BIOMASS MATERIAL AMENDMENT MAINTAINED THE STRUCTURE OF UNDERGROUND CULTURAL RELICS BY DECREASING THE VARIATION OF SOIL WATER CONTENT

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Abstract. Consistency of soil water content in the case of underground cultural brick relics is critical for the preservation of their structure and existence. However, natural topographical activity and illegal digging often damage water permeability and retention capacity of the soil layer covering the underground brick relics. To maintain the stabilization of underground brick relics' structure, a 2% biomass amendment was applied to the soil layer near a centuries-old relic at east China. The results showed that biomass amendment technology improved the soil water permeability and retention capacity by maintaining soil water content in a certain range. The analogous calculation showed that the biomass amendment technology improved the change range of the internal friction angle along the precipitation intensity from 24.81°-31.14°in the control to 25.03°-31.28° under biomass treatment. Soil cohesion in biomass treatment was kept in a smaller range than that of control treatment. Biomass treatment held a lower range for the horizontal and vertical pressure originating from surrounding soil caused by heavy short-time rainfall compared to the control. This study demonstrated that biomass amendment can improve the performance of soil shearing strength through the better regulation of soil hydraulic characteristics.

Keywords: architectural heritage, ancient mausoleum, historic preservation, water permeability, loading effect

Introduction

Ancient nobles and emperors often arranged grand and magnificent underground architectures for their mausoleums or tombs. Today, archaeological excavation founds a large number of these high-grade underground architectures, which have been buried for hundreds or even thousands of years (Fu et al., 2020; Ying et al., 2015). When most architectures were buried at a certain depth at ancient ages, soil layers with different thicknesses were positioned on top to protect the underground arched structure, including walls and vault (*Fig. 1A*). This kind of soil layer is usually not positioned at a flat level, but as a mound piled above the ground on top of the tomb. In ancient China, for such emperors and generals' mausoleums, the mound is often large in scale to highlight the imperial identity and power (Shi et al., 2020). For such structures, the soil layers were stacked on the top of the mausoleums, shaping a trapezoid with a large surface on the bottom of the structure. The shape of the top soil layer was always square before Eastern Han Dynasty approximately two thousand years ago. This square shaped soil layer was reformed into a flat-round shape since Eastern Han Dynasty (*Fig. 1B, C*) (Xiong, 2014). Then it had become the most widely used and most common form of soil sealing in the history of Chinese tombs. However, both of these two shapes of soil sealing layer upon the underground cultural relics were at the risk of erosion by plurosion effect after hundreds or thousands of years.

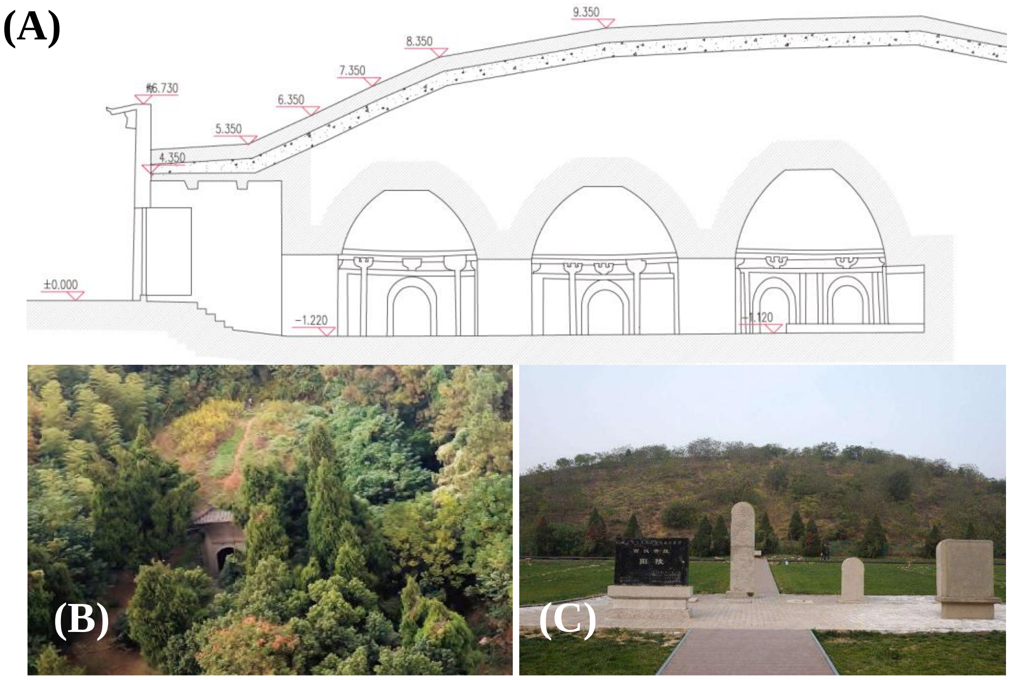

Figure 1. *The typical views of mausoleums in Nanjing. (A), vertical section view of the two mausoleums of Southern Tang Dynasty; (B), Aerial view of Shunling mausoleum; (C), Aerial view of Hanjing mausoleums*

The protection of underground cultural relics is an important step to inherit the excellent human traditional culture, but our understanding of the underground relic environment related to heritage conservation is still limited (Chen et al., 2007). To protect the underground mausoleum, the soil sealing layer is one of the most important objects to prevent the underground structure from flooding or structural failure from the presence and pressure of groundwater respectively (Liu et al., 2019b). This layer acts as a balancing element to ensure the stability and sturdiness of the mausoleum's 'cap'. At the same time, it prevents ground water ingress due to its low porosity. The consistency of water content ensured the effectiveness of protective effect in the sealing soil layer (Zhang et al., 2001). This soil watertight property can be kept in a short time, but changes in hydrogeological permeability and topography in hundreds or thousands of years often lead to deterioration of the water-tightness and further structural failure (Cao et al., 2021; Guo and Huang, 2002). Changes in water content may lead to a radical change in the bulk density of the overlying soil (Kemper and Rosenau, 1984). After water ingress and saturation, the additional water increased the bulk structure density resulting in structure deformation and plausible failure. The soil water displacement from the structure to the nearby ground formations will cause the reduction in density and buoyancy effect to underground architecture, which resulted in the deformation or failure to the underground architecture. These adverse effects were found not only on the top structure of the mausoleum but also on the stability of the murals and carvings inside the tomb (Zhang et al., 2001). Additionally, an increase in soil water content generally affects the mechanical properties of the soil overlying layer itself (Oades, 1984). Specifically, numerous studies confirmed that changes in the water content of unsaturated soils could result in the unbalance of shear strength index, which will cause potential systemic risks, such as instability of retaining walls and landslides (Cokca et al., 2004; Fredlund et al., 1995; Liu et al., 2019c). The amendment of high polymer materials to soil sealing layer are often used to prevent seepage water caused by rainfall and groundwater movement (Ma and Zhu, 2016). However, polymer anti-seepage materials cannot change the water absorption and drainage capacity of the soil layer. In addition, polymer materials will disturb the metabolic activity of the aboveground plants. Consequently, the changes in ecosystem on the top of ancient architecture will affect the landscape as well as the overall aesthetics of such scenic spots. It has been demonstrated that soil organic matter can effectively maintain water content, as well as it is beneficial to the growth of plants as it promotes fertility (Liu et al., 2019a; Oades, 1984). Therefore, the amendment of organic biomass to modify the properties of upper soil layer can be beneficial for the structural stability of such underground cultural relics.

In this study, organic biomass was amended to the upper soil layer to estimate its effect on the change of soil water content and subsequent possible influences on mechanical properties of underground relic structures. The experiment was performed in a green space near an ancient emperor’s mausoleum with centuries of history in Nanjing City, China (Li et al., 2016). This typical underground architecture is at the risk of rainfall and weathering after a long history of crustal movement or illegal tomb trespassing. The findings from this study will be beneficial for the development of strategies to improve the state of such underground structures in the meet of the new generations of architecture and archaeology.

Materials and methods

Experimental site

The experimental site was set in a green park nearby the two mausoleums of the Southern Tang Dynasty situated in Nanjing City (31°76-32°87′N, 117°50-118°90′E), Jiangsu Province, China. The two mausoleums of Southern Tang Dynasty, Qinling Mausoleum and Shunling Mausoleum, were built between 937 AD and 975 AD according to archaeological studies (Yuan et al., 2016). The surface structures for the two mausoleums have been destroyed, leaving behind only the two mounds. The dilapidated mound of Qinling Mausoleum is about five meters high and 30 meters in diameter. The Shunling Mausoleum, built against a mountain slope, has a mound smaller than that of Qinling Mausoleum. Remnant earth banks in the south and southwest of Shunling Mausoleum were probably the boundaries of the original mausoleum garden. The terrace inside was probably the foundation of the mausoleum hall. In the reclaiming land on the terrace, tenants had unearthed several bricks, three plinths, broken tiles, and white porcelain items. Annual precipitation of the study site varies between 979 and 1113 mm. The recent temperature fluctuates from -2.6 ℃ to 40 ℃ with an average value of 17 ℃ (average of 2019 as reference). Relative humidity fluctuated between 15.8% and 100% (http://data.cma.cn/en).

Field improvement experiment

To assess the role of the carbon-rich biomass amendment on the underground structure, two 4 m^2 (2 m × 2 m) fields were selected in the studied site on April 18, 2019.

In Nanjing, the largest short-term rainfall generally occurs during summer, so a three-month field study was performed during this period in the two selected fields. We expect that this period will be representative to cover the worst-case scenario in terms of the water saturation level in soils. Both fields were dug down to 1.0 m using a small excavator. In one of the two fields, the soil was excavated and mixed with biomass material at a ratio of 1:50 in weight by weight according to the previous studies of biomass amendment (Ding et al., 2014; Zhang et al., 2020). Another field was set as the unamended control treatment, the soil in this field was dug out, mixed well but without biomass amendment. The biomass matter was naturally air-dried manure without composting. Before mixing with soil, the biomass was ground to debris and sieved through a 2 mm sieve. Then the mixed soil with biomass material was filled back into the plot. In both plots, three EC-5 soil moisture sensors (Decagon Devices, Pullman, WA, USA) were buried at a depth of 60 cm to monitor soil water content in real-time (*Fig. 2*). The EC-5 soil moisture sensors used were connected to an EM50 data acquisition unit. The data acquisition frequency was set at once every 3 h. Consequently, each EC-5 sensor could collect 8 soil moisture data per day. After 3 months, the EC-5 sensors and EM50 data collector were taken out (August 8, 2019). The real-time monitoring data of the soil moisture content after approximately 3 months (from April 18 to August 8) were analyzed with ECH2O utility software (v3.2.0) (Decagon Device Inc., USA). The rainfall data were recorded by HOBO meteorological station (HOBO RX3003, US) located at the two mausoleums of the Southern Tang Dynasty.

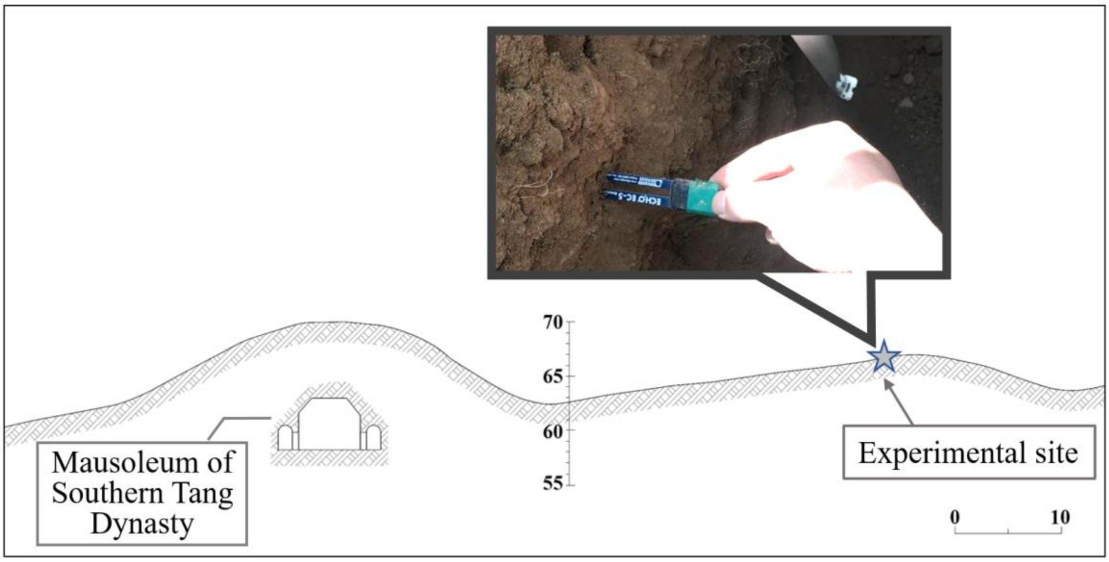

Figure 2. *The experimental site near the mausoleum of Southern Tang Dynasty*

Estimation of the relationship between soil water content and shearing strength

A laboratory experiment was performed to determine the relationship between soil water content and shearing strength. Soil samples were collected at the green park in our experiment field. Before use, the soils were air-dried, homogenized, and screened through a 2 mm sieve. Gravel, roots, and other impurities were carefully removed. Based on the actual water content during the field experiment, 6 levels of soil water content (from 0.09 to 0.44 m^3/m^3 at intervals of 0.07 m^3/m^3) were set for the test. A certain amount of deionized water was sprayed into the soils to meet the calculated water demand. Then the mixed soil sample was sealed with plastic wrap and kept in a dry container for 24 h to complete soakage. Triaxial compression tests were undertaken with an automatic triaxial compression system (STSZ-9, Zhejiang Tugong Instrument Co., Ltd., China). The shear velocity was 0.80 mm min^{-1}, and four confining pressures, i.e. 100, 200, 300, and 400 kPa, were applied to determine shearing strength. The shear strength parameters, the cohesion (c) and internal friction angle (φ), were calculated in accordance with Standards for Soil Test Methods (GB/T50123-1999). According to the laboratory experiment, the relationship between soil water content and shearing strength was listed as following equations (*Eq. 1* and *2*) (*Fig. 3*).

$$\varphi = 20.559w^{-0.207} \tag{Eq.1}$$

where φ is the internal frictional angle, and w is the soil water content.

$$c = -807.87w^2 + 449.5w + 7.4117 \tag{Eq.2}$$

where c is cohesion, and w is soil water content.

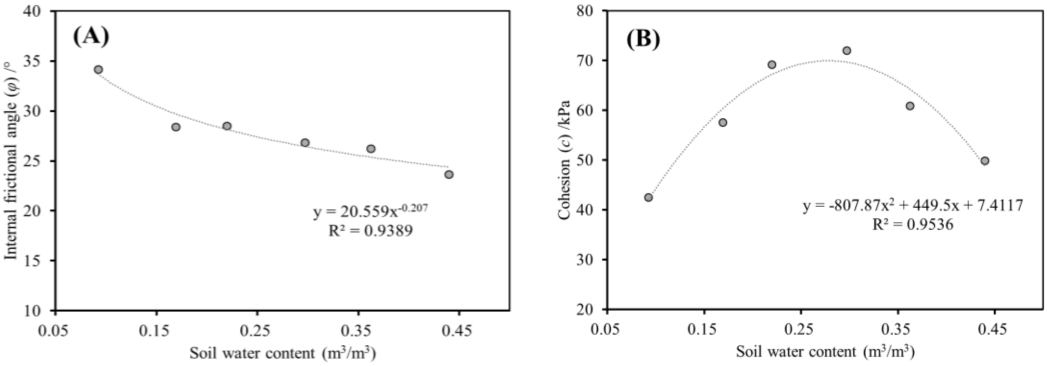

Figure 3. *Relationship between soil water content and shearing strength parameters (A, internal frictional angle; B, cohesion)*

Data analysis

Statistical analysis was implemented using the IBM Statistical Product and Service Solutions (SPSS) Statistics for Windows (Version 16.0). The data were expressed as means of measurements with standard deviation (SD); different letters indicate significant differences among different treatments. Analysis of variance (ANOVA) was performed to determine the significance of the biomass amendment, followed by Tukey’s HSD test. Differences of $p < 0.05$ were considered significant.

Results

Effects of biomass amendment on soil water content

The soil water content for both the unamended control and biomass treatment changed consistently during rainfall periods (*Fig. 4*). It can be observed that during the first three days, from April 18 to April 20, no difference appeared in the water content, likely due to insufficient compaction after the mechanical filling of the excavation. This period can be considered as the adaptation period for soils. After the adaption period, the soil water content will have its peaks after heavy rainfall and then gradually decrease, corresponding to the process of the soil storing and draining water. It can be generally said that the higher the rainfall intensity, the higher value of the soil water content. These results confirm that the buried soil moisture sensor can accurately and real-time record the dynamic changes of the soil moisture, which in other words supports that is a credible data acquisition basis for the study of the water status in underground soil.

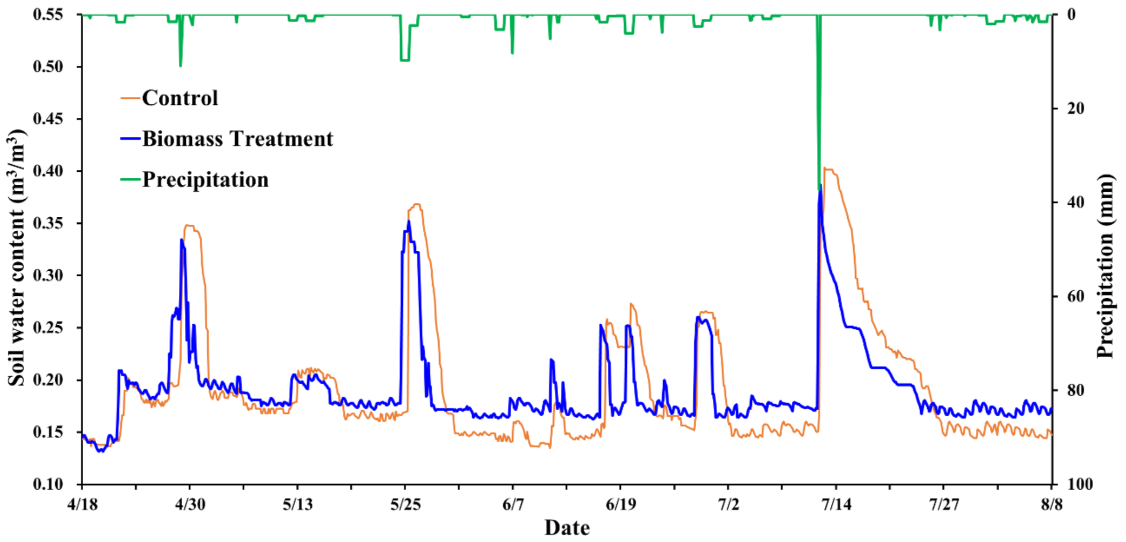

Figure 4. *Soil water content and rainfall in the experimental area from 18th Apr to 8th Aug 2019*

To assess the influence of consistent rainfall type and short-time heavy rainfall type on soil water content, two typical rainy periods were selected for further analysis (*Fig. 5*). One period was a rainfall process consistent from April 28 to April 30, and the total rainfall in these three days was 33.56 mm (*Fig. 5A*). The other period was a short-time heavy rainfall occurred on July 12, when the rainfall reached 57.62 mm within 9 h (*Fig. 5B*). The slow rainfall process in April, which was distributed within 3 days, made the maximum and minimum values of soil water content as 0.349 $m^3 \cdot m^{-3}$ and 0.168 $m^3 \cdot m^{-3}$ respectively in the control treatment (*Fig. 5A*). While in biomass treatment, the peak and valley value of water content showed as 0.330 $m^3 \cdot m^{-3}$ and 0.175 $m^3 \cdot m^{-3}$ during the three days of rainfall in late April (*Fig. 5A*). During the short-term heavy rainfall period, the minimum and maximum values of soil moisture content in the control treatment were 0.401 and 0.144 respectively, while the minimum and maximum values of soil moisture under biomass treatment were 0.387 and 0.164 respectively.

In both consistent rain processes and short-time heavy rain processes, the maximum value of soil water content in biomass treatment was lower than the control treatment. This phenomenon of the maximum water content value indicated that biomass treatment could benefit the drainage capacity when the environmental water increased either in a consistent slow rain type or a short-time heavy rain type. The minimum value of soil water content in the two observed rain periods showed a lower value in biomass treatment than that of control. Furthermore, the consistent rainfall made soil water content in biomass treatment maintained at the range of 0.283~0.334 only for 12 h, while it made soil water content in control treatment maintained at the range of 0.313~0.348 for 96 h (*Fig. 5*). During the short-time heavy rainfall period, the soil water content in biomass treatment decreased rapidly after reaching the peak value and decreased to the minimum value on the 11th day after the end of this short-time heavy rainfall. However, in the control treatment, soil moisture did not decrease significantly after reaching the peak value, but lasted about 48 h in the range of 0.313 ~ 0.401 m^3·m^{-3}, and reached the minimum value 13 days after the end of short-time heavy rainfall (*Fig. 5B*). This phenomenon indicates that the addition of biomass changes the water permeability of the soil.

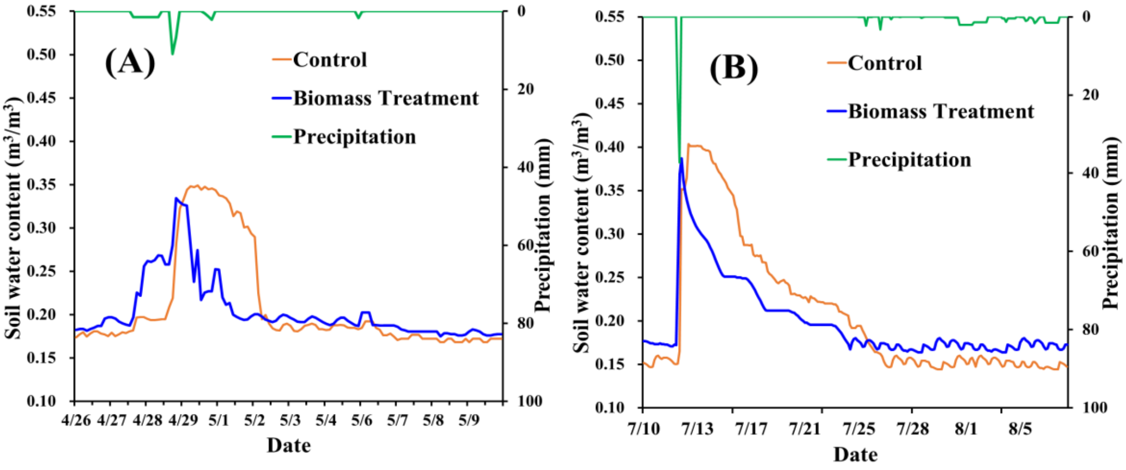

Figure 5. *The changes of soil water content under two typical rainfall periods (A, period from April 26 to May 10; B, period from July 10 to August 8)*

Effects of biomass amendment on soil shear strength

To assess the effect of soil water content on the underground relics, an analogous calculation was performed based on the structure data from the Shunling mausoleum, one of the tombs of Southern Tang Dynasty at Nanjing (*Fig. 6*). The bottom of the tomb is 8 m deep, the side wall is 2 m high, and the width of the tomb is 5 m. The back of the wall is upright and smooth, the roof is an arch structure. The ground surface is approximated by a horizontal plane (*Fig. 6*). To assess the response of soil shear strength from the biomass amended treatment, soil density (ρ), internal frictional angle (φ), and cohesion (c) were calculated according to the fitting equation. Since the first three days, from April 18 to April 20, were a period with no differentiation (soil adaptation), all the shear strength parameters were calculated from the data obtained from April 21 to August 8. The minimum, maximum value, and variance of the data during this period were listed in *Table 1*. It can be observed that the maximum value of these three parameters in the biomass amended treatment was lower than that of the control treatment, while the minimum value was higher than that of the control. The control treatment had a higher variance than that of the biomass amended one, indicating a more divergent data set.

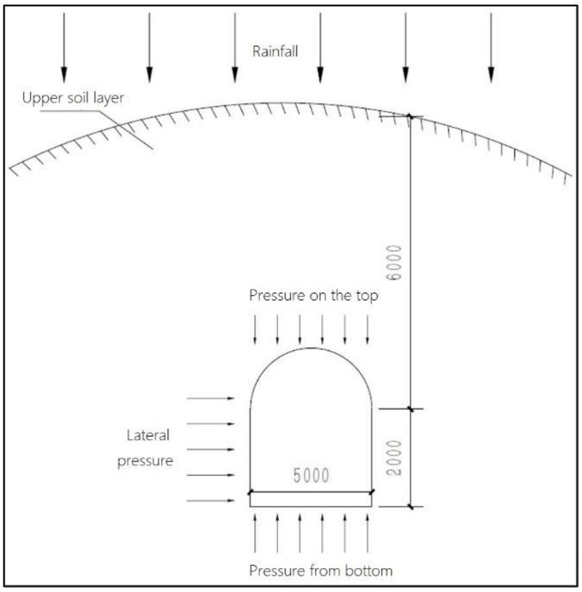

Figure 6. *Schematic diagram of force in the Shunling mausoleum*

Table 1. *The soil shear strength parameters in control and biomass treatments*

	Soil density (*ρ*)	Internal frictional angle (*φ*)	Cohesion (*c*)
Control_{max}	17.54	31.14	69.94
Control_{min}	16.51	24.81	53.25
Control_{var}	0.05	2.45	22.39
Biomass_{max}	17.47	31.28	69.94
Biomass_{min}	16.50	25.03	52.61
Biomass_{var}	0.02	1.02	11.09

Control_{max}, the maximum value parameter in Control treatment; Biomass_{max}, the maximum value parameter in Biomass treatment. Control_{min}, the minimum value parameter in Control treatment; Biomass_{min}, the maximum value parameter in Biomass treatment. Control_{var}, the variance value parameter in Control treatment; Biomass_{var}, the variance value parameter in Biomass treatment

Effects of biomass amendment on horizontal and vertical force on the underground relics

The changes in horizontal and vertical pressures caused by biomass amendment were assessed by analogy calculation in Shunling mausoleum. Since the burial time of the underground relics has been hundreds of thousands of years, static pressure was considered in this case. The short-time heavy rainfall period, from July 10 to August 8, was used for the estimation of the maximum expected horizontal and vertical pressure on the underground relics. The horizontal pressure on the lateral wall of the underground relics, in this case, was calculated at the depth of 6.00 m, 6.50 m, 7.00 m, 7.50 m, and 8.00 m (*Table 2*). It was found that the maximum and minimum value of the horizontal pressure on the retaining wall at different depths was very similar between the control and the biomass amended trials. However, the variance of the horizontal pressure at each depth was lower in biomass amended treatment compared to the control (*Table 2*).

Table 2. *The horizontal pressure on retaining wall of different depth in control and biomass treatments*

	Horizontal pressure on retaining wall of different depth /kPa				
	6.0 m below	**6.5 m below**	**7.0 m below**	**7.5 m below**	**8.0 m below**
Control_{max}	209.35	226.79	244.24	261.68	279.13
Control_{min}	5.81×10^{-3}	6.29×10^{-3}	6.78×10^{-3}	7.26×10^{-3}	7.74×10^{-3}
Control_{var}	4517.6	5301.9	6148.9	7058.7	8031.3
Biomass_{max}	207.13	224.39	241.66	258.92	276.18
Biomass_{min}	5.81×10^{-3}	6.29×10^{-3}	6.78×10^{-3}	7.26×10^{-3}	7.74×10^{-3}
Biomass_{var}	4543.6	5332.7	6184.3	7099.3	8077.4

Control_{max}, the maximum value parameter in Control treatment; Biomass_{max}, the maximum value parameter in Biomass treatment. Control_{min}, the minimum value parameter in Control treatment; Biomass_{min}, the maximum value parameter in Biomass treatment. Control_{var}, the variance value parameter in Control treatment; Biomass_{var}, the variance value parameter in Biomass treatment

To assess the resultant vertical pressure on the underground relics resulting from biomass amendment, the pressure on the top of chamber, the pressure from the bottom of chamber, and the buoyant pressure to chamber taken into consideration based on analogy calculations (*Fig. 7*). The vertical pressures in this case were calculated based on the data from April 21 to August 8. The maximum pressure on the top of the tomb from the biomass amended trial was estimated 0.56 kPa lower than that of control, while the minimum pressure on top of the tomb was 0.93 kPa higher in biomass treatment than that of the control treatment (*Fig. 7A*). A similar phenomenon was observed in the pressure from the bottom and buoyancy to the chamber. It was found that 0.90 kPa decrease of the maximum pressure from the bottom because of biomass treatment, while 1.49 kPa increase of the minimum pressure from the bottom due to biomass treatment (*Fig. 7B*). Biomass made the buoyant pressure of chamber 0.34 kPa decrease and 0.56 kPa increase compared to control treatment (*Fig. 7C*). The variance of all the three vertical pressures was less than two-fifth times lower in biomass treatment than that of control treatment.

Discussion

The hydraulic behavior of the soil layer on top of the underground relics plays a vital role in the stability of the engineered structure and subsequently in the conservation of the heritage. In this study, biomass amendment to soil was trialed to assess its effect on the soil hydraulic curve and the parameters of soil strength and structure for the purpose of protecting underground culture relics.

The impact of biomass amendment on soil water content

The biomass amendment was extensively used to improve soil structure in numerous studies mainly due to its direct effect of the increase in soil organic matter (Buss et al., 2016; Dessureault-Rompré et al., 2020; García-Orenes et al., 2005; Liu et al., 2016). In this study, the in situ experiment showed that the biomass amended soil can decelerate the loss of water avoiding large fluctuations in the soil water content when rainfall is relatively slow and of light intensity; while when short-term heavy rainfall, the biomass treatment can seep water quickly to avoid water accumulation. The increased organic matter due to biomass amendment improves soil physical properties (Haynes and Naidu, 1998; Oades, 1984). The humus produced by the decomposition of organic matter can increase soil adhesion and promote the formation of aggregates (Kholodov et al., 2019). The soil organic matter is pliable, flocculent and porous, and the cohesive pressure is not as strong as that of soil (typically clay particles); clay particles are easy to form scattered aggregates after being coated with organic matter, which renders the soil also pliable and no longer forms hard lumps (Kemper et al., 1987). This subsequently can improve soil structure, and alter soil permeability, water storage, and aeration.

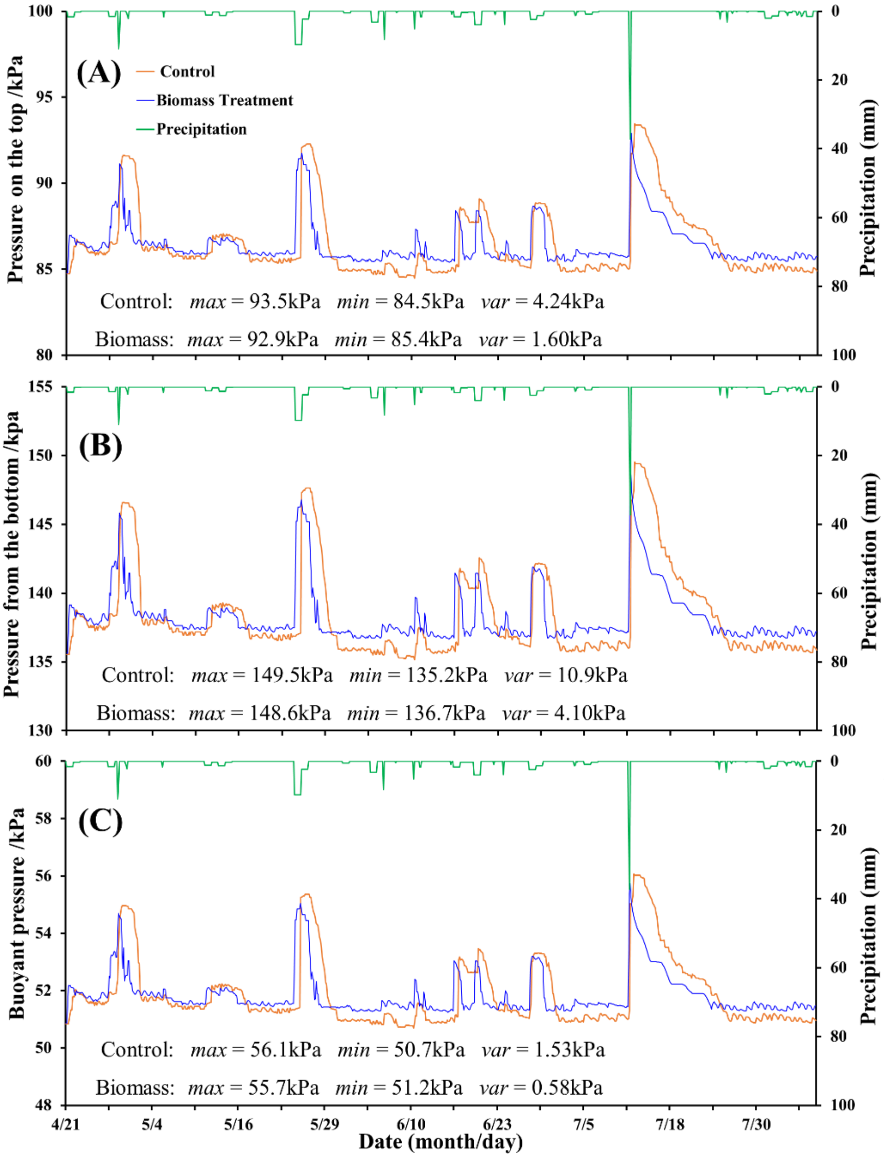

Figure 7. *Vertical force on the underground relics in control and biomass treatments. (A), the pressure on the top of chamber; (B), the pressure from the bottom of chamber; (C), the buoyancy to chamber*

The biomass amendment can alter the soil's chemical properties and promote the growth of above-ground vegetation (plants) (Gebhardt et al., 2017; Quaye et al., 2011).

Organic matter contains nitrogen, phosphorus, sulfur, calcium, magnesium, and other trace elements, which will directly change the proportion of nutrient elements in the soil. Soil organic matter can enhance the ability to decompose soil mineral components (Torn et al., 1997). The increased nutrients will promote the growth of aboveground plants. Humic acids in organic matter can enhance plant respiration and nutrient absorption, vitamins (Tremblay et al., 2002). Some hormones in organic matter can promote plant growth and development. Humic acids in biomass matter have been proved to be a kind of physiologically active substance (Al-Taey, 2018), which can accelerate seed germination, enhance root activity and promote crop growth. The growth of plants on the soil base up the underground relics is beneficial for maintaining soil water content. Therefore, in summary, biomass material not only has the function of water retention and storage, but also has the function of drainage, which can maintain the stability of the water content of the soil within a certain range protecting the underground relic overburden.

The impact of biomass amendment on soil engineering strength

For underground relic buildings, the solid structure will not dramatically change in a local range, but the change of water content will relatively affect the shearing strength parameters of the underground soil layer (Zhang et al., 2001). In this study, the analogy calculation showed that an increase in water content will lead to an increase in the soil bulk density, which in turn will increase the lateral earth pressure on the walls of the underground cultural relics. Moreover, within a certain range, the deeper depth could lead to higher underground pressure and subsequently greater risk on the structure of underground heritage. The water storage and water retention effect of biomass materials could keep the soil moisture content at a relatively high level, which consequently increases the weight of the overlying soil layer and reduce the influence of buoyancy on the small deformation of the tomb structure. When soil water content increases, the liquid index increases, and the mechanical strength of soil decreases, the stability of soil will then get affected (Kemper and Rosenau, 1984). The gravity of soil increases with the increase of water content. Generally, for cohesive soil, the gravity can increase by 1/7 ~ 1/315 after soil saturation (Chao et al., 2018). The weight of the collapsed body increases with the increase of gravity, which accelerates the collapse of the soil cave vault. When the water content increases, it expands, when it is dry, it shrinks, and then vertical cracks appear, the soil gets deteriorated, and its mechanical strength decreases (Liu et al., 2019b; Ringelberg et al., 2014). These changes of building materials are conducive to the infiltration of rainwater and surface water, then it will accelerate the potential erosion and make the vault of the soil cave collapse more easily. Soil moisture has a floating effect on soil (Li et al., 2021). The buoyancy is directly proportional to the volume of soil water content. When the water content decreases, the buoyancy decreases, and the soil mass changes from effective gravity to natural gravity. Combined with other factors, it may lead to the instability of the soil at the top of the soil cave, resulting in collapse. Therefore, the biomass amendment to the soil base could maintain the stability of the arch voucher of the underground heritage.

Conclusion

In this study, the amendment of biomass can improve the stability of the soil layer on top of ancient underground cultural relics. The presence of biomass assists in the regulation of the water content and subsequently maintain the protective effect of this overlying soil layer against deterioration and structural failure. The amendment of biomass material to soils not only has the ability to securely retain and store water but also to promote accelerated drainage. For the soil shear strength, an increase of water content due to biomass amendment increases the soil bulk density, which in turn increases the lateral earth pressure on the walls of underground cultural relics. Biomass amendment reduces the possibility for structure buoyancy and increased the stability of the arch voucher. Further study should be conducted with other types of soils and the associated calculation equations should be modified according to the soil types.

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