14th International Conference on Structural Safety and Reliability - ICOSSAR'25
1-6 June, 2025 - Los Angeles California, USA
R. Ghanem, E. Johnson, S. Masri and A. Olivier (Eds)

SHAKING TABLE TESTS FOR VIBA-SOIL-STRUCTURE INTERACTION

PIERFRANCESCO CACCIOLA*[1], LAN LI[1], WILLIAM DOBNEY[2], FUYUN HUANG[1], QU WANG[1], ALESSANDRO CONTENTO[1] AND BRUNO BRISEGHELLA[1]

[1] College of Civil Engineering, Fuzhou University
No.2 Xueyuan Rd., Minhou, Fuzhou, Fujian 350116, China
p.cacciola@fzu.edu.cn; 200510012@fzu.edu.cn; huangfuyun@fzu.edu.cn; wangqu1989@fzu.edu.cn; alessandro@fzu.edu.cn, bruno@fzu.edu.cn,

[2] School of Architecture, Technology and Engineering, University of Brighton
Cockcroft Building, Lewes Road, BN2 4GJ, Brighton, UK
W.Dobney1@uni.brighton.ac.uk

Key words: Vibrating Barriers, structure-soil-structure interaction, shake table test, Fujan Tulou.
Abstract. The ViBa is a massive structure hosted in a box within the soil and tuned to reduce the vibrations of existing structures in the event of seismic action. It exploits the well-established Structure-Soil Structure Interaction (SSSI) mechanism, thereby protecting the built environment in a non-invasive way through its radiated wave field. The efficiency of the ViBa has been proven to date through theoretical, numerical and experimental studies, but it has not yet been tested on a large shake table. Preliminary experimental tests on the 4m × 4m shake table at Fuzhou University have been undertaken for the first time to test the efficiency of the ViBa technology for the seismic protection on a realistic case study. A 1:100 model of a Fujan Tulou has been selected for this application. The shake table tests focused on the efficiency of the ViBa buried in the 2m × 2m × 2m soil box filled with sand. Response-spectrum-compatible ground motion time histories consistent with the Chinese response spectrum have been simulated through a stochastic approach and used for the test. Preliminary results, herein presented, show the Vibrating Barrier did reduce the base acceleration of the Tulou.

1 INTRODUCTION

Hakka Tulou are well known, massive traditional earth constructions located in the Fujian Province (China) and part of the UNESCO list of World Heritage building. There are more than 23,000 Tulou in the provinces of Southwestern China, some of which date back to over 1300 years [1]. Recently, the seismic response of these structures has been partially investigated, along with other studies examining their resilience to the natural environment [2], [3]. The buildings are of particular interest in understanding the resilience of these sustainable-built dwellings. The buildings have withstood many earthquakes, which included a strong earthquake (Richter scale 7.0) in 1918 [2]. The earthquake caused a significant three-meter crack to the Huanji Tulou; however, the crack has reportedly partially self-healed and reduced in size over time. Material testing carried out in [2] on the rammed earth and wooden elements of different

Tulou revealed significant differences in the material properties of each structure, depending, as expected, on the characteristics of the local earth at the construction sites. Finite Element (FE) studies based on microelements have been carried out in [3] showing the relevance of each sub-component in the overall dynamic behaviour of the Tulou. The seismic protection of such structure is of paramount importance for their heritage value. Conventional seismic protection strategies, mainly based on strengthening techniques or local devices such as dampers or seismic isolators, involve invasive structural interventions that could risk compromising the historical value of the Fujan Tulou structures. A non-invasive strategy, introduced in [4], exploits the interaction between a vibrating device, known as Vibrating Barrier (ViBa), and the adjacent structure to be protected through the Structure-Soil Structure Interaction (SSSI) mechanism. The Vibrating Barrier is, in its simplest configuration, a vibrating spring-mass-damper system, hosted in the soil, which is able to modify the dynamic response of the adjacent structure due to: i) response energy absorption through its coupling through the soils (in essence a tuned mass damper effect) and ii) modification of the ground motion underneath the structure, by means of its radiated wave field. The efficiency of the ViBa has been proven through a series of theoretical, numerical, and experimental studies [4-10]. In this paper, experimental tests on the 4m × 4m shake table have been undertaken at Fuzhou University to test the efficiency of the ViBa technology for the seismic protection of a physical model of a selected Fujan Tulou [3]. The ViBa has been designed following a stochastic approach extending the procedure proposed in [10] to the case of the ViBa device with viscous damping. A 1:100 model of the selected Tulou has been built scaling geometry and mechanical properties accordingly. Extensive experimental tests have been carried on for the calibration and characterization of the numerical model. The model has been initially considered fully fixed at its base and successively the soil-structure interaction effect has been taken into account. Specifically, a 2m × 2m × 2m soil box filled with sand has been used for this purpose. Soil-structure interaction calibration has been performed using a refined FE model excited by white noise recordings. Validation and verification have been then carried on using response-spectrum-compatible ground motion time histories consistent with the Chinese response spectrum using the method proposed in [11]. Preliminary results, herein presented, show the effectiveness of the Vibrating Barrier to reduce the base acceleration of the Tulou.

2 OPTIMAL VIBA DESIGN

The two-stage approach originally proposed in [10] and applied to the seismic protection of the Zoser pyramid is herein extended for the non-invasive protection of the selected Fujan Tulou. A reduced-order model capturing the ViBa-Soil-Tulou interaction is developed to reduce the computational effort of the optimization algorithm used to design the ViBa mechanical parameters. Specifically, a sub-structuring method [12], determined in the frequency domain, is used to condensate the Soil-Tulou system into complex-valued transfer functions and to reduce the order of the full system to just two translational degrees of freedom related to the translational ViBa displacement, U_V, and the displacement of its foundation, U_f. The method [10] consists of subdividing the full domain into two partitions: the first subdomain represents the Soil-Tulou system with a rigid excavation where the ViBa will be installed; the second subdomain comprises the internal structure of the ViBa, contained by a rigid box-foundation resting on a flexible soil medium modelled through soil-foundation impedance functions. A four-step analysis is then undertaken, comprising the following steps:

i) a steady-state analysis of the first subdomain subjected to bedrock ground motion displacement modelled as unitary constant function to derive the foundation input motion of the rigid excavation (assumed massless), $U_{FIM}(\omega)$, as well as the normalized displacement in the selected point of the Tulou, $U_p^{(1)}(\omega)$;

ii) a steady-state analysis of the first subdomain where a unitary displacement, $U_0(\omega)$, is applied to the centre of the rigidity of the excavation to derive the displacement in the previously selected point of the Tulou, $U_p^{(2)}(\omega)$, as well as the complex-valued soil-foundation impedance, $\widetilde{K}_h(\omega)$;

iii) a dynamic analysis of the soil-ViBa subdomain where the soil is modelled through the impedance $\widetilde{K}_h(\omega)$;

iv) the recovery of the complete displacement of the relevant point of the Tulou by adopting the principle of superposition, that is

$$U_p(\omega) = \left(U_p^{(1)}(\omega) + \frac{U_p^{(2)}(\omega)}{U_0(\omega)} U_f(\omega) \right) U_g(\omega) \tag{1}$$

Where $U_g(\omega)$ is the Fourier transform of the earthquake ground motion displacement model applied at the bedrock.

The displacement of ViBa foundation, $U_f(\omega)$, is determined considering the simple soil-ViBa system of Figure 1, where the foundation input motion $U_{FIM}(\omega)$ and the complex soil stiffness $\widetilde{K}_h$ are determined by FE analyses (i.e., step 1 and step 2). The governing equations of the reduced-order model can be written in the frequency domain as follows:

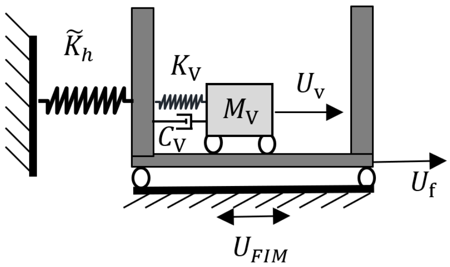

Figure 1: Soil-ViBa system.

$$\begin{cases} (K_V + i\omega C_V)\, U_V(\omega) - (K_V + i\omega C_V)\, U_f(\omega) - \omega^2 M_V X_V(\omega) = 0 \\ (\widetilde{K}_h(\omega) + (K_V + i\omega C_V))U_f(\omega) - (K_V + i\omega C_V)U_V(\omega) - \omega^2 M_f U_f(\omega) = \widetilde{K}_h(\omega) U_{FIM}(\omega) \end{cases} \tag{2}$$

Eq. (2) represents a system of algebraic equations in which $U_V(\omega)$ and $U_f(\omega)$, are the unknown ViBa's internal mass and foundation displacements, respectively; M_V and M_f are the masses of the ViBa and its foundation assigned a priori, whilst K_V and C_V are ViBa stiffness and viscous damping coefficient to be optimized. As a consequence, Eq. (1) can be rewritten as follows:

$$U_p(\omega,\boldsymbol{\alpha}) = H(\omega,\boldsymbol{\alpha}) U_g(\omega) \tag{3}$$

where the parameters to be optimised, listed in the design vector $\boldsymbol{\alpha} = [K_V, C_V]$, are made explicit in the transfer function. The optimization approach adopted in this paper follows a stochastic approach. Specifically, considering the ground motion acceleration modelled as Gaussian zero-mean stochastic process, fully defined by the knowledge of the power spectral density function (PSD), $G_{\ddot{U}_g}(\omega)$, it becomes straightforward to extend Eq. (3) using the Random Vibration Theory, as follows:

$$G_{\ddot{U}_p}(\omega,\boldsymbol{\alpha})=|H(\omega,\boldsymbol{\alpha})|^2 G_{\ddot{U}_g}(\omega) \quad (4)$$

where $G_{\ddot{U}_p}(\omega,\boldsymbol{\alpha})$ is the PSD function in terms of acceleration at the reference point of the Tulou.

The peak response acceleration, $\ddot{u}_{p,\mathrm{ViBa}}^{\max}$, of the reference point of the Tulou protected by the ViBa device can be derived from Eq. (4) in approximated fashion [13] as:

$$\ddot{u}_{p,\mathrm{ViBa}}^{\max}(\boldsymbol{\alpha}) \cong \eta_p \sqrt{\int_0^{\infty} G_{\ddot{U}_p}(\omega,\boldsymbol{\alpha})\mathrm{d}\omega} = \eta_p \sqrt{\lambda_0(\boldsymbol{\alpha})} \quad (5)$$

where λ_0 is the zero$^{\mathrm{th}}$-order spectral moment and η_p is the peak factor.

The objective function of the optimization approach is therefore the minimization of the peak acceleration in a selected point, that is:

$$\min_{\boldsymbol{\alpha}>0}\left(\ddot{u}_{p,\mathrm{ViBa}}^{\max}(\boldsymbol{\alpha})\right) \quad (6)$$

Other response parameters can be used in lieu of the maximum acceleration on the condition of relevant transfer functions are determined at stages 1 and 2 of the procedure, as done for example in [7] where the response strain energy spectral density has been selected as synthetic parameter to be minimized. The optimization problem can be written as minimization of the objective function which can be solved with standard iterative algorithms for constrained optimization. The advantage of this approach in comparisons to an equivalent surrogate model is that it can be applied to any complex structure, avoiding simplistic assumption inherent in the surrogate soil-structure-interaction models. On the other hand, the calculation of $U_p^{(1)}(\omega)$ and $U_p^{(2)}(\omega)$ could be quite time consuming depending on the dimension of the problem.

3 SHAKE TABLE TEST SET UP

Main objective of this work was to perform shake table tests on a ViBa-soil-structure system using real soil. In this regard, the experimental campaign required a thorough manufacturing of the scaled structure as well as the development of an accurate FE model for ViBa design.

3.1 Tulou model preparation

In order to perform shake table tests including soil structure interaction, a 1:100 scaled model has been developed considering equivalent materials defined using the similitude criteria shown in Table 1. The modulus of elasticity, E = 1000MPa, and unit weight, w = 16kN/m^3, of the earth structure at the prototype scale defined in [3] have been used as reference. Silicone rubber has been selected as the material with closest properties in the scaled configuration. After making the mould using a laser cutter, silicone rubber has been cast and left to set for a couple of days. Following demoulding, the internal timber frame structure, made also with the aid of a laser cutter, has been positioned and finished using a fast-setting adhesive. Figures 2 show the construction stages of the scaled Tulou used in the experimental tests.

Table 1: Scaling factors for 1g simulation in terms of the scale factor λ [12].

Parameter	Dimension	Prototype	Model
Stress, pressure	$ML^{-1}T^{-2}$	1	$1/\lambda$
Strain	-	1	1
Length, displacement	L	1	$1/\lambda$
Velocity	LT^{-1}	1	$1/\sqrt{\lambda}$
Acceleration, gravity	LT^{-2}	1	1
Mass	M	1	$1/\lambda^3$
Volume	L^3	1	$1/\lambda^3$
Force	MLT^{-2}	1	$1/\lambda^3$
Time	T	1	$1/\sqrt{\lambda}$
Frequency	T^{-1}	1	$\sqrt{\lambda}$

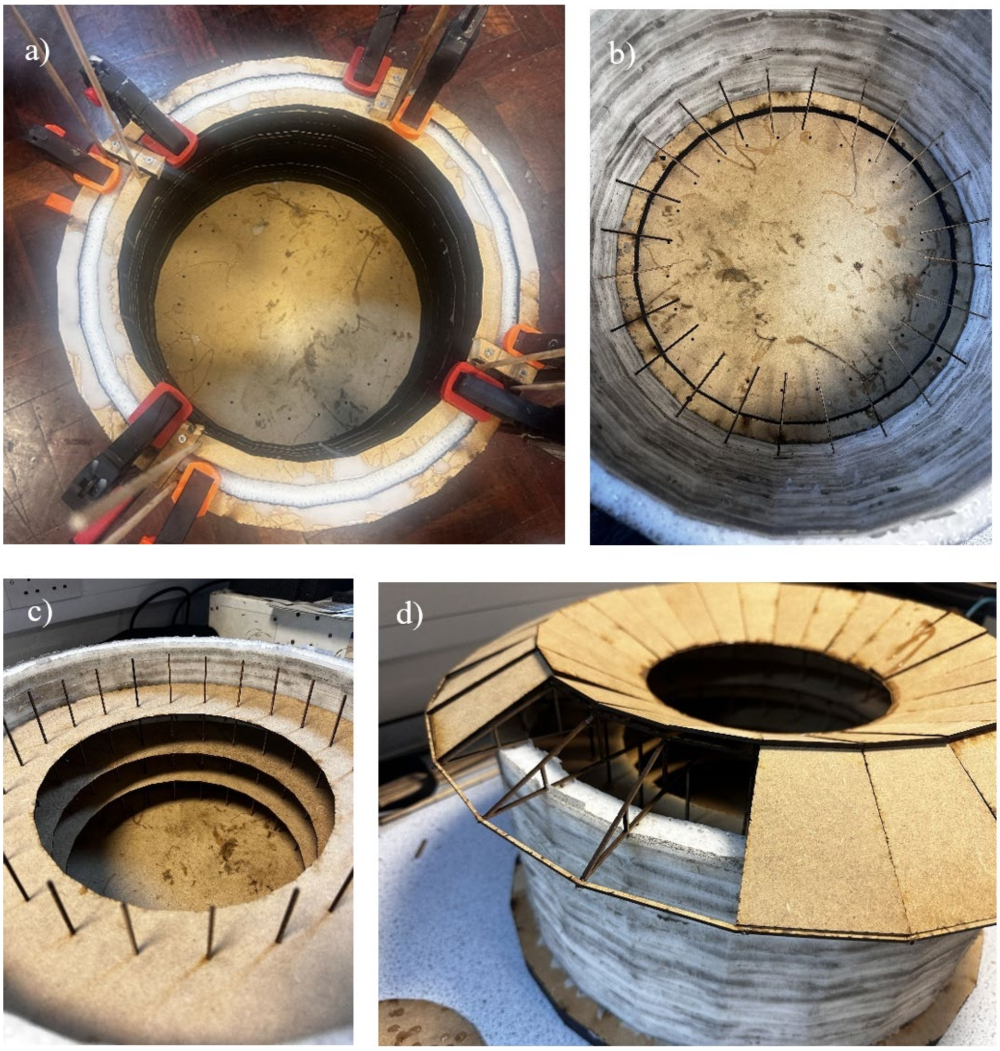

Figure 2: Illustrative stages of Fujan Tulou model preparation.

3.2 Model calibration

The numerical model, shown in Figure 3, has been developed in SAP2000, considering the mechanical properties of silicone rubber previously used in earlier research contributions (i.e. [5] and [8]). These values have been subsequently updated to match the dynamic response of the scaled Tulou, using a bench uniaxial horizontal motion shake table (Quanser Shake Table II 46 × 46 cm, operational bandwidth 0-20 Hz, peak acceleration 2.5g).

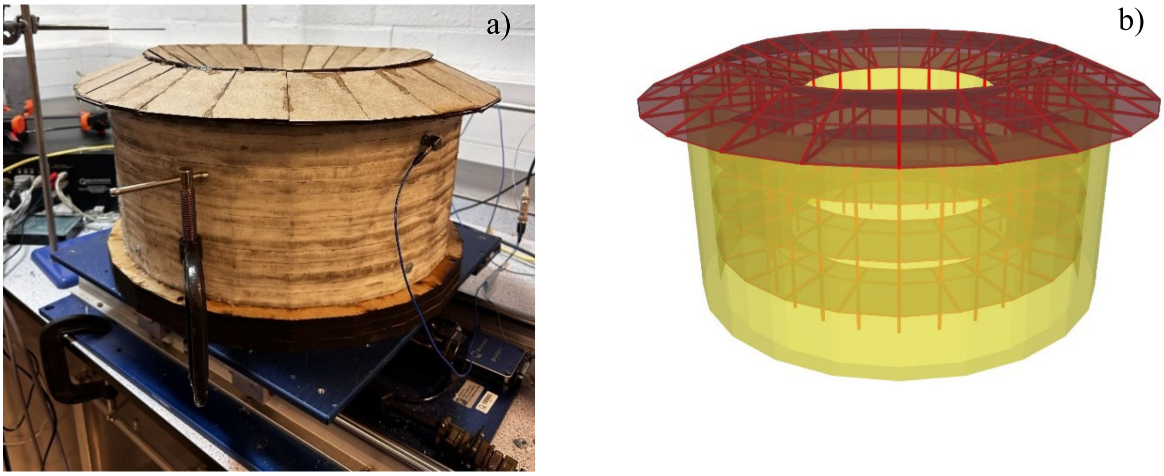

Figure 3: Fully Fixed model calibration: a) experimental set up; b) numerical FE model.

This initial calibration has been essential to reduce the number of variables (and associated uncertainties) involved in the second stage model calibration considering soil-structure interaction. In this regard, the 4m × 4m biaxial shake table at the College of Civil Engineering, Fuzhou University, has been used for the soil-structure interaction model (Figure 4). It should be noticed that soil material has not been scaled differently relative to the Tulou model, as the objective of this study was to use real soil rather than a scaled alternative material, as done in previous contributions (see e.g. [4], [5], [7] and [8]). As a consequence, the soil would be 100 times stiffer at the prototype scale. This implies that, at the prototype scale, the used soil behaves similarly to a real-scale rock soil, which represents the least favourable condition for the ViBa to operate effectively [5]. White noise tests have been initially carried out for the calibration of the model. For the soil-structure interaction study, the soil box (including steel, lateral EPS, and soil) has been added to the calibrated FE model of the Tulou, which was initially assumed to be fully fixed.

Table 2: Calibrated Mechanical Parameters for the Soil-Structure interaction model.

Material	Modulus of Elasticity [Pa]	Density [kg/m^3]	Poisson's ratio
Silicone Rubber	164879.33	1093	0.47
MDF	5.00E+09	897	0.25
Soil	8482143	1500	0.3
Steel Box	2.100E+11	7850	0.3
EPS	100000	20.39	0.3

Table 2 presents the calibrated mechanical parameters used in the numerical model. Figure 5 shows the comparison of the experimental and numerically evaluated response acceleration Power Spectral Density (PSD) functions at the top and bottom of the Tulou. The latter have been determined using the recorded acceleration of the shake table as the input in the FE model. From the figure it can be appreciated the excellent matching of the two set of measurement, especially at the top of the Tulou.

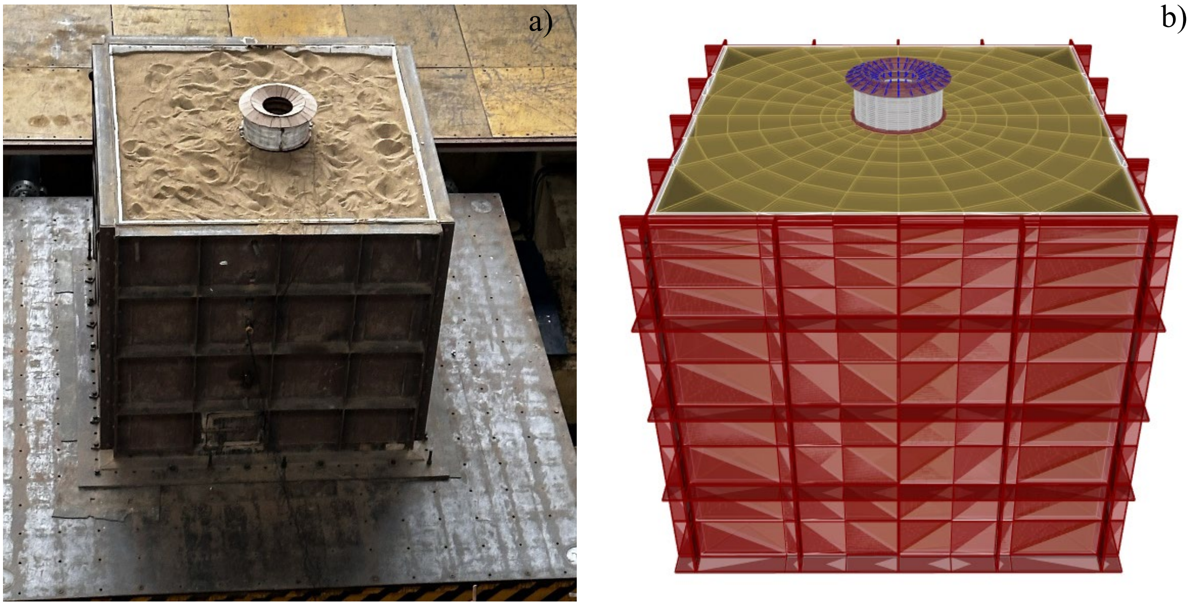

Figure 4: Soil-Tulou interaction test: a) experimental set up; b) numerical FE model.

A randomly selected set of response spectrum compatible ground motion time histories consistent with the Chinese response spectrum for rock soil has been then used for model validation and verification.

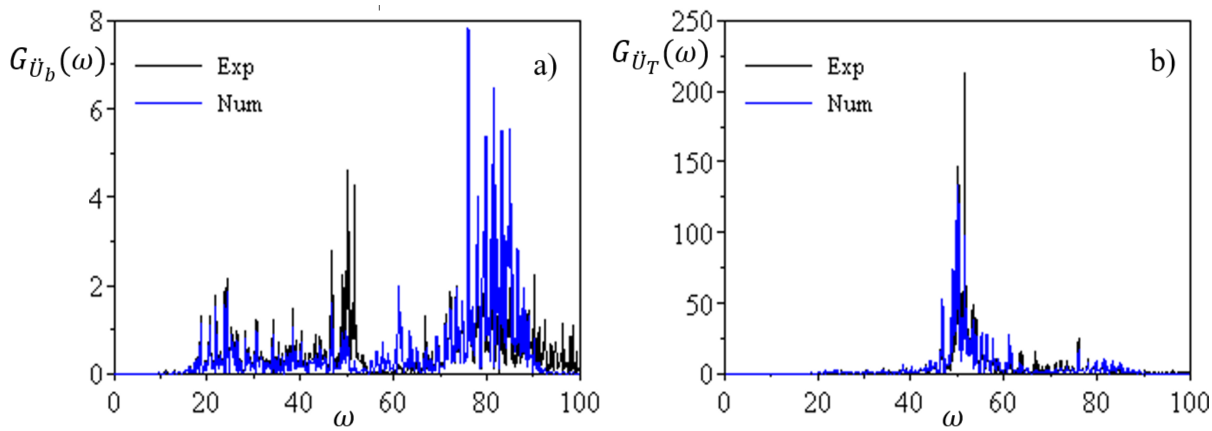

Figure 5: **Calibration**. Comparison between Shake Table and FE average Displacement Fourier Transform using clipped white noise ground motion time histories: a) bottom and b) top of the Tulou.

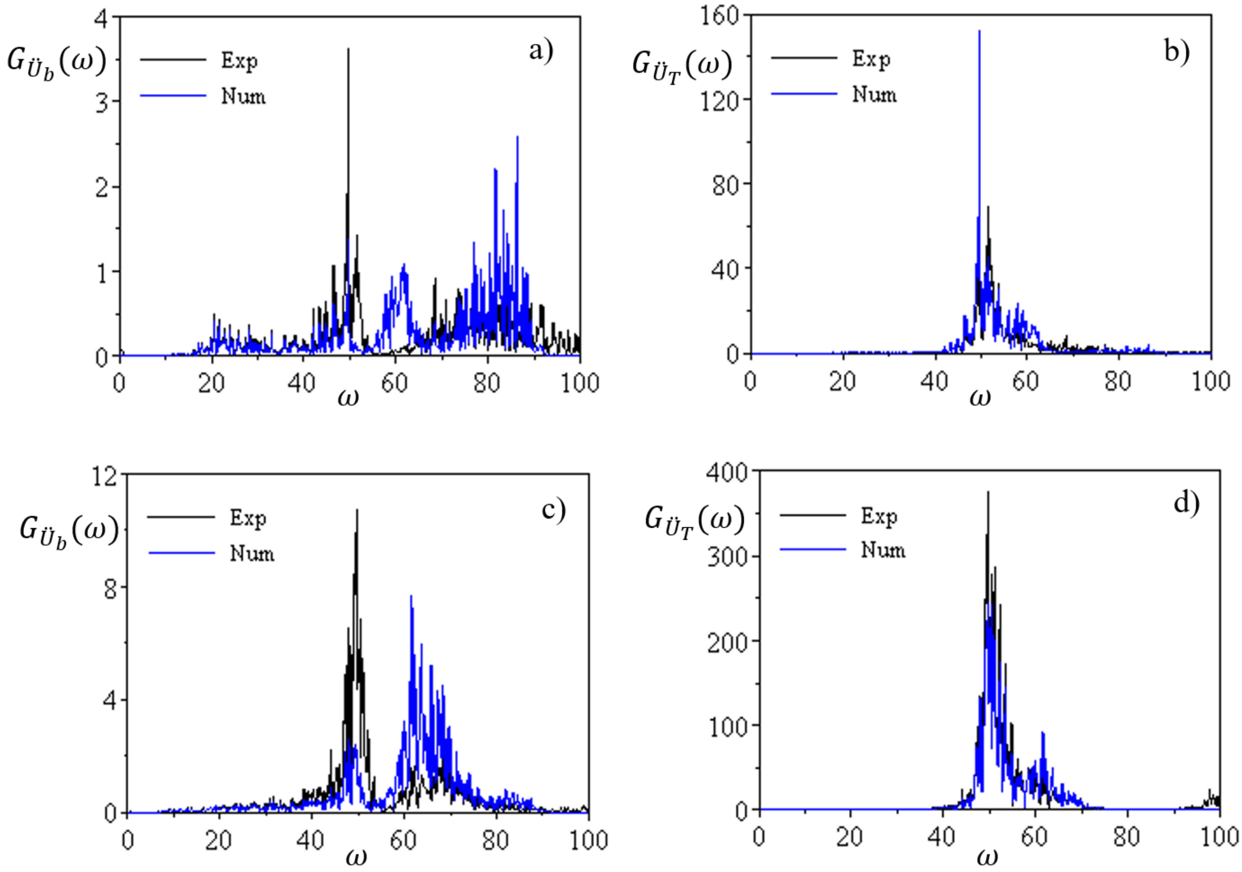

Figure 6: Verification. Comparison between Shake Table and FE average Displacement Fourier Transform using response-spectrum-compatible ground motion time histories for two level of excitation: a) and b) 0.05g; c) and d) 0.1g.

Figures 6 show the comparisons of the measured response acceleration PSD functions for two level of excitations, namely 0.05g and 0.1g. Also in this case, the results are in excellent agreement at the top of the Tulou, while some discrepancies can be found at the bottom of the Tulou.

3.3 ViBa design

Once the numerical model has been calibrated, the multi-step design approach described in Section 2 has been applied to determine the mechanical parameters of the ViBa. In this regard, an illustrative distance of 10cm (i.e. 10m in prototype scale), between the outer edges of ViBa and Tulou foundations has been considered.

The ViBa foundation has been made in acrylic (with a weight $M_f = 0.6378$ kg) while the ViBa mass is made of steel ($M_V = 3.9$ kg), less than half of the weight of the Tulou. The optimal values determined by the optimization algorithm using as selected parameter the base displacement led to a damping coefficient $C_V = 0.0076$ Nm/s and stiffness $K_V = 1.518\times10^4$ N/m.

Figure 7 presents the displacement power spectral densities of the Tulou with and without the ViBa protection. The absorbing feature of the ViBa to reduce the energy response is clearly evident. In order to perform the experimental tests, stiffness close to the optimal values has been secured using a series of commercially available springs. The optimal damping, on the other hand, was not imposed due to manufacturing limitations as the optimal damping was practically close to zero. The measured damping ratio, using the logarithmic decay method, led to a value of 6%.

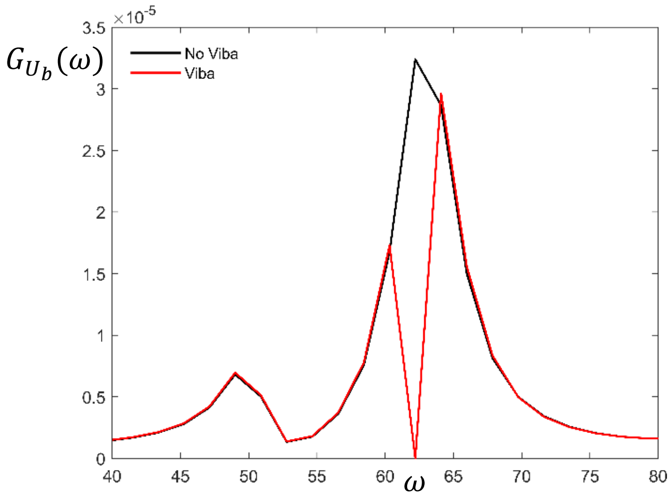

Figure 7: Power spectral density functions for the top and bottom accelerations at selected joints of the Tulou with and without the ViBa.

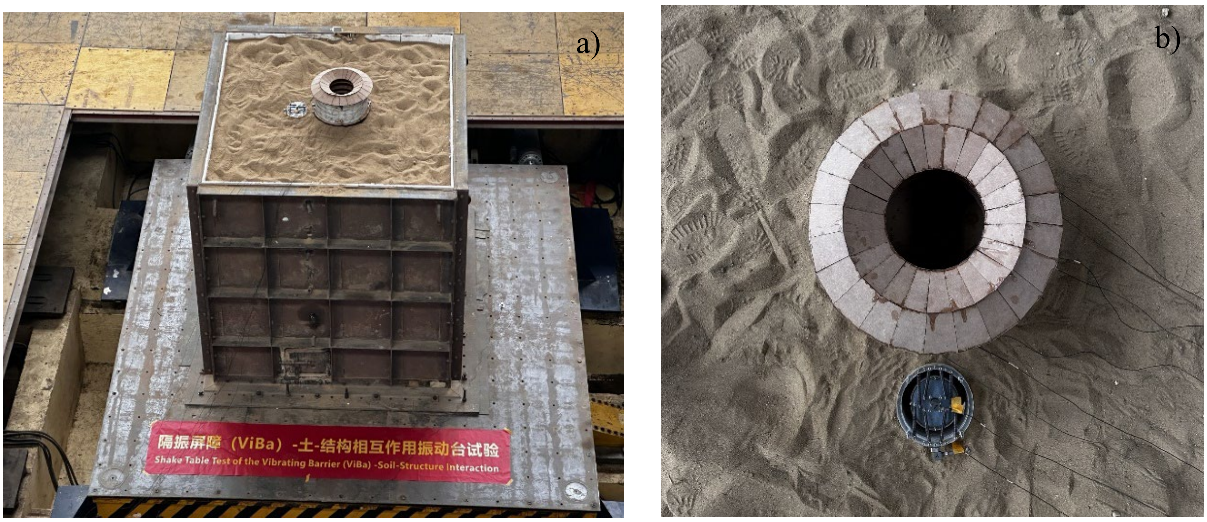

Figure 8: Shake Table set-up for ViBa-soil-Tulou testing a) overall arrangement, b) top view.

4 SHAKE TABLE RESULTS

Shake table experimental tests have been then carried on ViBa-soil-Tulou system. Figure 8 shows the experimental set up. Three randomly selected spectrum compatible ground motion time histories have been used for this purpose.

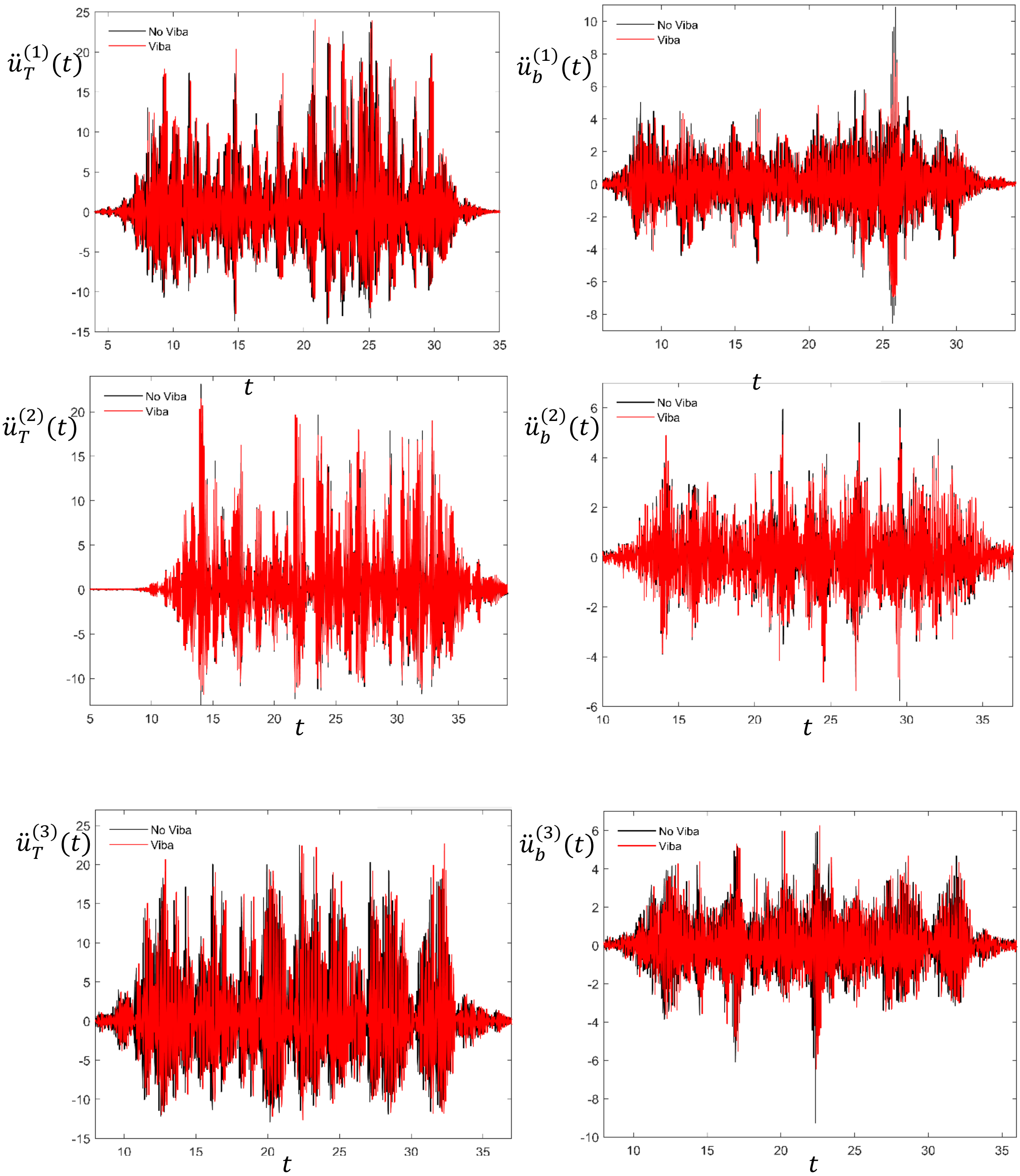

Figure 9: Recorded acceleration time histories [m/s^2]at the top a) and bottom b) of the Tulou under three randomly selected response spectrum compatible ground motion time histories.

As it can be seen from the comparisons between the measured trajectories (Figure 9), the ViBa was marginally effective to reduce the acceleration at the top of the Tulou. This was expected for the higher stiffness of the soil with respect to the structure itself. On the other hand, significant reduction has been observed at the base of the Tulou due to the ViBa radiated wave field.

It should be emphasized that, due to the high rigidity of the soil compared to the flexible behavior of the Tulou, the coupling mechanism, which could otherwise modify the dynamic response of the structure, was not significant. This further highlights the importance of uniformly scaling the properties of each material when studying soil-structure interaction and structure-soil-structure interaction.

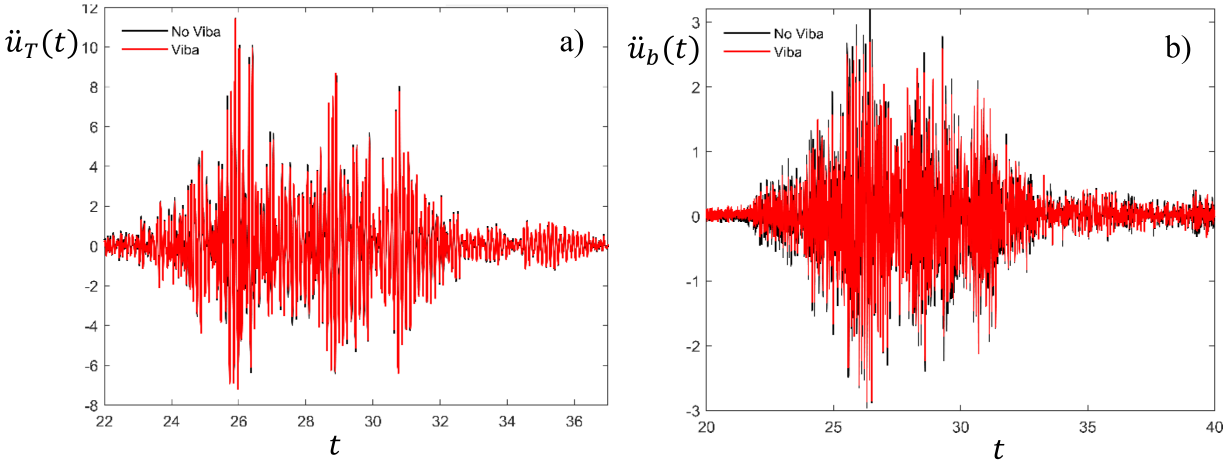

Figure 10: Recorded acceleration time histories [m/s^2] at the top a) and bottom b) of the Tulou under Taiwan earthquake.

Finally, a real ground motion time history recorded after the Taiwan 1999 earthquake has been used for further validation (see Figure 10). Similar trends have been observed also in this case, with a marginal reduction at the top of the Tulou and more significant (about 16%) at its base.

5 CONCLUDING REMARKS

Preliminary shake table tests for ViBa-soil-Tulou interaction study have been presented in this paper. A 1:100 scaled model of a Fujan Tulou has been built and tested using the shake table facility at Fuzhou University. The ViBa has been designed following a stochastic approach showing a clear absorption of energy corresponding to the peak acceleration power spectrum at a selected point of the Tulou.

Experimental tests showed a significant reduction of the accelerations at the base of the Tulou. Interestingly, although it was not possible to scale the mechanical properties of the sand used in the experiment, the ViBa showed promising features also in this realistic case scenario. Further tests are clearly needed to follow up this preliminary study.

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