Hindawi
Shock and Vibration
Volume 2022, Article ID 3439431, 6 pages
https://doi.org/10.1155/2022/3439431

Research Article

Dynamic Characterization of a Reinforcement Rammed Wall for the Earthen Ruins

Bei Liu,[1] **Yucheng Shi**,[1] **Kun Liu**,[2] **Tao Li**,[1] **and Shaopeng Wang**[1]

[1]*Lanzhou Institute of Seismology CEA, Lanzhou 730000, China*
[2]*Lanzhou Institute of Geotechnique and Earthquake CEA, Lanzhou 730000, China*

Correspondence should be addressed to Yucheng Shi; shiyc@gsdzj.gov.cn and Kun Liu; liukun@gsdzj.gov.cn

Received 1 November 2021; Accepted 5 February 2022; Published 10 March 2022

Academic Editor: Shan Gao

In recent years, the earthen ruins' cultural relics have aroused people's extensive attention, and the protection of them is more and more urgent. The aim of the paper is to present the essential results of an ongoing research on a reinforced rammed earthen wall in the Suoyang ancient city (Guazhou, China). A variety of methods to combining aerial survey, dynamic test, and numerical model is provided with the purpose of estimating the structural characteristics of the ancient rammed wall. An aerial geometric survey based on high-resolution images made by unmanned aerial vehicle (UAV) has been approached to acquiring a 3D model. An ambient vibration test has been adopted by using vibration pick-ups. The experimental data were dealt with the operational modal analysis (OMA) followed by comparing with the numerical results delivered by the model. Meanwhile, the results showed the maximum displacements and corresponding positions of the structure under the three modes by the finite element model (FEM).

1. Introduction

The conservation of ancient civilization architectures has received wide attention from the countries in which history carried vital cultural heritage. For instance, the earthen ruins are normally subjected to the intrinsic deterioration in time and the natural hazards [1]. Within the circumstance, they are of the greatest importance to develop and apply the reasonable methods for the sake of identifying the considerable structural parameters. Some scholars have conducted relevant research studies on the earthen ruins. For example, Li and Liu conducted field pulsation tests on the earthen site walls and obtained the spectral characteristics between the bottom and top of the walls as well as the self-oscillation period [2–4]. They correlated the structural properties of earthen sites and focused only on a certain point, i.e., obtaining the frequencies and periods at the bottom or the top of the site walls. However, the structural properties of a point for the wall usually were differed from the whole structure. The best way to access the structural dynamic characterization is to establish the dynamic monitoring system which is based on the vibration test. And, it can be safely applied to historical structures [5]. Frequency response function curvature technique and the modal analysis have extensive usage in the structural health monitoring [6]. Given the excitation force, both methods can be effective to detect damage in civil structures, while the latter may be the better method to access the dynamic characterization in the case of unknown excitation force. One of the ways to solve the above problem is the operational modal analysis (OMA). OMA is widely adoptable to masonry civic belfry [7], the masonry tower [8, 9], and other historical masonry buildings [10–13]. Pavlovic proposed an expeditious and low-cost procedure for the structural identification of historic masonry towers [14]. Numerical simulation is a very convenient method to understand the mechanical properties of structures. This method, combining with the vibration test, is also widely taken in civil engineering. Boscato [15, 16] has acquired the detection, localization, assessment, and prediction of damage for three different multileaf masonry specimens by the comparison between the experimental and numerical modal data calculated by the commercial finite element method (FEM). It is worth noting that the method has great advantages for nonlinear analysis [17].

The experimental work depicted in the paper followed an elementary investigation on a reinforcement rammed wall located in the Suoyang ancient city (Guazhou, China), under which actual conditions indicated that it has been strengthened and in order to avoid the loss of an ancient cultural architecture (Figure 1). We are all known that the currently conditions are the result of the restoration process against the other walls in the ancient city. While, there are ruins of the wall at different degrees of erosion damage. As the government departments pay more and more attention to the protection of cultural relics, strengthened cultural relics are processing. The wall is trapezoidal in cross section with two sides of about 6.5 m and 4.2 m; it is 10 m tall and the thickness of the rammed layer is 0.1 m. The top surface of the site is roughly terrace-shaped. Simplifying the actual situation can allow us to gain Figure 2. A trebling method is revealed combining an accurate aerial survey based on pictures processing, vibration testing, and FEM.

In the last decades, the possibility to conduct 3D surveys of intricate and inaccessible constructions has become more interesting for structural identification combining with the development of aerial measurements [18, 19]. In the paper, considerable amounts of images were taken by using unmanned aerial vehicle (UAV), which is subsequently drawn to make a 3D model. Furthermore, an ambient vibration test has been carried out using nine high-sensitivity seismic accelerometers. Measurements of velocity have been recorded for estimating dynamical parameters, including natural frequencies and mode shapes. The research is also ongoing to adjust a suitable numerical model and to access the positions and size of the maximum displacements of the reinforced rammed wall.

2. Aerial Photographic Survey and the 3D Model from UAV Technology

With the development of UAV technology, it is widely used in field investigations, especially in dangerous or inaccessible places [20]. Based on the high-resolution images provided by UAV technology, the size of the wall and the structural characteristics of the site provide the optimal case study for conducting architectural and geometric measurements.

The configuration used in the experiment can be epitomized into four stages: operation planning, data acquisition, data processing, and postprocessing representations. A considerable number of superimposed pictures can be obtained from the drone flight. It is commonly believed that the complete layout of the whole structure, the plan view, the one elevation, and the lower side of the wall could be generated from the datasets. Plotting the range of the flight on the remote controller, the target level of accuracy depended on the flight altitude, and as such, we must adjust the flight height. The flight was carried out using a Phantom 4 manufactured by DJI, which flew at an altitude of 80 m. Reducing the height can improve the accuracy, but it would greatly increase the cost of image processing. Thus, we need to take the height into account for processing costs. The flight range is the continuous walls in the east of Suoyang ancient city, and the object to be studied in the paper is a part of it. Therefore, it is necessary to intercept from them (Figure 3).

Figure 1: The reinforced site wall.

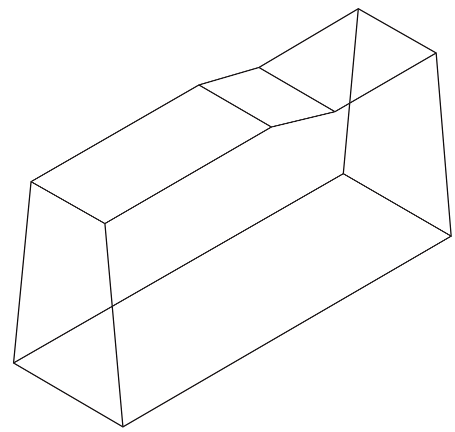


Figure 2: The simplified model of the wall.

3. Data Processing and Analysis

The dynamic characterization with reference to natural frequencies and corresponding modes has carried out the OMA using vibration response action under conditions by virtue of classical measurements.

3.1. Experimental Procedures and Methods. The dynamic response of the reinforced wall has been measured by using nine uniaxial accelerometers. The INV 3060S intelligent signal acquisition and processing system developed by COINV were selected as the experimental equipment, and the 941 B vibration pick-ups developed by Institute of Engineering Mechanics CEA were selected as the sensors. The sensitivity of the sensor was 23 V-s/m. The 9 sensors were divided into three groups; each group has 3 sensors in which the two horizontal and one vertical direction were measured, respectively. Placing three sets of vibration pick-ups in three positions for the purpose of the identification of vertical, horizontal, and torsional vibration modes, the sensors' arrangement is reported in Figure 4. There are three experiments in the testing methodology, each recording 300 s time series with a sample rate of 204.8 Hertz. Three sets of vibration pick-ups were named as A1, 1, and 2. The one point of A1 has been installed in the bottom of the wall as a reference system for the analysis, and the others were placed on the top of the wall. Each point has three arrows

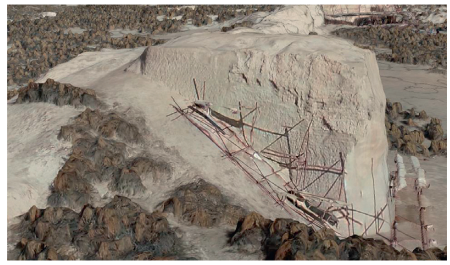


Figure 3: The reinforced wall in Suoyang city: virtual 3D model.

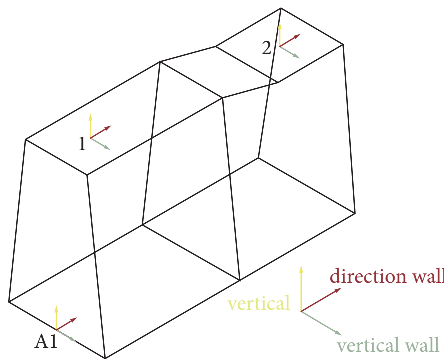


Figure 4: The sensors' arrangements in the wall.

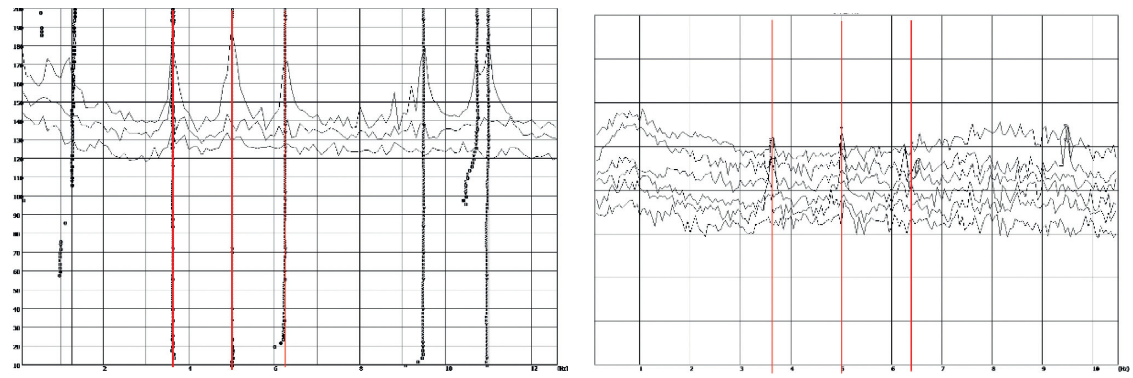
representing the three directions in which it is measured (Figure 4). It should be noted that the red arrow is the direction wall, the green arrow is the vertical wall, and the yellow arrow is the vertical.

3.2. Data Processing: SSI and EFDD. The data obtained from the sensors were processing by the stochastic subspace identification (SSI) algorithm in the time domain and the enhanced frequency domain decomposition (EFDD) method for identifying the modal parameters [21, 22]. Since the power spectral density spectrum estimated from the raw velocity data and the corresponding references [23, 24], the range of the frequencies should be below 10 Hertz. The ambition vibration data were processing to a cut-off frequency of 10 Hertz. Natural frequencies and vibration modes of the reinforced wall were estimated by using the SSI and EFDD. Figures 5(a) and 5(b) show the stability diagram for the SSI and the singular values of the spectral matrices of the testing for the EFDD, respectively.

The paper identified the frequencies and modes of the first-three orders (Figure 6). As shown in Figure 5, the frequencies identified by the stability diagram obtained by the SSI method and the singular values obtained by the EFDD method are basically the same (Table 1).

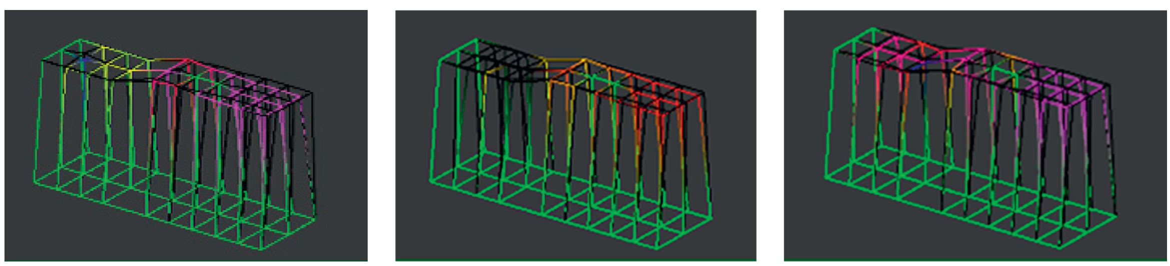
4. Results and Discussion

The experimental results in term of natural frequencies and related modes have summarized in the previous section. The numerical modelling of masonry structure has been investigated by many researchers [25, 26]. Meanwhile, the cloud map is applied to analysis the mechanical properties, which is widely used in masonry structures [27]. In the paper, the simplified numerical model was determined by the aerial survey carried out by direct method. The parameters with the material properties were gained from reference [28]. Due to the influence of historical and natural hazards, the material itself is damaged to varying degrees and unknowable. Hence, the parameters were acquired in the laboratory (density and elastic modulus) which need to be modified. In the study, the frequencies gained from the field test and the frequency obtained by finite element analysis were compared and analyzed. The final material property parameters (density and elastic modulus) were taken from combining specific formulas for calculation [29]. Figure 7 shows the results of the numerical modal analysis. The comparison between the results in Figures 6 and 7 revealed a good consistency between the experiment and FEM. The same can be seen when compared with the modes. The first two orders of deformation appeared in the horizontal direction. The first-order can be regarded as transverse bending, and the second order can be considered as torsional deformation occurring in the plane. The third order of deformation occurred in the vertical direction. Meanwhile, the paper reports on the results that the maximum displacements and positions correspond to each of the three modes [30]. What is interesting is that, in the maximum positions, the displacements are the same, which are all near the left top of the free surface, and the corresponding displacements are 0.071 mm, 0.077 mm, and 0.065 mm, respectively. As can be seen from the figure, the first-three orders of modes' vibration are not complicated, due to the limitations of the experimental equipment, and the OMA can only identify the lower orders of modalities. The sensors were not positioned on either side of the top surface; therefore, the torsional



(a) (b)

Figure 5: The pictures with two different techniques. (a) Stability diagram for SSI. (b) Singular value for EFDD.

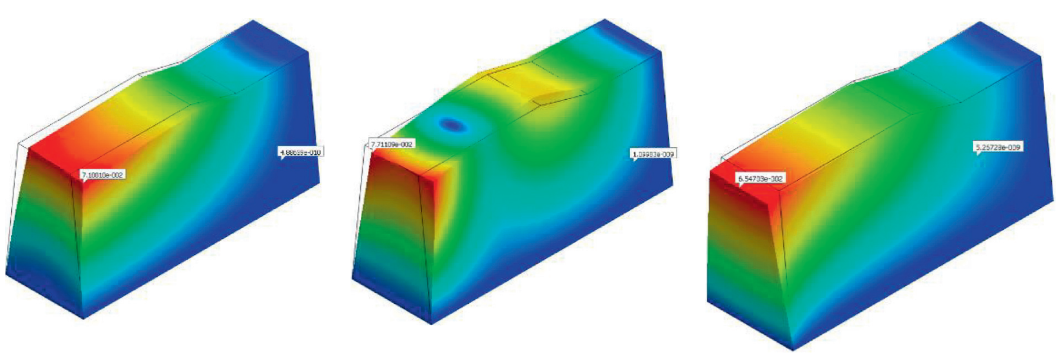


(a) (b) (c)

Figure 6: Experimental frequencies and vibration modes. (a) First-order transverse bending, $f_1 = 3.626$ Hz, and damp = 0.861%. (b) Second-order left and right torsion, $f_2 = 5.018$ Hz, and damp = 0.416%. (c) Third-order vertical bending, $f_3 = 6.372$ Hz, and damp = 1.876%.

Table 1: The frequencies and damping for the research.

Modes (#)	SSI		EFDD		Mean	
	Freq (Hz)	Damp (%)	Freq (Hz)	Damp (%)	Freq (Hz)	Damp (%)
1	3.629	1.19	3.624	0.532	3.626	0.861
2	5.012	0.82	5.024	0.012	5.018	0.416
3	6.251	1.52	6.493	2.232	6.372	1.876



(a) (b) (c)

Figure 7: Numerical frequencies and vibration modes. (a) First-order transverse bending, $f_{1\mathrm{FEM}} = 3.34$ Hz, (b) second-order left and right torsion, $f_{2\mathrm{FEM}} = 5.417$ Hz, and (c) third-order vertical bending, $f_{3\mathrm{FEM}} = 6.098$ Hz.

modes in the vertical direction were not identified. In fact, there are higher order torsional modes in the vertical direction, as evidenced by the FEM results. The 3D model obtained from the UAV flight was applied to be built as accurate as possible. Because the modelling built in the paper is regular, there are some slight differences in details from the actual one, such as the existence of a partial gap at the top of the wall which is neglected in the finite element model. More importantly, the wall is more nonuniform and nonhomogeneous on account of the effects of historical and natural disasters. This could explain the discrepancies between the experimental and FEM analyses.

5. Conclusion

Based on the results and discussion presented above, the conclusions are obtained as below:

(1) It is presented by applying the UAV technology to the research object, and the classical test was performed by using high-sensitivity sensors. The vibration tests were attempted both to compare effectiveness of different techniques (SSI and EFDD) on such constructions and to conduct the dynamic structural identification.

(2) An elementary comparison between the simplified numerical FEM and the OMA results demonstrated that we need to take the changes in material parameters caused by the damage against the structural system into account.

(3) The experimental tests will be reported with the structural unreinforced for the purpose of investigating the change of the dynamic properties between the reinforced wall and the unreinforced. This will give us a significant amount of useful information on the seismic effect for the reinforced wall.

Data Availability

The data were obtained by the author through practical tests, and part of the data were quoted from relevant references and indicated within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Bei Liu and Yucheng Shi were the main authors of the article. Bei Liu was the first author and participated in the whole process of the field experiment and data analysis; meanwhile, Shi Yucheng was the corresponding author of the paper and has also revised the paper. Kun Liu participated in the whole process of the experiment and modified the paper. Tao Li and Shaopeng Wang participated in the whole field experiment.

Acknowledgments

The authors would like to thank the National Key Research and Development Program of China (2020YFC1522200) and the Fundamental Research Funds for the institute of Earthquake Forecasting, China Earthquake Administration (2019IESLZ04) for their financial support for the manuscript, through the project "The Study on Degradation Process and Protection Technology of Earthen Ruins under multi-field coupled." The authors also acknowledge S. D. Wei, from COINV, for his support with test methods and software processing. The authors also wish to thank Y. X. Lu, P. H. and Chi et al. for their contributions to this research activity.

References

[1] M. L. Sun, X. D. Wang, and Z. X. Li, *A Primer on the Conservation of Earthen Sites*, Science Press, Beijing, China, 2010, in Chinese.

[2] T. L. Li, "Disease characteristic and dynamic test analysis of jiaohe ancient city," *Journal of Seismological Research*, MSC Thesis in Chinese, Lanzhou Institute of Seismology, CEA, Lanzhou, China, 2020.

[3] T. L. Li, Y. C. Shi, K. Liu, Y. X. Lu, C. Y. Wang, and Z. Y. Xian, "Disease characteristics and dynamic test analysis of jiaohe ancient city," *Journal of Seismological Research*, vol. 43, no. 3, pp. 456–462+601, 2020, in Chinese.

[4] K. Liu, T. L. Li, Y. C. Shi, H. M. Tang, and Z. Y. Xian, "Dynamic response analysis of inner wall soil site in the ancient gaochang city," *Journal of Disaster Prevention and Mitigation Engineering*, vol. 40, no. 6, pp. 1–7, 2020, in Chinese.

[5] G. Boscato, L. Z. Fragonara, A. Cecchi, E. Reccia, and D. Baraldi, "Structural health monitoring through vibration-based approaches," *Shock and Vibration*, vol. 2019, Article ID 2380616, 5 pages, 2019.

[6] M. C. Porcu, D. M. Patteri, S. Melis, and F. Aymerich, "Effectiveness of the FRF curvature technique for structural health monitoring," *Construction and Building Materials*, vol. 226, pp. 173–187, 2019.

[7] S. Casciati and R. Al-Saleh, "Dynamic behavior of a masonry civic belfry under operational conditions," *Acta Mechanica*, vol. 215, no. 1-4, pp. 211–224, 2010.

[8] B. Gianni, B. Michele, and G. Saverio, "In situ static and dynamic investigations on the "Torre Grossa" masonry tower," *Engineering Structures*, vol. 52, pp. 718–733, 2013.

[9] G. Carmelo, G. Marco, and S. Antonella, "One-year dynamic monitoring of a historic tower: damage detection under changing environment," *Mechanics*, vol. 51, pp. 2873–2889, 2016.

[10] C. Carla, C. Rainieri, M. A. Aiello, and G. Fabbrocino, "On-site assessment of masonry vaults: dynamic tests and numerical analysis," *Geofizika*, vol. 28, no. 1, pp. 127–143, 2011.

[11] N. Nisticò, S. Gambarelli, A. Fascetti, and G. Quaranta, "Experimental dynamic testing and numerical modeling of historical belfry," *International Journal of Architectural Heritage*, vol. 10, no. 4, pp. 476–485, 2016.

[12] A. C. Altunisik, S. Adanur, A. F. Genc, M. Gunaydin, and F. Y. Okur, "An investigation of the seismic behaviour of an ancient masonry bastion using non-destructive and numerical methods," *Experimental Mechanics*, vol. 57, no. 2, pp. 245–259, 2016.

[13] C. Pepi, M. Gioffrè, G. Comanducci, N. Cavalagli, A. Bonaca, and F. Ubertini, "Dynamic characterization of a severely damaged historic masonry bridge," *Procedia Engineering*, vol. 199, pp. 3398–3403, 2017.

[14] M. Pavlovic, S. Trevisani, and A. Cecchi, "A procedure for the structural identification of masonry towers," *Journal of Nondestructive Evaluation*, vol. 38, no. 2, 2019.

[15] G. Boscato, E. Reccia, D. Baraldi, and A. Cecchi, "Sensitivity to damage imperfection for multileaf masonry walls based on vibrational analyses," *Shock and Vibration*, vol. 2018, Article ID 2321589, 14 pages, 2018.

[16] G. Boscato, E. Reccia, and A. Cecchi, "Non-destructive experimentation: dynamic identification of multi-leaf masonry walls damaged and consolidated," *Composites Part B: Engineering*, vol. 133, pp. 145–165, 2018.

[17] D. Baraldi, C. B. De Carvalho Bello, A. Cecchi, E. Meroi, and E. Reccia, "Nonlinear behavior of masonry walls: FE, DE, and FE/DE models," *Composites: Mechanics, Computations, Applications, An International Journal*, vol. 10, no. 3, pp. 253–272, 2019.

[18] E. Ippoliti, A. Meschini, and F. Sicuranza, "Structure from motion systems for architectural heritage. A survey of the internal loggia courtyard of palazzo dei capitani, ascoli piceno, Italy," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5/W4, pp. 53–60, 2015.

[19] M. Gioffré, N. Cavalagli, C. Pepi, and M. Trequattrini, "Laser Doppler and radar interferometer for contactless measurements on unaccessible tie-rods on monumental buildings: santa maria della consolazione temple in todi," *Journal of Physics: Conference Series*, vol. 778, no. 1, Article ID 012008, 2017.

[20] R. Argiolas, A. Cazzani, E. Reccia, and V. Bagnolo, "From lidar data towards hbim for structural evaluation," *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2/W15, no. 2/W15, pp. 125–132, 2019.

[21] B. Peeters and G. De Roeck, "Stochastic system identification for operational modal analysis: a review," *Journal of Dynamic Systems, Measurement, and Control*, vol. 123, no. 4, pp. 659–667, 2001.

[22] Y. G. Chen and Z. Y. Zhong, "An improved stochastic subspace method for modal parameter identification for bridge structures under ambient excitation," *Journal of Vibration and Shock*, vol. 39, no. 16, pp. 196–204, 2020, in Chinese.

[23] D. Foti, M. Diaferio, N. I. Giannoccaro, and M. Mongelli, "Ambient vibration testing, dynamic identification and model updating of a historic tower," *NDT & E International*, vol. 47, pp. 88–95, 2012.

[24] M. Diaferio, D. Foti, and N. I. Giannoccaro, "Non-destructive characterization and identification of the modal parameters of an old masonry tower," in *Proceedings of the IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems Proceedings*, Naples, Italy, September 2014.

[25] M. Marchi, R. Butterfield, G. Gottardi, and R. Lancellotta, "Stability and strength analysis of leaning towers," *Géotechnique*, vol. 61, no. 12, pp. 1069–1079, 2011.

[26] D. Abruzzese, L. Miccoli, and J. Yuan, "Mechanical behavior of leaning masonry Huzhu Pagoda," *Journal of Cultural Heritage*, vol. 10, no. 4, pp. 480–486, 2009.

[27] N. Kassotakis, V. Sarhosis, B. Riveiro et al., "Three-dimensional discrete element modelling of rubble masonry structures from dense point clouds," *Automation in Construction*, vol. 119, Article ID 103365, 2020.

[28] Y. C. Shi, X. D. Wang, M. Q. Hu, and S. Li, "Seismic safety analysis of typical earthen archaeological sites in Northwest China," *World Earthquake Engineering*, vol. 26, pp. 148–152, 2010, in Chinese.

[29] Y. L. Wang, "A Theoretical study on structural stability assessment for historical ramparts in dry areas," PhD Dissertation in Chinese, Xi'an University of Architecture and Technology, Xi'an, China, 2018.

[30] M. Betti and A. Vignoli, "Modelling and analysis of a Romanesque church under earthquake loading: assessment of seismic resistance," *Engineering Structures*, vol. 30, no. 2, pp. 352–367, 2008.