Journal of Southeast University (English Edition) Vol. 29, No. 3, pp. 289 - 293 Sept. 2013 ISSN 1003—7985

Finite element analysis of the Taizhou Water Station Site

Pan Jianwu[1] Chun Qing[2]

([1]Civil Engineering Department, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)
([2]School of Architecture, Southeast University, Nanjing 210096, China)

Abstract: The Taizhou Water Station Site is an ancient masonry structure ruin built in the Southern Song Dynasty. The main structure was severely damaged. In order to understand its current structural properties and provide a scientific basis for protection design, nonlinear finite element analysis and parameter analysis are carried out. The crack patterns, deformations and stresses of the main structure under four load cases are analyzed by nonlinear finite element analysis, and the effect of the backfill bulk density and modulus on the maximum principal tensile stress and maximum compressive stress are studied by parameter analysis. The results show that the most unfavorable condition for the foundation is the combination of weight + backfill soil pressure + additional load; the most unfavorable load case to the main structure is weight + backfill soil pressure + water pressure + additional heap load; the maximum principal tensile stress of the main structure is very sensitive to the changes in the bulk density of the backfill soil.

Key words: finite element analysis; Taizhou Water Station Site; ancient masonry structure

doi: 10.3969/j.issn.1003 - 7985.2013.03.011

The Taizhou Water Station was built in the Southern Song Dynasty (1127—1279) in China. It was a half-underground masonry structure and the function was to vessel traffic for the south gate of the ancient Taizhou City. The ruin was discovered in 2009 and was considered to be very valuable in studying the history of the ancient city of China. It was approved as a municipal heritage conservation unit in 2010.

Some researchers have done site testing and the finite element analysis (FEA) on several types of ancient masonry structures such as tower, tomb, etc[2-8]. Zhang and Xi[1] carried out a stability analysis of the ancient wall of Pingyao City by ANSYS. Lei et al.[2] also did reinforcement technique researches on Pingyao ancient city wall. Yang and Chen[3-4] did some discussion on the maintenance and strengthening of the Nanjing city wall. Liang[5] studied the protection and strengthening techniques of the Tower of Niya Site in Xinjiang. Deng[6] did some security analysis and reinforcement research on the ancient brick-and-clay city gate structure in Nanjing. Jing et al.[7] did safety analysis of Shangfang Tumulus in Nanjing by ANSYS. Some foreign scholars also did some researches on ancient brick architecture by finite element analysis[8-10]. But the research concerning the water station site has seldom been analyzed. The load case of a water station site is more complicated because the load cases are combined with self weight, backfill soil pressure, water pressure, and additional heap load, etc.

The length of the Taizhou Water Station Site is 28.6 m, and the width is 14.15 m. It has been found locally collapsed and severely damaged, so there are security risks, as shown in Fig. 1. In order to understand the true state of the structure and its material properties, and to provide a scientific basis for protection design, some works on detection, identification and finite element analysis are carried out.

(a) (b)

Fig. 1 Present view of the Taizhou Water Station Site. (a) Inside view; (b) Outside view

1 Detection and Identification

We select three seriously weathered and fracture positions on the wall, and conduct the field test to the bricks and mortar with non-destructive testing methods (see Fig. 2). The test results show that the strength level of the bricks is about 7.5 to 10 MPa, and the compressive strength of the mortar is about 0.8 to 1.3 MPa.

The wall integrity of both sides of the gate arch is relatively good, but the wings of the walls have a larger range of collapse (see Fig. 1(b)). The appearance of bricks shows a mild form of weathering, breakage, and local rammed earth scouring. There is a very obvious hole in the east part of a wall with the size of about 1.9

Received 2013-01-12.

Biography: Pan Jianwu (1976—), male, doctor, associate professor, panjianwu@nuaa.edu.cn.

Foundation item: The National Natural Science Foundation of China (No. 51108238).

Citation: Pan Jianwu, Chun Qing. Finite element analysis of the Taizhou Water Station Site[J]. Journal of Southeast University (English Edition), 2013, 29(3): 289 - 293. [doi: 10.3969/j.issn.1003 - 7985.2013.03.011]

m in height, 1 m in width and 0.95 m in depth (see Fig. 2). There is also a very obvious hole in the west part of the wall with the size of about 0.3 m in height, 0.4 m in width and 0.5 m in depth. Fig. 2 to Fig. 4 show the present condition of the wall holes, weathered bricks and damaged foundation, respectively.

Fig. 2 Wall holes

Fig. 3 Weathered bricks

Fig. 4 Damaged foundation

2 FEA Model

In order to obtain better insight into the hidden security risks, the ANSYS™ software is used to do nonlinear finite element numerical simulation analysis on the main structure, mainly studying stress characteristics and security of the main structure under load case combinations such as backfill, flooding, additional heaped load, etc.

1) Simplification and assumptions

The main structure of the Taizhou Water Station Site is made of bricks, stones, and rammed earth composite materials. It is very complex and seriously damaged with poor integrity. So we assume that the main holes in the walls have already been repaired. The wall brick is simplified as an isotropic continuous homogeneous material. Geometric dimensions are modeled with practical mapping size, and internal dimensions are modeled according to the survey results. Because it is similar to biaxial symmetry, we take 1/4 part of the whole main structure to establish the FEA model.

2) Parameter values

Considering the test data, the geological survey report and masonry specification, in accordance with the principle of partial conservative value[7], the parameter values of FEA models are as follows: ① The density, the elastic modulus, the Poisson ratio, the compressive and tensile strengths of wall brick are 2 200 kg/m^3, 1 112 MPa, 0.2, 0.8 MPa and 0.06 MPa, respectively. ② The density, the elastic modulus, the Poisson ratio, the cohesion, the internal friction angle of backfill soil are 1 900 kg/m^3, 20 MPa, 0.35, 10 kPa and 20°, respectively; ③ The density, the elastic modulus, the Poisson ratio of undisturbed soil are 1 900 kg/m^3, 40 MPa, 0.35, respectively; ④ Water pressures (including the lateral pressure and buoyancy) are directly applied to the main structure as surface loads; ⑤ The additional heap load on the backfill soil is 5 kPa.

3) Element and meshing

Commercial finite element software ANSYS™ (version 13.0) is used to establish a solid model, and then it is meshed. The finite element mesh is shown in Fig. 5. The element types are Solid45 (modeling the backfill soil and undisturbed soil, using the Drucker-Prager constitutive model) and Solid65 (modeling the main structure, using the William-Warnke failure criterion, considering cracking and crushing). The element size is about 0.5 m. The number of elements is approximately 2.1×10^4.

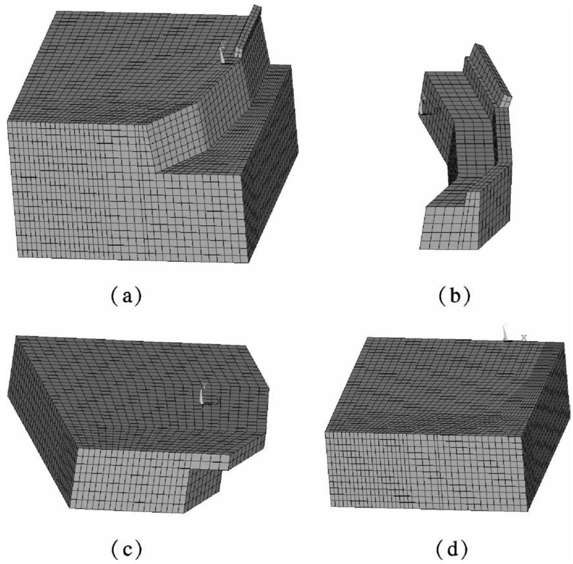

Fig. 5 FEA model. (a) Whole model; (b) Main structure; (c) Backfill soil; (c) Undisturbed soil

3 Analysis Type

3.1 Nonlinear analysis

Nonlinear analysis is carried out to study the crack pattern, deformation, the stress of the main structure, and the stress of foundation under the combined effect of four load cases, including: 1) Weight + backfill soil pressure.

This case mainly simulates overburdened backfill soil. 2) Weight + backfill soil pressure + water pressure. This case mainly simulates the situation about the combination of adverse conditions after overburdened backfill soil due to the high water level, and backfill drainage due to poor permeability etc. 3) Weight + backfill soil pressure + additional loading. This case mainly simulates adverse conditions such as loads of outbuildings, construction of temporary heap load after overburdening of backfill soil. 4) Weight + backfill soil pressure + water pressure + additional heap load. This case mainly simulates adverse conditions considering the combined influences of 2) and 3).

3.2 Parameter analysis

The material of the main structural model is considered as linear elastic material, and then analysis is carried out to study the impact of such factors as backfill bulk density and elastic modulus on the maximum principal tensile stress and maximum principal compressive stress of the main structure.

4 Analysis Results

4.1 Nonlinear analysis results

The FEA analysis results of all the load cases are shown in Fig. 6 to Fig. 9. According to the results of the four load cases, the most unfavorable load case to the foundation is load case 3 (weight + backfill soil pressure + additional heap load). It causes the base pressure to be slightly larger than the bearing capacity of the foundation. It also causes some cracks to occur at the end part of the wall, as shown in Fig. 8. The base pressures caused by the other three load cases are less than the bearing capacity of foundation, but the surpluses are insufficient, as shown in Fig. 6, Fig. 7, and Fig. 9.

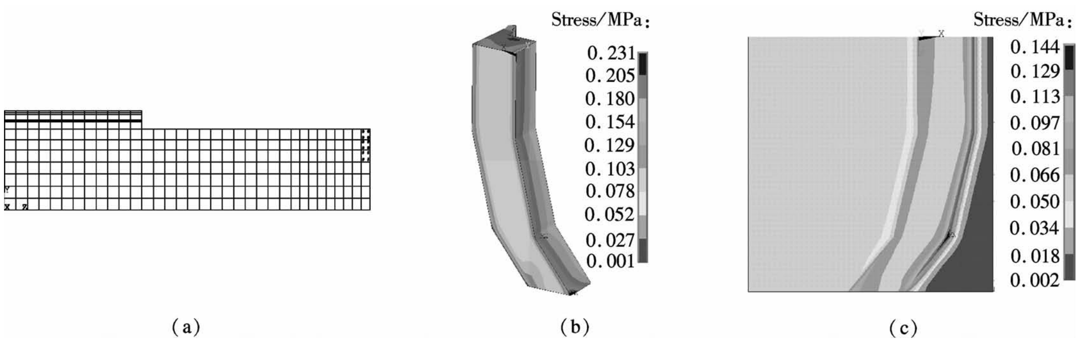

Fig. 6 Result of load case 1. (a) Cracks (lateral view); (b) S3; (c) Base S3

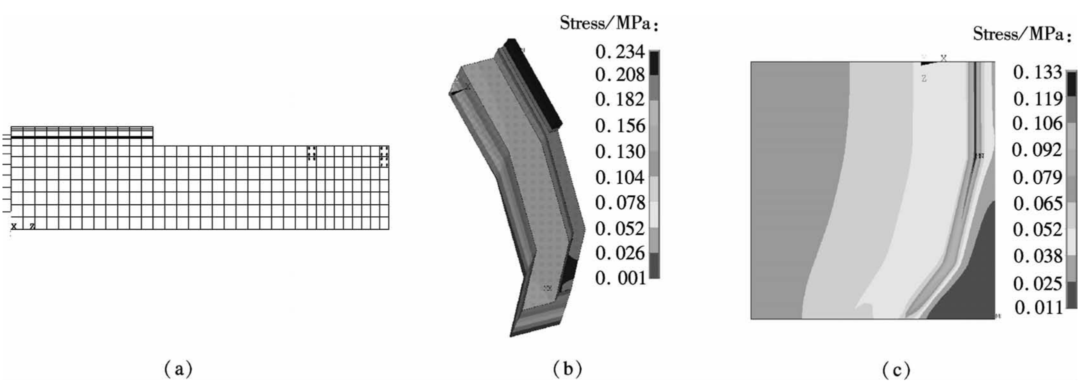

Fig. 7 Result of load case 2. (a) Cracks (lateral view); (b) S3; (c) Base S3

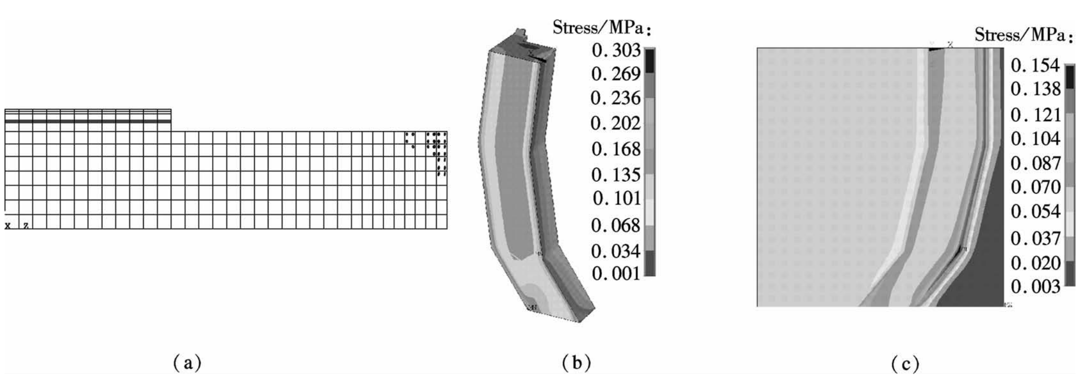

Fig. 8 Result of load case 3. (a) Cracks (lateral view); (b) S3; (c) Base S3

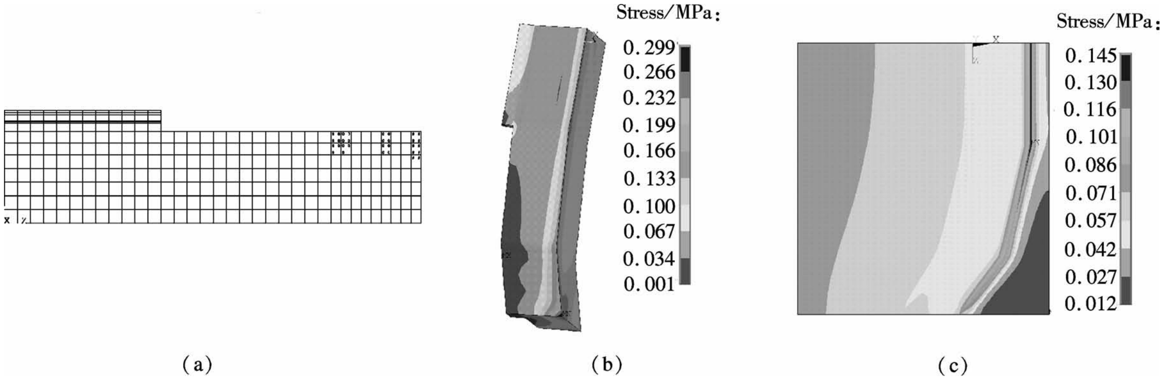

Fig. 9 Result of load case 4. (a) Cracks (lateral view); (b) S3; (c) Base S3

The most unfavorable load case to the main structure is load case 4 (weight + backfill pressure + water pressure + additional heap load). It causes that many cracks occur at the end part of the wall, as shown in Fig. 9.

In all the load cases, the main structure does not appear as a crushing sign, and the principal compressive stress has a large amount of surplus. The lateral displacement of the main structure is also small; namely, the main structure has a high overall stability.

4.2 Parameter analysis results

The relationships between the principal stress and the backfill density, and the relationships between the principal stress and the elastic modulus are shown in Fig. 10(a) and Fig. 10(b), respectively. The maximum first principal stress is defined as S1Max and the maximum third principal stress is defined as S3Max.

S1Max and the backfill bulk density show a nearly linear growth relationship (see Fig. 10(a)). When the bulk density increases from 14 to 19 kN/m^3, S1Max is increased by 62%. It shows that S1Max is very sensitive to the changes in the backfill bulk density. S3Max and the backfill bulk density show a nonlinear growth (see Fig. 10 (b)). When the bulk density is between 14 and 17 kN/m^3, small changes occur in S3Max. When the bulk density increases from 17 to 19 kN/m^3, S3Max is increased by 14%. S1Max and the backfill elastic modulus show a nonlinear reduction relationship (see Fig. 10 (b)). S1Max is decreased 31% when the elastic modulus increases from 5 to 30 MPa. S3Max and the backfill elastic modulus also show a nonlinear reduction relationship (see Fig. 10(b)). When the elastic modulus increases from 5 to 30 MPa, S3Max is decreased by 23%. Therefore, S1Max and S3Max are quite sensitive to the changes in the elastic modulus of the backfill soil.

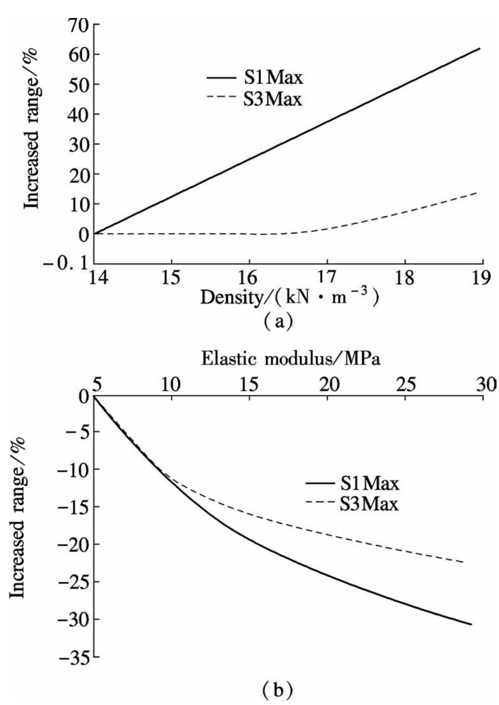

Fig. 10 Parameter analysis results. (a) S1max and S3Max vs. backfill density; (b) S1Max and S3Max vs. backfill elastic modulus

5 Conclusions

Based on the above site testing and FEA analysis results, the following conclusions and recommendations can be presented:

1) Effective measures should be taken to strengthen the base ground and improve the bearing capacity of the foundation.

2) Serious damage in the main structure of the Taizhou Water Station Site such as cracks or holes should be repaired with methods such as grouting.

3) After repair, the waterproof layer and drainage system should be prepared carefully. Reliable measures should be taken to reduce the soil pressure on the crack-prone parts. The backfill soil should have good permeability and its bulk density should be small.

4) Additional load should be avoided being delivered directly to the main structure. If unavoidable, lightweight materials should be selected, and technical measures should be taken to make the load evenly delivered to the original main structure, to avoid severe local uneven load. The construction load should be strictly controlled in the repair and strengthening construction.

5) A regular inspection system should be established,

and the long-term deformation and subsidence of the main structure should be monitored.

References

[1] Zhang Wenge, Xi Xiangdong. Stability analysis of the ancient wall of Pingyao city [J]. *Building Structure*, 2009, **39**(3): 110 – 112. (in Chinese)

[2] Lei Honggang, Lu Jianguo, Wu Tao. Reinforcement techniques research of Pingyao ancient city wall [J]. *Building Structure*, 2007, **37**(S1): 234 – 237. (in Chinese)

[3] Yang Ming. Discussing the maintenance and strengthening of Nanjing city wall [J]. *Building Structure*, 2010, **40**(S1): 291 – 294. (in Chinese)

[4] Chen Lanlan, Cao Shuangyin. Application of grouting in rehabilitation of front gate of the Imperial Palace in Nanjing [J]. *Building Structure*, 2007, **37**(S1): 258 – 260. (in Chinese)

[5] Liang Tao. Protection and strengthening of the tower of Niya Site in Xinjiang [J]. *Dunhuang Research*, 2008, **112**(6): 34 – 38. (in Chinese)

[6] Deng Chunyan. The security analysis and reinforcement research of ancient brick-and-clay city gate structure [D]. Nanjing: Southeast University, 2004. (in Chinese)

[7] Jing Denghu, Zhao Guodong, Mu Baogang, et al. Safety analysis of Shangfang Tumulus in Nanjing [J]. *Special Structure*, 2009, **26**(2): 71 – 74. (in Chinese)

[8] Levy R, Dawson P. Using finite element methods to analyze ancient architecture: an example from the North American Arctic [J]. *Journal of Archaeological Science*, 2009, **36**(10): 2298 – 2307.

[9] Balocco C, Grazzini G. Numerical simulation of ancient natural ventilation systems of historical buildings. A case study in Palermo [J]. *Journal of Cultural Heritage*, 2009, **10**(2): 313 – 318.

[10] Tsesarsky M, Gal E, Machlav E. 3-D global-local finite element analysis of shallow underground caverns in soft sedimentary rock [J]. *International Journal of Rock Mechanics and Mining Sciences*, 2013, **57**(1): 89 – 99.

泰州水关遗址的有限元分析

潘建伍[1]　淳　庆[2]

([1] 南京航空航天大学土木工程系,南京 210016)

([2] 东南大学建筑学院,南京 210096)

摘要:泰州水关遗址是始建于宋代的古砌体城墙遗址,其主结构已严重残损. 为了解其结构现状,为保护修缮设计提供科学依据,进行了有限元分析和参数分析. 利用有限元分析法分析了 4 种工况下的裂缝模式、变形和应力;用参数分析法研究了回填土容重、模量等因素对主体结构主拉应力最大值和主压应力最大值的影响. 结果表明:对地基最不利的工况组合是自重 + 回填土压力 + 附加堆载;对主体结构最不利的工况组合是自重 + 回填土压力 + 水压力 + 附加堆载;主体结构的主拉应力最大值对回填土容重的变化很敏感.

关键词:有限元分析;泰州水关;古砌体结构

中图分类号:TU365