Stability Analysis of Earthen Sites Reinforced with Stabilized Soil Including Calcified Ginger Nuts based on Finite Element Numerical Simulation

Xiaoying Hu¹, Dandan Li¹, Erxing Peng²*, Yaling Chou¹, Qifeng Li³ and Bing Dang³

¹School of Civil Engineering, Lanzhou University of Technology, Lanzhou, China
²State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China
³The Third Institute of Geology and Minerals Exploration, Gansu Provincial Bureau of Geology and Minerals Exploration and Development, Lanzhou, China

*Email: erxingpeng@lzb.ac.cn

Abstract. The stability of the earthen sites wall of Niutoucheng in Lintan County is studied by using the strength reduction method and finite element analysis software ABAQUS. The stability of the model before and after the reinforcement of the central undercutting wall of the earthen sites was analyzed. The strain distribution and stability safety factor variation before and after reinforcing earthen with calcined ginger nuts are discussed. The results show that the development of plastic strain zone is significantly restrained after reinforcing undercutting zone by using stabilized soil including calcined ginger nuts. The stability safety factor of the earthen sites wall model after the central undercutting presents an increasing trend. The stability safety factor of the model before undercutting is 1.430. The stability safety factor of the model is 1.959 and 1.966 after ramming for 7d and 14d, respectively. The judgment of plastic strain zone development and the stability safety factor of a model can be used to guide application of stabilized soil including calcined ginger nuts in engineering practice.

1. Introduction

As cultural relic resource, earthen sites take the soil as the building material and are the products from human production and life in history [1]. About 30% of the world's ruins are earthen sites [2]. As one of the four ancient civilizations, China has a long history of earthen ruins, which stretch for thousands of miles. Especially in the northwest of China, due to the arid natural environment, many earthen sites have been preserved [3]. Niutoucheng is a witness of a long civilization and splendid culture in a certain period of human history. However, due to the early age of the earthen sites in our country, there are serious diseases such as crevices, collapse, flaky denudation, and gullies [4-9]. Therefore, the protection of historical and cultural heritage is urgently needed.

As an important research content of earthen sites protection engineering, the stability of earthen sites has attracted much attention. Numerical simulation is the most widely used method to assist the analysis and evaluation of rock and soil stability in recent years. It can establish a model through the principle of simplification and use numerical simulation software to calculate the stability safety factor, and then evaluate the stability of rock and soil. In the application of numerical calculation method of earthen sites stability, Wang et al. [10] use the finite difference software to analyze the wall stability of the Ming Great Wall Site in Gulang County under static action. The distribution law of wall displacement and the
distribution characteristics of stress field under different undercutting depths are obtained. He, Wang, Shi, et al. [11-13] used simulation software to conduct stability analysis and numerical simulation on the grave of General Gaogouli and put forward targeted protection measures. Wang et al. [14] used simulation software to analyze the dynamic time history of undercutting walls in the Shandan Ming Dynasty. The instability and partial collapse of wall undercutting under the action of a strong earthquake are obtained. Chai et al. [15] conducted numerical simulation on the length, inclination angle, and interval of soil nails, and evaluated the anchoring effect on tensile cracks under different working conditions. Zhang et al. [16] made ANSYS stability analysis and simulation on Cave 1 and Cave 2 of Yungang caves. Cang et al. [17] conducted numerical analysis of soil stability of the soft ground foundation. Liu et al. [18] studied the application of finite element software ANSYS in the pile mountain projects.

The ginger nuts is a kind of calculus produced in the quaternary loess deposition process, and its main mineral components are 70% ~ 80% calcium carbonate and 20% ~ 30% clay [19]. The modified ginger nuts under the calcination condition of 1000℃ have the basic properties of small shrinkage deformation, large porosity, strong resistance to freeze-thaw, and water stability [20]. The ginger nuts after calcination are called the calcined ginger nuts, which are non-toxic and pollution-free materials. The calcined ginger nuts are mixed with other soil to form chemically stabilized soil. When the stabilized soil is used for reinforcement, the curing period is moderate, and the construction is convenient. Due to the characteristics of the earthen sites, the calcined ginger nuts can be a good curing agent for the rammed soil.

In this paper, the finite element strength reduction method is used to calculate and analyze the stability of the earthen sites before and after ramming with the stabilized soil of calcined ginger nuts. The validity of this method in the ramming of earthen sites is verified, which can be used as a reference for similar reinforcement construction of the ancient sites in the future.

2. Project overview
The earthen sites of Niuoutoucheng are located in the west of Lintan County. Niuoutoucheng site is about 1,155 meters long from north to south, 245 meters wide from east to west, and 45 meters narrow from east to west. It has a perimeter of more than 1,300 meters and an area of about $8 \times 10^4 m^2$. It is composed of the inner city and outer city. The inner city is in the south and the outer city is in the north, and the terrain in the city is ladder-shaped.

The wind erosion of the Niuoutoucheng site is mostly concave in elevation, especially in the south of the eastern section of the north wall outside the site, shown in figure 1. Based on the situation of elevation concave, this paper takes the Niuoutoucheng site of central undercutting of Lintan County as the research object. And ABAQUS finite element analysis software is used to analyze the stability of the site before and after the reinforcement of the earthen sites to provide a basis for the protection and reinforcement of the earthen sites.

![Figure 1. South elevation of east section of north wall of outer city](image-url)
According to the field investigation results, the dry density of rammed soil in the original earthen sites is about 1.60g/cm$^3$. The soil parameters of the earthen sites are shown in Table 1. In this area, the earthen site undercutting is mostly concave in the elevation, which generally develops within the range of 1.50 m from the ground, and the undercutting depth mainly ranges from 0.20 m to 0.60 m, especially in section II of the south elevation of the east section of the north wall of the outer city of the earthen sites. The undercutting shape of this section is shown in Table 2.

| Soil layer          | Unit weight (γ/kN/m$^3$) | Internal friction angle (φ/°) | Cohesion (c/kPa) | Elastic Modulus (E/MPa) | Poisson’s ratio (V) |
|---------------------|--------------------------|------------------------------|------------------|-------------------------|-------------------|
| Original earthen sites | 16.38                   | 20.00                        | 12.38            | 100.00                  | 0.30              |
| Surface soil        | 18.70                   | 20.00                        | 23.00            | 30.00                   | 0.35              |

| Site monomer                     | Undercutting section height | Undercutting section depth | Undercutting shape |
|----------------------------------|----------------------------|---------------------------|--------------------|
| Section II of south elevation of east section of north wall of outer city | 1.75                       | 0.50                      | arch               |

3. Laboratory test
Taking the loess as the ramming material and the calcined ginger nuts as the curing agent, the mechanical properties of the calcined ginger nuts stabilized soil can be tested. Firstly, the rammed loess is prepared into the stabilized soil containing a low dosage of calcined ginger nuts. Under the condition of maximum dry density and optimum moisture content, according to the “Standard for Geotechnical Test Methods” (GB/T50123-1999), soil samples with different dosage of calcining materials were made by using 61.8mm*20mm ring knife. The soil samples were demoulded after standing and cured under indoor conditions.

After demoulding, the shear rate was adjusted to 0.8mm/min for the rapid shear test. Four parallel soil samples were taken, and axial pressures of 50kPa, 100kPa, 150kPa, and 200kPa were applied, respectively. Under the action of vertical pressure, the horizontal shear force was applied to shear the soil samples and the mechanical properties of low dosage were studied. The results show that after 7 days of curing, the internal friction angle and cohesion of soil are 20 and 56, respectively. After 14 days of curing, the internal friction angle and cohesion of soil are 38 and 75, respectively.

4. Finite element simulation of ramming reinforced earthen site

4.1. Simulation scheme
The strength reduction method means that the shear strength parameters of soil are continuously reduced by adjusting the strength reduction coefficient in the calculation, and the reduced parameters are continuously substituted into the model for calculation until the failure sliding surface is obtained. The minimum value of stability is obtained. At present, the soil stability analysis method is mainly based on the elasto-plasticity theory of rock and soil, considering the constitutive relation and stress-strain relationship of soil. And because the destruction of earthen sites in this region is mainly due to the weakening of soil strength caused by natural conditions such as wind erosion and rain erosion, the strength reduction method is suitable and practical.

The stability is mainly evaluated by the strength reduction coefficient $F_r$, and the corresponding $F_r$ value when the soil is unstable is the stability safety factor of the model soil. According to the laboratory
test results of calcined ginger nuts stabilized soil, the performance parameters of rammed soil reinforced with different curing times were obtained, and the shear strength parameters of soil were continuously reduced by strength reduction coefficient. Then the reduced parameters were substituted into the model for calculation until the plastic through zone was formed in the model and the stable safety coefficient was obtained. In the calculation and analysis, the variation range of $F_r$ is 0.50-2.00. The calculation method of strength parameters $c_m$ and $\varphi_m$ after reduction is shown in equations (1) and (2): 

\[
c_m = \frac{c}{F_r}
\]

(1)

\[
\varphi_m = \arctan\frac{\tan\varphi}{F_r}
\]

(2)

When strength reduction method is used for calculation, the ideal elastic-plastic model is adopted, and the Mohr-Coulomb failure criterion is used as the yield criterion [21]. Different yield criteria will have a great impact on the results. Shear strength and maximum shear stress are the key factors affecting soil instability. Using the Mohr-Coulomb criterion, the dilation angle should be defined. The soil material of the earthen sites is normally consolidated soil, which mainly presents shear shrinkage in the shear process [22]. Using finite element analysis and calculation, when dilation angle is equal to 0 ($\psi=0$), it is the non-associative flow rule. This method completely ignores the dilatancy of soil, which results in conservative calculation results and a large difference between the calculated deformation and the actual deformation [21-23]. When the dilation angle is equal to the internal friction angle ($\psi=\varphi$), it is the associative flow rule. This method means that the soil will have unlimited volume expansion in the shear process [24]. When the dilation angle is set to an indefinite value ($\psi=\varphi/2$), the calculation is more in line with the stability analysis of layered slope [25], which is more suitable for the analysis and calculation of the stability of rammed earthen sites.

The evaluation criteria to judge whether the soil reaches the critical failure state mainly include the nonconvergence of the calculation results, the sudden change of displacement at the feature points or parts, the formation of continuous through a zone in the plastic strain zone of the soil, etc. In this paper, according to the characteristics of the earthen sites, $F_r$ is determined as its safety factor when the earthen sites form a plastic through the zone.

4.2. Model establishment

Based on the wind erosion of section II of the south elevation of the east section of the north wall of the outer city of Niuoucheng site, a model of the central undercutting state is established. The undercutting site model is 3.47 m high, 2.10 m wide at the bottom, and the undercutting shape is arched. The undercutting zone is 1.75 m high and 0.50 m deep.

According to the simplification principle established by the finite element model, the actual three-dimensional site monomer is simplified into a two-dimensional site section with arch shape undercutting, as shown in figure 2. Because the actual site undercutting amount of the site is much smaller than the site volume, and the undercutting disease is complex, the simplified model only considers the impact of undercutting damage on the stability of the site.

In the calculation and analysis, the original earthen site material, surface soil, and rammed soil reinforced with calcined ginger nuts are all set as uniform bodies. The top on the right side of the model is taken as the feature point. The free quadrilateral meshes were used for the undercutting areas, and the quadrilateral structural meshes were used for the other areas, and the mesh model was obtained by dragging and rationalizing some sharp meshes.
4.3. Calculation parameters
According to the change of strength reduction coefficient $F_r$, the material parameters of the original earthen site and the performance parameters of the new rammed soil at different times under low dosage were calculated, as shown in table 3 and 4. Then assign values to the corresponding zone in the model. The stability safety factor of the central undercutting model after reinforcement is calculated and determined. The influence of different times after low dosage rammed soil reinforcement on the reinforcement effect is analyzed.

Table 3. Original earthen site parameters

| Reduction coefficient $F_r$ | $c_m$/(kPa) | $\phi_m$/(°) |
|---------------------------|-------------|--------------|
| 0.50                      | 24.76       | 36.05        |
| 0.75                      | 16.50       | 25.88        |
| 1.00                      | 12.38       | 20.00        |
| 1.25                      | 9.90        | 16.23        |
| 1.50                      | 8.25        | 13.63        |
| 1.75                      | 7.07        | 11.74        |
| 2.00                      | 6.19        | 10.31        |

Table 4. Performance parameters of calcined ginger nuts stabilized soil at low dosage

| Reduction coefficient $F_r$ | 7  | 14 |
|---------------------------|----|----|
|                           | $c_m$/(kPa) | $\phi_m$/(°) | $c_m$/(kPa) | $\phi_m$/(°) |
| 0.50                      | 112.00 | 36.05   | 150.00 | 57.38 |
| 0.75                      | 74.66  | 25.88   | 100.00 | 46.17 |
| 1.00                      | 56.00  | 20.00   | 75.00  | 38.00 |
| 1.25                      | 44.80  | 16.23   | 60.00  | 32.00 |
| 1.50                      | 37.33  | 13.63   | 50.00  | 27.51 |
| 1.75                      | 32.00  | 11.74   | 42.85  | 24.05 |
| 2.00                      | 28.00  | 10.31   | 37.50  | 21.33 |
4.4. Calculation results and analysis

Before reinforcement, the result cannot converge when the analysis steps \( t=0.5381 \). It shows that at this time, due to the soil strength reduction, the model begins to appear plastic through the zone, and the earthen site wall model becomes unstable. At this time, the corresponding safety factor \( F_r = 1.430 \). The model plasticity diagram of this analysis step is shown in figure 3.

![Figure 3. Plastic diagram of earthen site model before central undercutting and reinforcement](image)

Compared with the model before reinforcement, the plastic zone began to appear in the model after reinforcement for 7 days when \( t = 0.570 \). Until \( t = 0.8337 \), the plastic zone of the earthen site model is basically through, and the model begins to instability. At this time, the corresponding safety factor \( F_r = 1.959 \), as shown in figure 4. The safety factor was 1.966 when the model was unstable for 14 days after reinforcement.

![Figure 4. Plastic diagram of earthen site model after central undercutting and reinforcement](image)

The variation curve of the displacement of the feature points of the central undercutting model with the strength reduction coefficient \( F_r \) before reinforcement, as shown in figure 5. When the displacement changes suddenly, the plastic zone begins to appear in the earthen site model. The strength reduction coefficient \( F_r \) is 1.430 before reinforcement; the calculation results cannot converge. The plastic zone of the model is basically through, and the feature points in the model show horizontal and vertical displacement mutation. At this time, the model tends to be unstable. When the strength reduction coefficient \( F_r \) of the central undercutting model is 1.959 after 7 days of reinforcement with calcined ginger nuts, the plastic zone of the model is basically through. After 14 days, when \( F_r \) is 1.966, the plastic zone of the model is basically through.
Variation trend of horizontal displacement

Variation trend of vertical displacement

Figure 5. The relation curve between feature point displacement and \( F_r \) of the central undercutting model

In conclusion, the safety factor of the central undercutting models will be improved after the reinforcement with a low dosage of calcined ginger nuts. For the central undercutting model, the stability safety factor of the model is 1.9659 after 7 days of reinforcement and 1.966 after 14 days of reinforcement, which is higher than the safety factor of 1.430 without reinforcement. Using the finite element numerical simulation method, the stability safety factor of the model of the earthen sites before and after reinforcement is compared and analyzed. The effectiveness of ramming is verified, and the laws are summarized, which can be used as a reference for guiding similar reinforcement projects of earthen sites in the future.

5. Conclusions

In this paper, through field investigation and laboratory tests, the relevant mechanical parameters of earthen sites and ramming soil containing calcined ginger nuts are determined. In addition, the strength reduction method and the finite element analysis software ABAQUS are used to analyze the strain distribution and the change law of safety factor. The conclusions are as follows:

After the reinforcement with a low dosage of calcined ginger nuts, the time for the plastic zone and plastic penetration zone to appear in the model is increased compared with that without reinforcement.

Through the analysis of the model of the central undercutting earthen sites, the stability safety factor before the reinforcement of the central undercutting is 1.430, the stability safety factor after the reinforcement for 7 days is 1.959, and the stability safety factor after the reinforcement of for 14 days is...
1.966, which shows that the measures of using a low dosage of calcined ginger nuts to strengthen the earthen sites are effective.

The stability safety factor of the central undercutting model increased by 36.99% and 37.48% after 7d and 14d of reinforcement compared with that without reinforcement.

Acknowledgement
This work has been supported by the National Natural Science Foundation of China (41901079, 41971093), Gansu University Innovation Fund Project (2020A-026), Provincial Natural Science Foundation of Gansu Youth Fund (20JR5RA435), Hongliu outstanding young talents support program of Lanzhou University of Technology (062006) and Opening Foundation of Research Center on Levee Safety Disaster Prevention (LSDP202104).

References
[1] Li Z X, Wang X D and Sun M L 2011 Conservation of Jiaoho ancient earthen site in China. *J Rock Mech Geotech, 3* pp 270-281
[2] Jaquin Paul and Augarde 2012 Earth building: history, science and conservation *IHS BRE Press*
[3] Sun M L, WANG X D and Li Z X 2010 Preliminary Discussion on Soil Site Protection *Science Press* [In Chinese]
[4] Yao X 2018 Analysis of rain erosion damage mode of typical Ming Great Wall sites in Yuyang District *Science of Conservation and Archaeology, 6* pp 82-89 [In Chinese]
[5] Shang J J 2019 Research on the protection of the great wall of Ming Dynasty in shoukoupu, Datong *World of Antiquity, 02* pp 31-34 [In Chinese]
[6] Pang G, Chen K Y and Chen D T 2020 Research progress on in-situ protection status and technology of earthen sies in moiety environment *Constr Build Mater, 253* pp 119-219
[7] Chu W M, Xia Y, Luo X L, Wang L Q and Zhang S X 2019 Statistics and disease control of earthen sites in Heritage Museum *Human Cultural Heritage Preservation, 00* pp 126-130 [In Chinese]
[8] Liu T F 2020 A preliminary study on the treatment of diseases of earthen sites: a case study of the protection and repair of Longshan cultural relics at Yuhui village site *China National Exhibition, 14* pp 52-53 [In Chinese]
[9] Zhang Q Y, Chen W W, Fan W J and Liu D W 2021 The effect of polyvinyl alcohol solution with a high degree of alcoholysis on the expansion and cracking behaviour of quicklime-treated soil in earthen sites *B Eng Geol Environ*
[10] Wang Y W, Tie Z, Pei Q Q and Guo Q L 2021 Numerical analysis of the influence of cut on the stability of soil ruins under Static Load *Geotechnical Engineering Technology, 04* p 216 [In Chinese]
[11] He M C, Liu C Y, Wang S R, Yang G X, Mao L Q and Wang X B 2005 Research on deformation and failure mechanism on the grave of General Gaogouli a national key cultural relic protection project *China Journal of Rock Mechanics and Engineering, 13* pp 2220-2224 [In Chinese]
[12] He M C, Wang S R, Yang G X, Mao L Q and Sun C H 2004 Stability evaluation and protection measures of the general cemetery in Gaogouli *Rock and Soil Mechanics* pp 459-462 [In Chinese]
[13] Shi H Y, Yang J N, Han D D and Yang J 2017 numerical analysis of stability and reinforcement measures of Gaogouli general cemetery *Science Technology and Engineering, 33* pp 151-157 [In Chinese]
[14] Wang X D, Shi Y C and Li K 2011 Study on the mechanism of cutting instability of rammed earth Great Wall *Northwestern Seismological Journal, 33* pp 381-385 [In Chinese]
[15] Chai X J, Lin Z D and Yang Z P 2009 Soil nailing technology for repairing tensile crack of ancient soil kiln *Rock and soil mechanics* pp 140-4 [In Chinese]
[16] Zhang A 2008 H three-dimensional finite element study on the stability of Yungang Grottoes 1 and 2 based on strength reduction method *Wuhan: China University of Geosciences* [In Chinese]
[17] Cang J J, Guan Y F, Chen H J and Liu J C 2012 Numerical analysis of foundation settlement and soil stability of mucky soil mound project in soft soil area Journal of Water Resources and Architectural Engineering 01 pp 31-35 [In Chinese]
[18] Liu X J, Li H Q and Lei H Y 2004 Application of large finite element software ANSYS in Duishan project Rock and Soil Mechanics 2 pp 357-360 [In Chinese]
[19] Gansu Institute of Cultural Relics and Archaeology 1983 The Qin'an Neolithic site excavation report (I and II) excavate and harvesting (China) Cultural Relics 11 pp 21-30 [In Chinese]
[20] Chen W C, Wang S J, Li L, Zhang X P and Wang Y B 2018 Mechanical properties test of modified aggregate Rock and Soil Mechanics 05 pp 1796-1804 [In Chinese]
[21] Li C Z, Chen G X and Fan Y W 2006 Slope stability analysis by strength reduction finite element method based on ABAQUS Journal of Disaster Prevention and Mitigation Engineering 2 pp 207-212 [In Chinese]
[22] Fei K and Zhang J W 2010 Application of ABAQUS in geotechnical engineering China Water&Power Press [In Chinese]
[23] Chen X, Zhang X W and Miao J L 2017 Effect of soil dilatancy on the stability of soil slope system Journal of Chongqing Jiaotong University (natural science ) 1 pp 52-57 [In Chinese]
[24] Zhang X W 2015 Stability analysis and evaluation of dilatancy soil slope system Beijing: Beijing Jiaotong University [In Chinese]
[25] Chen C F, Wang X C and Zhang P 2015 Sensitivity studies of dilatancy angle for open-pit slope the stability based on ABAQUS Journal of Qingdao University of Science and Technology (Social sciences) 4 pp 10-15 [In Chinese]