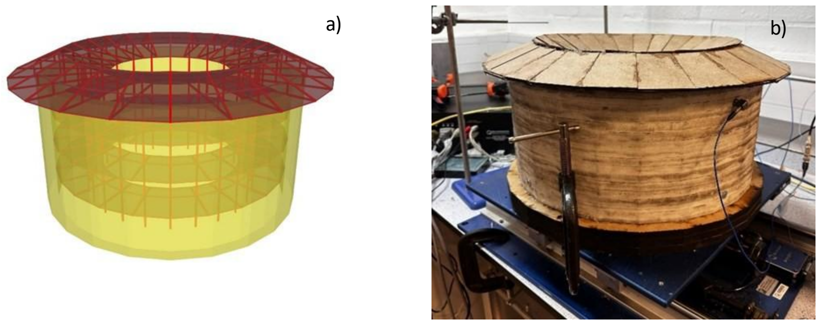

Figure 2: a) Finite element model of Tulou b) Experimental model of Tulou (Tested at the University of Brighton, UK)

Once constructed, the model was calibrated with a similar numerical model (Figure 2a) and hence the ViBa designed to reduce the peak acceleration of the Tulou. This model was calibrated alongside a numerical model before being shipped to Fuzhou university to be tested on their 4 x 4m biaxial shake table. The ViBa was designed following the method set out by [4] which aims to reduce the peak acceleration of the response of the structure and this aim was tested and then compared to the numerical model. The design was compared between the Sap2000 model and MATLAB analytical calculations.

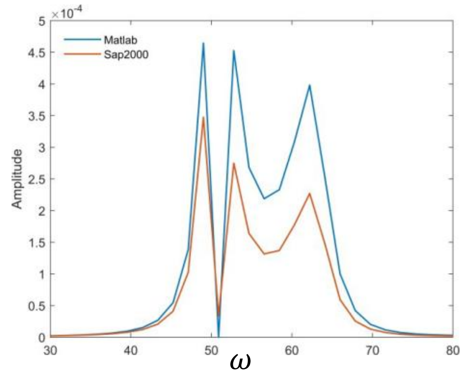

Figure 3: Comparison of the steady state analysis between analytical calculations and the finite element model (Figure 5a)

Before testing of the ViBa the experimental model and numerical model where calibrated using the experimental results as shown in the following graphs as the top and bottom of the Tulou (Figure 4) which further verifies the experimental results according to the numerical model.

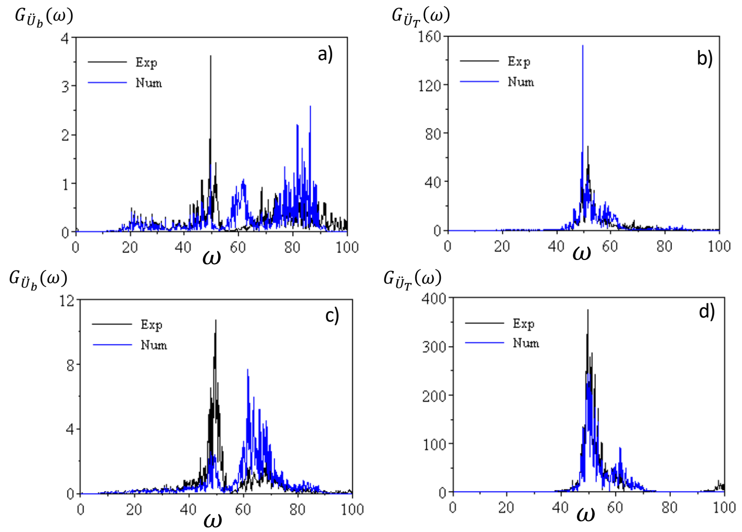

Figure 4: Verification. Comparison between shake table and finite element average Displacement Fourier Transform using response spectrum compatible ground motion time histories for two level of excitation: a) and b) 0.05g; c) and d) 0.1g.

The experimental reduced scale model along with the designed ViBa was tested for on soil for the first time (Figure 5b). Despite the soil being a lot stiffer that the rubber Tulou model the ViBa was able to carry a small (16%) reduction to the peak acceleration at the top of the Tulou which was expected.

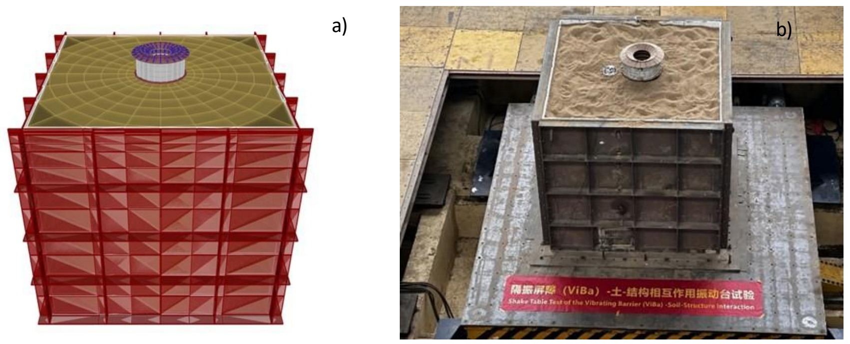

Figure 5: ia) Finite element model of Tulou on soil box b) Shake table test of the Tulou protected by the ViBa (Tested at Fuzhou University, China)

ENVIRONMENTAL MODEL

The second model was constructed using a synthetic rock material made from a plaster, sand and water mix in order to provide a similar material to the rammed earth used in the Hakka Tulou with a similar unit weight and elastic modulus. Due to the brittle nature of the material, a plaster and water mix was used to harden the outside edges of the Tulou wall.

Figure 6: Environmental model being tested in the Environmental chamber at different conditions

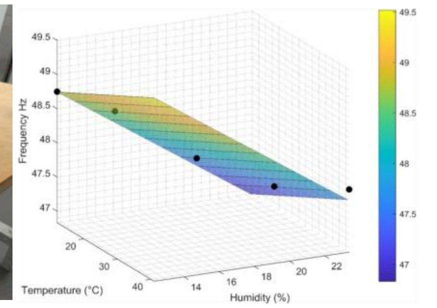

Figure 7: 3D plot showing the effect of temperature and humidity on the frequency of the Tulou.

The model was then tested in an environmental chamber (Figure 6) in order to assess how the fundamental frequency of the Tulou at the top of the Tulou's wall changes with different temperature and humidity levels (Figure 7). As the ViBa was designed for one climate, the following conditions are necessary to consider. From the linear relationship in Figure 7 it shows how the temperature surrounding the Tulou has a much larger effect on reducing the Tulou's frequency than the humidity does likely given that the increased absorption of water from the increase in humidity level would increase the mass of the Tulou walls and hence reduce their frequency.

COMBINED MODEL

The linear relationship shown in Figure 7 between the natural frequency and the temperature and humidity was then applied to the reduced scale model with and without the ViBa. In order to consider this relationship, the elastic modulus of the Tulous wall was changed at the same rate as the frequency change. Three different data points were analyzed with a large variation in temperature and humidity (Figure 8a and 8b). As the ViBa has been designed to reduce the maximum acceleration at one point when different climate conditions are considered the frequency of the Tulou changes and hence the ViBa has very slightly less reduction compared to the initial climate conditions.

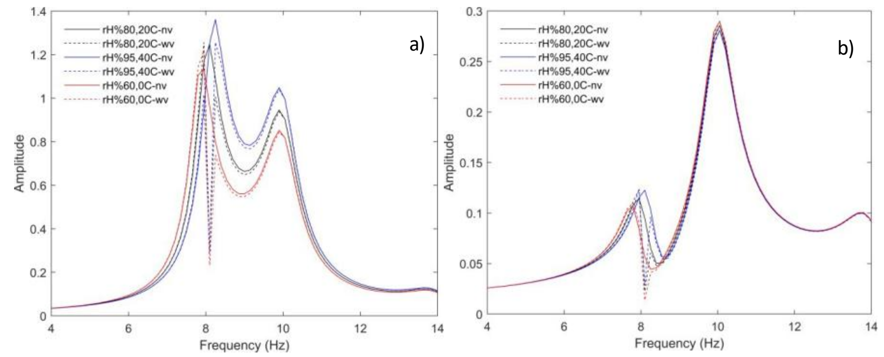

Figure 8: Comparison of the reduction from the ViBa for different climate conditions a) Top of the Tulou wall b) Bottom of the Tulou wall

CONCLUDING REMARKS

To conclude, the following research project has detailed evidence that the ViBa is effective as a method of improving seismic resilience for structures at different temperatures and humidity levels. The levels the of temperature and humidity considered were taken to be worst case values; for the climate in the location of the Tulou however, other climate conditions may need to be tested further. The research assumes the rammed earth material is linear elastic and hence further non-linear analysis should be considered. Further research is necessary to provide a full-scale model of the ViBa and structure in order to truly represent it.

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