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A comprehensive evaluation of the development degree and internal impact factors of desiccation cracking in the Sanxingdui archaeological site

Xue Yao[1] and Fan Zhao[2*]

Abstract

Desiccation cracking is a common deterioration that occurs in archaeological excavation sites and greatly threatens long-term preservation. The aim of this research is to comprehensively evaluate the development degree of desiccation cracking (DOC) and explore the relationships between soil properties and its development. Seven indicators are selected to comprehensively describe the DOC, and principal component analysis (PCA) is applied to calculate the weight of each indicator. Linear correlation analysis (LCA) is adopted to calculate the correlations of six soil properties and DOC. The results showed that each indicator has an influence on the DOC. The clay particle content, clay mineral content, and plasticity index showed a positive correlation with the DOC, and the moisture content showed a negative correlation. This research proposed a comprehensive evaluation method to describe the development degree of deterioration at the earthen site, and the results revealed the internal factors influencing desiccation cracking from a qualitative perspective, which can lay a foundation for further conservation research.

Keywords Desiccation cracking, Development degree, Internal impact factors, Comprehensive evaluation

Introduction

The Sanxingdui site is located in Guanghan, Sichuan Province, China (Fig. 1a). It is the capital of ancient Shu and was founded in the late Neolithic age and continuously used in the late Shang dynasty. It was first excavated in 1986 when two sacrifice pits were discovered. Numerous valuable artefacts were excavated (Fig. 1b), such as ivory, gold masks, and bronze ware, which is significant for studying the origin of ancient Shu.

In 1997, the Sanxingdui Museum was opened. The museum exhibition focused on the numerous relics, while the sacrifice pits were backfilled with the protective method without reservation. In 2019, a new round of archaeological excavation was started, which included the No. 3 to No. 8 sacrifice pits. At the beginning of the excavation, the exposed sites and relics were covered with plastic film to prevent the site from losing water quickly before the protective shelter was built. Due to the corresponding measures, desiccation cracking was not obvious at the early stage of excavation. After the completion of the protective shelter (Fig. 1c), a relatively closed environmental control system was constructed in the archaeological excavation work area to prevent fragile artefacts such as ivory to become destroyed by temperature and humidity fluctuation based on the concept of preventive conservation (Fig. 1d). Considering the effectiveness of environmental control, the system was established in the

*Correspondence:
Fan Zhao
zhaofan_163@163.com
[1] Department of Tourism and History Cultural, Southwest Minzu University, Chengdu 610041, Sichuan, People's Republic of China
[2] The Sichuan Provincial Cultural Relics and Archaeology Research Institute, Chengdu 610041, Sichuan, People's Republic of China

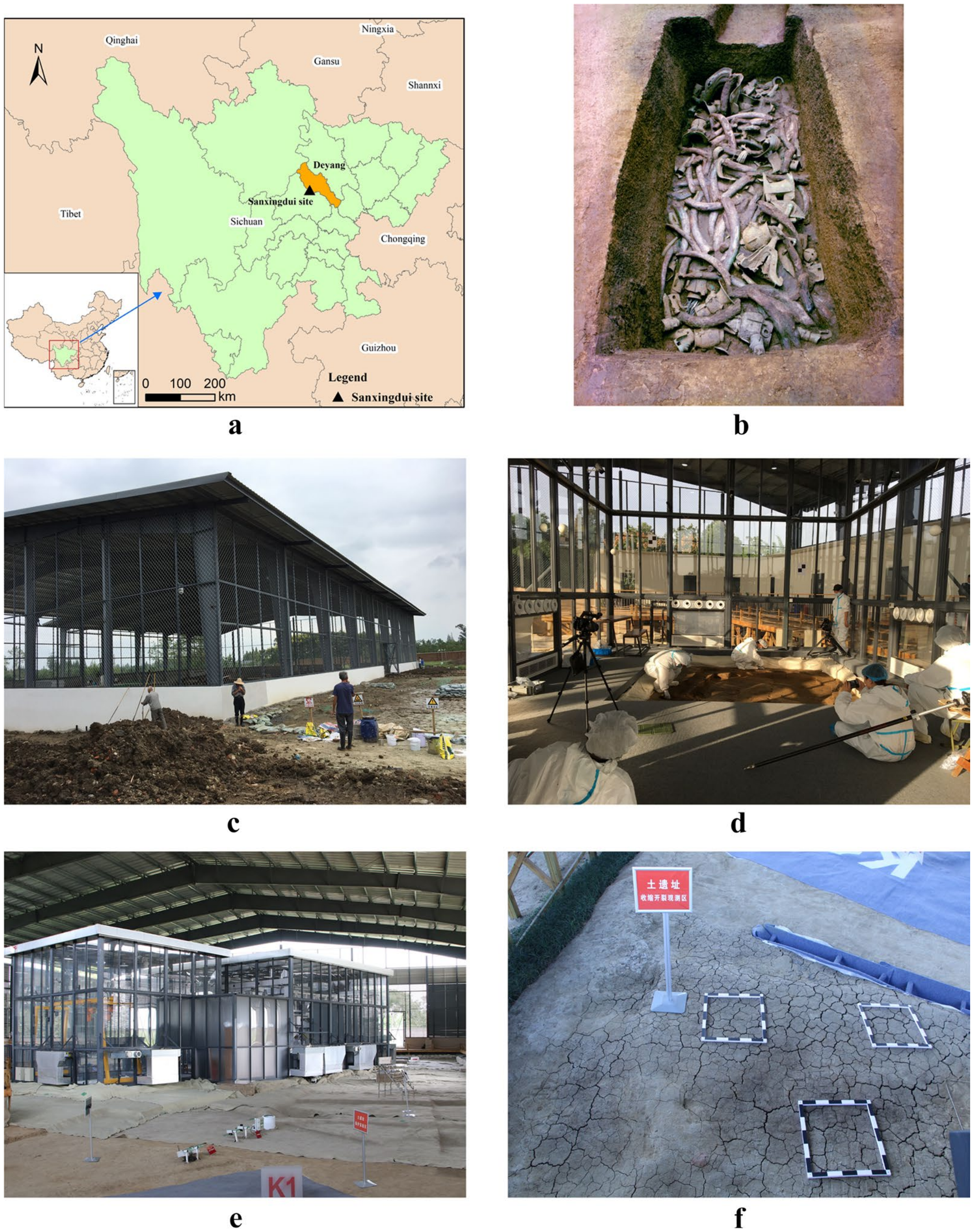


Fig. 1 The Sanxingdui site and desiccation cracking on site (**a** location of Sanxingdui site. **b** No. 2 sacrifice pit excavated in 1986. **c** protective shelter construction. **d** microenvironment control system. **e** the workspace in the protective shelter. **f** desiccation cracking development)

workspace only. The rest of the area of the site is in the protective shelter but out of the environmental control area (Fig. 1e). The protective structure effectively protects the site from rainfall erosion and stops the water supply to the site soil from atmospheric rainfall, which leads to desiccation cracking occurring on the surface of the site soil in the protective shelter (Fig. 1f). This heavy deterioration weakens the engineering properties of the site soil and results in an unsafe condition. The Sanxingdui site is essential to study the origins of the ancient Shu civilization, providing important evidence to prove the diversity of Chinese civilization. At the Sanxingdui site, an in situ preservation site museum is planned; however, heavy desiccation cracking has threatened the long-term preservation of the site.

Desiccation cracking is a common type of deterioration that occurs in archaeological excavation sites and leads to the degradation of soil engineering properties. Specifically, it will change the microstructure, decrease the stability and bearing capacity, and dramatically increase the permeability of the soil [1, 2], hindering the long-term preservation of an archaeological site. Existing research on this deterioration in archaeological sites focuses on the deterioration investigation [3, 4], performance form [5–7], development procedure [8–10], and impact factors [11, 12]. According to the investigation and literature review [13–17] of sites in China, both archaeological sites and earthen architecture sites have suffered from heavy desiccation cracking. According to engineering geological research, desiccation cracking in soil is a common and natural phenomenon. An unexcavated site often has a high water content, and once excavation begins, evaporation occurs. Subsequently, the site soil may lose water, shrink, and crack, which will destroy the integrity of the site [18–21]. Soil properties, evaporation rate, environmental temperature, and soil mass structure are important factors affecting desiccation cracking. The initial moisture content of the soil, initial dry density, clay particle content, clay mineral content, and plasticity index affect desiccation cracking [22–27]. The existing research results provide an important theoretical reference for this research, but for the special research object of archaeological sites, it still has certain inapplicability, which is embodied in two aspects. First, in the field of geotechnical engineering, saturated paste samples are often used to study the shrinkage cracking of soil. Due to the widespread application of conservation shelters, few archaeological research objects are in a saturated state. The relevant conclusions drawn from test methods are largely unrepresentative of the actual situation at the archaeological excavation site. Second, in terms of studying the influencing factors of desiccation cracking, most existing research conclusions are drawn from the single-variable method, and the weights of various factors have not been compared [7, 12, 25, 26]. In this process, there is no comprehensive indicator to illustrate the degree of desiccation, and the contribution of each factor is not quantified. This is not beneficial for conservators to judge the urgency and main control factors and is not conducive to targeted protection and reinforcement in the later stage of excavation. Previous research studies have used seven indicators to describe desiccation cracking, independently or in combination [18, 28–32]. There is a certain correlation between these indicators, but a single indicator cannot fully reflect the development of desiccation cracking. For conservators, the existing research results are not conducive to quickly determining the severity of deterioration. It is necessary to judge the development degree of desiccation cracking (DOC) quickly and effectively once excavation begins, and this is the premise of the scientific conservation of archaeological excavation sites. Therefore, this research aims to explore a comprehensive indicator and evaluation method for the DOC in archaeological sites. On this basis, we explain the correlation between soil properties and desiccation cracking from the perspective of the formation mechanism.

This research proposes a quick and simple evaluation method for judging the DOC in archaeological sites, which offers a basis for simultaneous conservation and consolidation.

Methods

In this study, desiccation cracking is described by seven indicators, and principal component analysis (PCA) is used to calculate the weight of these indicators. The DOC is comprehensively characterized and evaluated with the raw data. Based on the above results, linear correlation analysis (LCA) is used to calculate the correlation between soil properties and DOC.

In situ monitoring

To scientifically characterize the DOC, ten monitoring points were established at the site, each having a quadrat size of 50 cm × 50 cm, and their locations are shown in Fig. 2. A digital camera was used to capture an orthophoto image of desiccation cracking in the quadrat, and MATLAB software was used to process the image. The seven indicators include the surface fissure ratio (R), the total length of the fissures (L), the average fissure width (W), the number of fissure nodes (Nn), the number of fissures (Ns), the number of soil blocks (Na), and the fractal dimension (K) [18, 28–32].

Geotechnical tests

To obtain relevant soil property data, representative soil samples were taken at a distance of 10 cm from the surface of the monitoring quadrat at the beginning of excavation. According to the "Geotechnical Test Method Standard" (GB/T50123-2019), the physical properties of the soil samples, including moisture content, density, specific gravity, particle composition properties, limit moisture content, and organic content, were tested. An X-ray diffractometer (Rigaku Dmax/2500, copper target, 40 kV, 100 mA, scanning continuous, range: 5 ~ 70°) was used to test the phase composition of the soil samples, and the K value method was used to calculate the mineral composition and relative content.

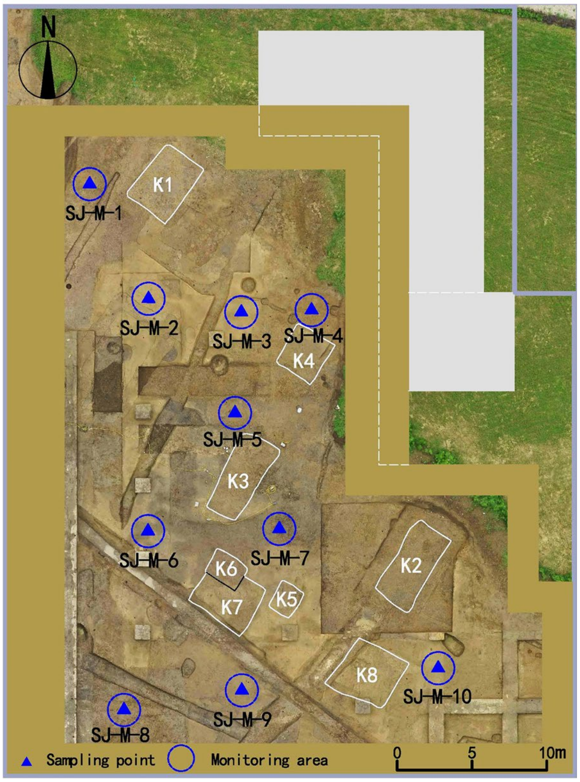


Fig. 2 Monitoring quadrat location

Principal component analysis

PCA is a commonly used data processing method [33–35]. In this research, data of seven indicators are dimensionally reduced by PCA to leverage its rigorous mathematical foundation. This process is performed by SPSS. Then, the eigenvalue (λ), percentage of variance (V) of each principal component, the cumulative variance (C), and the load factors (L) of each indicator were obtained. Using these initial data, the weight of indicator (W_j) can be calculated as Formula (1) by Excel.

$$W_j = CS_j \Big/ \sum_{j=1}^{m} CS_j = \left(\frac{\frac{L_{j1}}{\sqrt{\lambda_1}} \cdot V_1 + \frac{L_{j2}}{\sqrt{\lambda_2}} \cdot V_2 + \cdots \frac{L_{jn}}{\sqrt{\lambda_n}} \cdot V_n}{C} \right) \Big/ \sum_{j=1}^{m} \left[\frac{\frac{L_{j1}}{\sqrt{\lambda_1}} \cdot V_1 + \frac{L_{j2}}{\sqrt{\lambda_2}} \cdot V_2 + \cdots \frac{L_{jn}}{\sqrt{\lambda_n}} \cdot V}{C} \right] \tag{1}$$

In Formula (1), CS_j is the comprehensive score coefficient, which is a transition value in the calculation and can be omitted, n is the number of principal components, and m is the total number of indicators.

Linear correlation analysis

To explore the relation between certain soil properties and DOC, a comprehensive indicator to describe the DOC was set as D_i, and D_i was calculated by a weighted sum of every indicator as Formula (2). Because of the different units of each indicator, the raw data needed to be range normalized via Formula (3).

$$D_i = \sum_{j=1}^{m} W_j x'_{ij} \tag{2}$$

$$x'_{ij} = \frac{x_{ij} - x_{jmin}}{x_{jmax} - x_{jmin}} \tag{3}$$

In Formulas (2) and (3), i is the number of samples, D_i is the DOC of sample i, and W_j is calculated from Formula (1). x'_{ij} is the normalization data, x_{ij} is the raw data of the indicator of desiccation cracking, and x_{jmin} and x_{jmax} are the minimum and maximum of every indicator.

LCA is a commonly used method to study the relationship between two numerical variables. According to the relevant literature [7, 12, 25, 26], there is a certain correlation between the desiccation cracking indicator and soil properties. Most previous studies have explored the relationship between a single indicator and a single factor. In this study, LCA was used to explore the correlation between the comprehensive indicator D_i and conventional soil properties. The LCA calculation was carried out using SPSS.

The specific procedure in this research is shown in Fig. 3.

Results

Development of desiccation cracking

According to the monitoring results, during one month of exposure to the air, soil desiccation cracking developed rapidly, and after one month, it entered a stage of slow and stable development. The images (Fig. 4) show that the site soil experienced the development process of "rapid initiation of cracks—continuous expansion of cracks—formation of crack network". The whole process takes place within approximately one month. At stage 1, dendritic cracks grow rapidly on the soil surface. Then, the crack tips gradually extend, the widths and depths increase, and the soil surface forms an interconnected crack network at stage 2. In the later stage, the width and depth of fissures further increase, the growth rate slows, and a relatively stable fissure network forms on the soil surface.

The pictures in Table 1 show that the fissure network is intertwined, and different samples have different

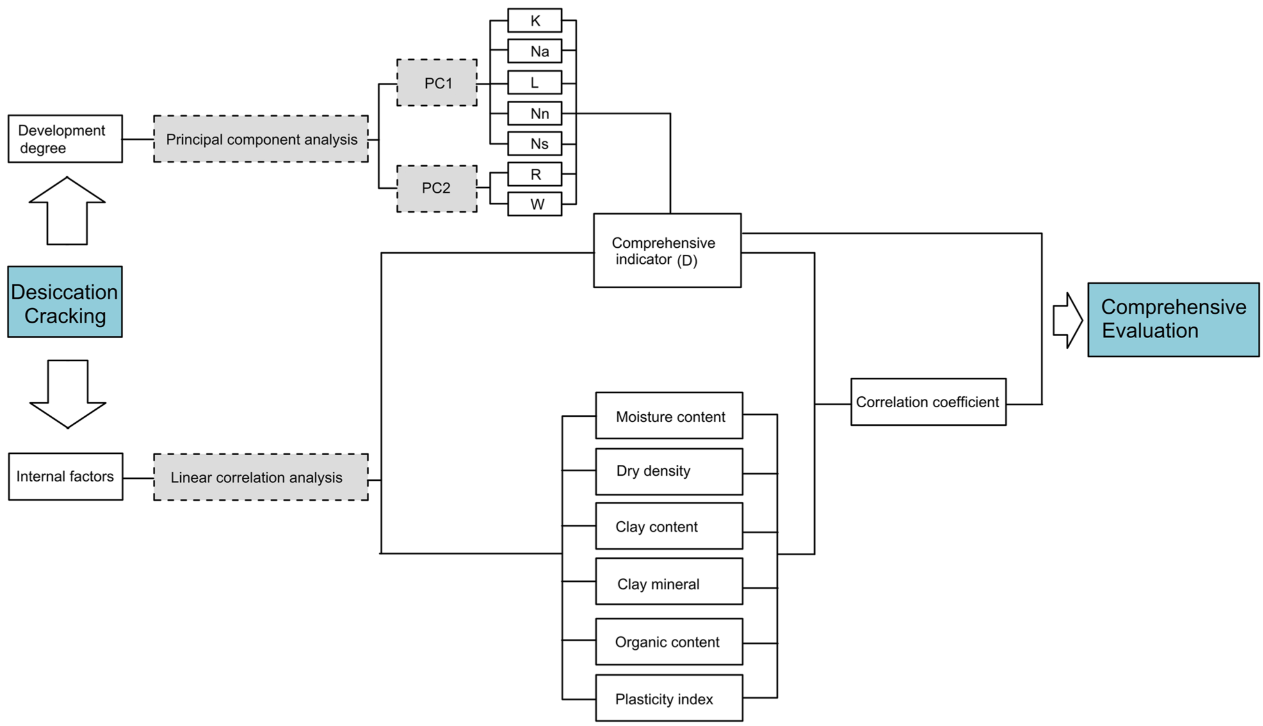


Fig. 3 Flowchart of the implementation procedure

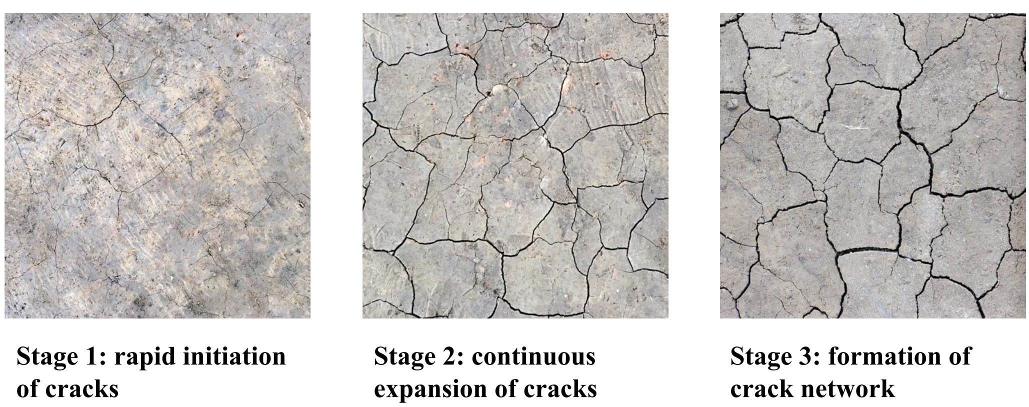


Fig. 4 Desiccation cracking development process

geometric characteristics. The damage effect of desiccation cracking on soil is manifested in two aspects: the development of the fissure itself and the cutting effect of the fissures on the soil.

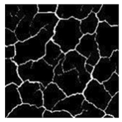
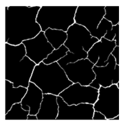
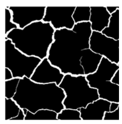
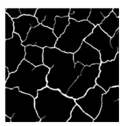
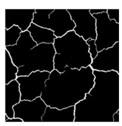
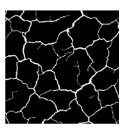
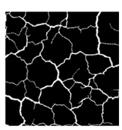
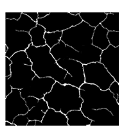
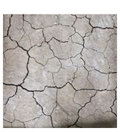
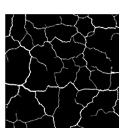
This study focuses on the state in which the desiccation cracking developed and stabilized, namely, stage 3. Relevant literature was referenced [25, 26, 28–32], and the data of seven indicators were collected. The monitoring quadrat and raw data are shown in Table 1.

PCA result

PCA was performed on the raw data of Table 1; the Kaiser–Meyer–Olkin (KMO) value was 0.686, and the significance value of Bartlett's test was less than 0.01. This result means that the raw data in Table 1 are suitable for PCA.

Table 2 shows the results of PCA. The eigenvalue (λ) of each principal component is the variance value it explains, and the sum of all the eigenvalues is equal to the total variance. Generally, when the eigenvalue value

Table 1 Desiccation cracking binarization and raw data

No	Original image	Digitized image	R (%)	L (cm)	W (mm)	Nn	Ns	Na	K
SJ-M-1			6.38	469	3.40	98	89	25	1.98
SJ-M-2			4.63	394	2.94	71	74	19	1.95
SJ-M-3			4.49	413	2.72	76	77	21	1.95
SJ-M-4			7.86	391	5.03	72	72	21	1.96
SJ-M-5			6.42	435	3.69	78	81	25	1.97
SJ-M-6			4.74	364	3.25	73	73	17	1.96
SJ-M-7			6.37	510	3.12	92	94	26	1.99
SJ-M-8			6.29	492	3.20	94	95	27	2.00
SJ-M-9			4.29	440	2.44	91	92	24	1.96
SJ-M-10			4.58	472	2.43	92	91	25	1.98

is greater than 1 (λ > 1), its corresponding principal component is selected for further analysis. The data in Table 2 show that the eigenvalues of the first two principal components are both greater than 1 (λ > 1), and the cumulative variance explained is 94.24%. In the following calculation, the first two principal components selected to represent the raw data information are reasonable.

The factor load coefficient (L) shows the contribution of the initial indicator to each of the two principal components. PC1 reflects the comprehensive information of the initial indicators L, Nn, Ns, Na, and K, which can be

Table 2 Results of PCA and weight calculation

Indicator	PC1	PC2	W_j
	$\lambda_1 = 4.589, V_1 = 65.56\%$	$\lambda_2 = 2.008, V_2 = 28.68\%$	
	$C = V_1 + V_2 = 94.24\%$		
	L_{j1}	L_{j2}	
R	0.177	0.981	0.138
L	0.977	0.024	0.166
W	− 0.307	0.946	0.053
Nn	0.943	− 0.125	0.144
Ns	0.971	− 0.184	0.143
Na	0.940	0.162	0.176
K	0.891	0.270	0.179

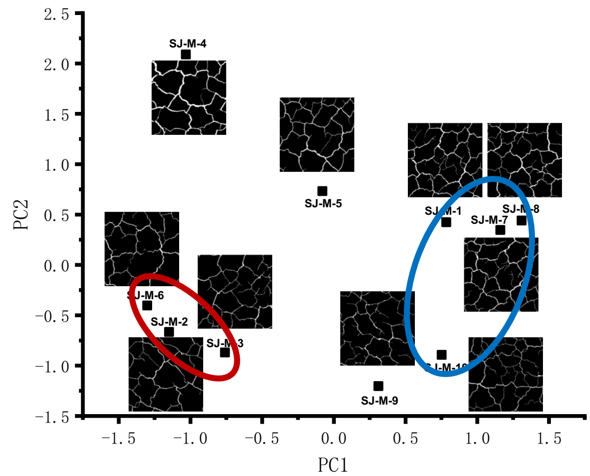


Fig. 5 Principal component scatter diagram of ten monitoring quadrats

treated as the damage to the soil structure induced by a fissure. PC2 reflects indicators R and W, which represent the development degree of the fissure itself. Combined with the variance of PC2, the contribution of initial indicators R and W is less than others. The weights of the seven indicators were calculated by Formula (1), and the result shows that each indicator contributes to describing the DOC. The weights in descending order are K > Na > L > Nn > Ns > R > W.

Comprehensive characterization of DOC

Combined with the weight of each indicator, the DOC (D_i) was comprehensively described by Formulas (2) and (3), as shown in Table 3. The result shows that the value of DOC is 0 ~ 0.9; the authors equally divided the DOC values into three levels based on expert opinions since there is no common principle about the classification of the DOC. The comprehensive evaluation of DOC in ten quadrats are shown in Table 3.

Based on the results of the PCA and comprehensive evaluation, the principal component scatter diagram of ten monitoring quadrats was drawn with Origin (Fig. 5) to illustrate the relationship between the PCA and in situ monitoring results.

From Fig. 5, the quadrats were classified into three clusters. SJ-M-2, SJ-M-3, and SJ-M-6 are in a cluster (red circle), and their comprehensive evaluation level is moderate compared with the result in Table 3. This is because the scores of both PC1 and PC2 of these three quadrats are low. From the digitized image, the desiccation cracking at this level mainly fissures that cut the surface soil into large blocks; the main fissures crosscut each other, and the intersections of the main fissures are often "Y" shaped; the number of fissures is not large, and their widths are not wide.

SJ-M-1, SJ-M-7, SJ-M-8, and SJ-M-10 are in a cluster with a severe development degree (blue circle). In these quadrats, the score of PC1 is significantly higher than that of PC2. According to the PCA results, the variance of PC1 is 65.558%, which is much higher than that of PC2 (28.682%). Thus, the comprehensive evaluation level is high. From the digitized image, in these quadrats, in addition to the main fissures, there are secondary fissures that are smaller than the main fissures and crosscut main fissures, often with "T"- or "+"-shaped intersections. The secondary fissures usually cut the soil into very small blocks. These fissures are wide.

The values of quadrats SJ-M4, SJ-M-5, and SJ-M-9 range from 0.3 to 0.6, and the comprehensive evaluation level is heavy. Combined with the digitized image,

Table 3 Development degrees

Development degree	Value	Number of quadrats	Total number of the level
Moderate	[0–0.3)	SJ-M-2 (0.105), SJ-M-3 (0.198), SJ-M-6 (0.087),	3
Heavy	[0.3–0.6)	SJ-M-4 (0.334), SJ-M-5 (0.495), SJ-M-9 (0.476)	3
Severe	[0.6–0.9)	SJ-M-1 (0.719), SJ-M-7 (0.812), SJ-M-8 (0.860), SJ-M-10 (0.613)	4

the fissures in these three quadrats are in two different forms. Fissures in SJ-M4 and SJ-M-5 are wide and cross-cut the quadrats into large blocks, while SJ-M-9 is cut by very small fissures that are narrower but more numerous. Combined with the data analysis, the PC2 of SJ-M-4 is much higher than that of PC1, and in SJ-M-5, PC2 is slightly larger than PC1, while in SJ-M-9, PC1 is slightly larger than PC2. Therefore, although their comprehensive evaluation levels are the same, the data points are scattered in Fig. 5.

Properties of the site soil

Soil properties are important factors influencing desiccation cracking. The basic soil engineering parameters are listed in Tables 4 and 5.

The data in Table 5 are the mineral compositions of the samples, which can be classified as primary minerals and secondary minerals. The primary minerals are the product of the physical weathering of the parent rock, which has little influence on the soil engineering properties. In this soil, clay minerals are secondary minerals. Secondary minerals are minerals with finer particles formed after the chemical weathering of primary minerals, which have a significant influence on the engineering properties of soil. In this research, the contents of montmorillonite and clinochlore are used to represent the clay minerals of the soil samples.

Based on engineering geological experimental research [26, 27, 31], the soil properties relevant to desiccation cracking are the moisture content, dry density, clay particle content (percentage of particles < 0.005 mm), clay mineral (montmorillonite and clinochlore) content, plasticity index, and organic content of the soil. In the following analysis, LCA will be used to explore the correlation between the above six properties and DOC.

Linear correlation analysis

The authors calculate the linear correlation coefficient between the six above-mentioned soil properties and the DOC with SPSS. The raw data and the calculation results are listed in Table 6.

The results in Table 6 reveal that the moisture content, clay particle content, clay mineral content, and plasticity index are strongly related to the DOC. The plasticity

Table 4 Properties of soil samples

No	Moisture content (%)	Natural density (g/cm^3)	Dry density (g/cm^3)	Specific gravity	Saturation (%)	Organic content (%)
SJ-M-1	21.8	2.01	1.65	2.74	90.5	0.95
SJ-M-2	24.3	2.03	1.63	2.72	99.3	0.78
SJ-M-3	22.9	1.95	1.59	2.73	86.8	0.59
SJ-M-4	22.5	2.07	1.69	2.73	99.8	0.48
SJ-M-5	20.7	1.99	1.65	2.72	86.7	0.51
SJ-M-6	23.5	2.03	1.64	2.71	98.2	0.79
SJ-M-7	22.2	1.91	1.56	2.74	80.8	0.38
SJ-M-8	21.9	1.94	1.59	2.73	83.6	0.53
SJ-M-9	21.6	1.95	1.60	2.71	84.8	0.35
SJ-M-10	22.5	1.94	1.58	2.72	85.3	0.43

No	Particle contents (%)							Identification of soil
	0.5–0.25 (mm)	0.25–0.075 (mm)	0.075–0.005 (mm)	< 0.005 (mm)	Liquid limit	Plasticity limit	Plasticity index	
SJ-M-1	0	4.03	46.07	49.90	39.7	22.5	17.2	Clay
SJ-M-2	2.18	21.74	58.70	17.38	27.0	16.3	10.7	Silty clay
SJ-M-3	5.02	19.26	56.66	19.06	29.8	16.3	13.5	Silty clay
SJ-M-4	2.34	4.89	45.18	47.59	39.8	22.2	17.6	Clay
SJ-M-5	0	9.40	69.84	20.76	35.9	20.3	15.6	Silty clay
SJ-M-6	2.59	16.96	60.83	19.62	27.2	16.8	10.4	Silty clay
SJ-M-7	0	3.06	42.75	54.19	42.5	23.6	18.9	Clay
SJ-M-8	1.15	4.63	50.51	43.71	40.9	23.7	17.2	Clay
SJ-M-9	4.40	23.60	53.77	18.23	27.4	16.6	10.8	Silty clay
SJ-M-10	6.42	17.04	52.98	23.56	29.8	18.3	11.5	Silty clay

Table 5 Mineral compositions of the soil samples

No.	Quartz	Albite	Potassium feldspar	Sodium magnesium sphalerite
SJ-M-1	51.9	19.4	5.0	5.9
SJ-M-2	58.1	23.7	6.4	5.7
SJ-M-3	52.3	25.1	11.1	6.1
SJ-M-4	42.4	17.7	13.9	0
SJ-M-5	51.8	16.8	0	10.4
SJ-M-6	38.7	29.8	7.2	13.1
SJ-M-7	45.4	12.8	5.3	0
SJ-M-8	50.1	13.5	0	0
SJ-M-9	49.3	21.5	5.9	0
SJ-M-10	34.8	30.5	11.4	9.6
No.	**Edenite**	**Muscovite**	**Montmorillonite**	**Clinochlore**
SJ-M-1	0	2.1	15.7	0
SJ-M-2	0	3.3	0	2.8
SJ-M-3	0	2.7	0	2.7
SJ-M-4	0	4.4	21.6	0
SJ-M-5	0	3.1	17.9	0
SJ-M-6	0	6.3	0	4.9
SJ-M-7	0	4.4	26.1	6
SJ-M-8	0	4.3	30.1	2
SJ-M-9	11.5	4.6	0	7.2
SJ-M-10	0	7.4	0	6.3

Table 6 Results of LCA

No	Development degree value	Soil properties					
		Moisture content	Dry density	Clay particle content	Clay mineral content	Organic content	Plasticity index
SJ-M-1	0.719	21.8	1.65	49.90	15.7	0.95	17.2
SJ-M-2	0.105	24.3	1.63	17.38	2.8	0.78	10.7
SJ-M-3	0.198	22.9	1.59	19.06	2.7	0.59	13.5
SJ-M-4	0.334	22.5	1.69	47.59	21.6	0.48	17.6
SJ-M-5	0.495	20.7	1.65	20.76	17.9	0.51	15.6
SJ-M-6	0.087	23.5	1.64	19.62	4.9	0.79	10.4
SJ-M-7	0.812	22.2	1.56	54.19	32.1	0.38	18.9
SJ-M-8	0.860	21.9	1.59	43.71	32.1	0.53	17.2
SJ-M-9	0.476	21.6	1.60	18.23	7.2	0.35	11.8
SJ-M-10	0.613	22.5	1.58	23.56	6.3	0.43	14.5
Linear correlation coefficient (R)		− 0.660*	0.419	0.678*	0.763*	-0.318	0.777**

*$p < 0.05$; **$p < 0.01$

index is significant at $P < 0.01$, and the moisture content, clay particle content and clay mineral content are significant at $P < 0.05$. Among these four factors, only the moisture content shows a negative result, and the remaining three factors show a positive result. The dry density and organic content show a weak rith DOC ($P > 0.05$).

Here, the LCA result is explained from the mechanism of desiccation cracking. The scatter plot in Fig. 6 shows the relation between four soil properties and DOC.

Desiccation cracking in soil occurs with soil water loss. With continuous evaporation, the soil particles move closer together under the action of the matric suction,

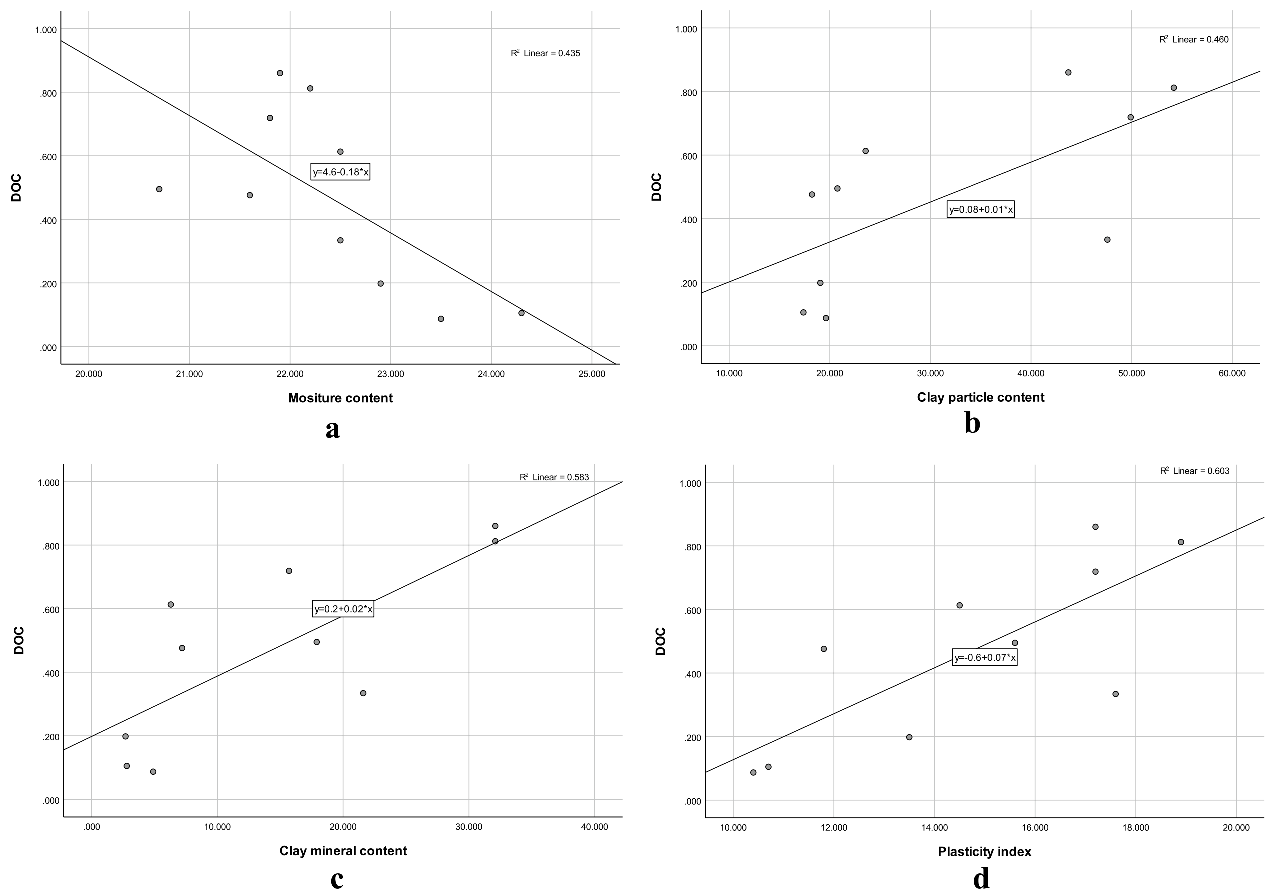


Fig. 6 Scatter plots of the soil properties and DOC (**a** moisture content and DOC. **b** clay particle content and DOC. **c** clay mineral content and DOC. **d** plasticity index and DOC)

resulting in visually detectable desiccation and shrinkage cracking at the macroscale. Water evaporation starts from the soil surface, so the surface soil shrinks and cracks first. When a fissure is formed, local energy is released; since the two sides of the fissure deform in opposite directions, the fissure tips become stress concentration areas, and the fissure develops downwards. Therefore, according to the formation mechanism of desiccation cracking, the moisture content and DOC are negatively correlated (Fig. 6a).

Desiccation cracking is a structural change of soil caused by volume shrinkage in the horizontal direction after water loss. Shrinkage is the premise of desiccation cracking. Based on the cohesive soil expansion and shrinkage theory, when the soil has a high moisture content, the smaller the soil particle sizes are, the thicker the water film around the soil particles, and the larger the space occupied by the water between the soil particles. Corresponding to the soil with low moisture, when the water outside the soil particles is reduced, the thickness of the water film is reduced. Under the action of matrix suction, soil particles are rearranged, interparticle voids enlarge, and macroscopically, the soil shrinks. The smaller the particle sizes are, the more obvious the effect of the clay particle content on soil shrinkage. The higher the clay particle content is, the greater the DOC value is, so the two show a positive correlation: Most data points are evenly distributed on both sides of the fitting line, so the clay particle content is strongly related to DOC (Fig. 6b).

The clay minerals are a kind of hydrous aluminosilicate with a layered structure, which affects the development of shrinkage cracking in two aspects. One is the particle size of the clay minerals. Generally, the size of the clay minerals is less than 2 μm. The effect of specific surface energy is similar to that of clay particle size. The other is the layered crystal structure. In the samples studied in this research, the main clay mineral is montmorillonite, and the second-most common is clinochlore. Montmorillonite possesses an active crystal lattice that easily absorbs water and expands while losing water and contracting. Omidi's research shows that the shrinkage rate of montmorillonite even reaches 16.4% [36]. The clay mineral content is one of the important factors that influence the development of desiccation cracking, and based on the LCA result, a higher clay mineral content corresponds to a higher DOC, with a highly positive correlation (Fig. 6c).

The plasticity index is closely related to the particle size and mineral composition of the soil. Generally, the smaller the soil particle size and the higher the clay mineral content are, the greater the plasticity index. The plasticity index comprehensively reflects the two factors above, and the scatterplot verifies the result that the plasticity index is strongly related to the DOC (Fig. 6d).

Discussion

In this study, the seven conventional desiccation cracking indicators all contribute to the DOC, although they have different weights, and the indicator D_i comprehensively reflects the seven indicators. The evaluation result can be revealed and explained by the in situ monitoring result. The conventional soil properties show different correlations with DOC.

Most existing studies [5, 8–10, 12] on desiccation cracking have been carried out in the laboratory by simulation tests, in which samples in small-scale models with high moisture (often more than 80%) were selected to simulate the desiccation cracking behaviour at earthen sites. Limited by the small sample scale and high moisture content, which is quite different from archaeological excavation sites, some of the conclusions in previous studies cannot be applied directly. The results from in situ monitoring in this research verify the development of desiccation cracking in references [8] to [10], and the desiccation cracking comprehensive evaluation based on the data acquired in the natural environment is more authentic than previous simulation tests. This study provides an important reference for quantitative research on the mechanism of desiccation cracking of archaeological sites in similar environments.

Most existing studies on desiccation cracking in archaeological sites [3–7, 13–17] have used qualitative methods to describe the development degree, based on judgement by experts. Although most experts have professional backgrounds, this characterization is subjective and is not beneficial for assessing the deterioration degree of sites precisely and objectively. In the field of geotechnical engineering, the development of desiccation cracking is characterized by single indicators or multiple indicators according to the research aims [18, 28–32]. However, these indicators reflect only certain aspects of desiccation cracking and cannot describe the damage effect to the archaeological site. In contrast to the results of existing studies, the results in this research show that the comprehensive indicator DOC involves seven conventional indicators, taking into account both the weight and value of each indicator. The weight represents the contribution of each indicator to the DOC, and the destruction effect of desiccation cracking on earthen sites is fully reflected by the weighted summation method. Compared with existing research, this characterization is more advanced because the data are objective and the calculation method is scientific. It is helpful for conservators on site to judge the development degree of deterioration over time.

The comprehensive evaluation results illustrate that there are two degradation aspects of desiccation cracking at the earthen site. One is the cutting effect of desiccation cracking (PC1), and the other is the development of desiccation cracking itself (PC2). Combining the monitoring, PCA, and comprehensive evaluation results, the value of DOC is often high in quadrats with high PC1. Notably, this result is closely related to the stage of data collection in which the desiccation cracking development was stable. At this stage, fissures developed at a very slow speed, and the value of the indicator characterizing the development of the fissure itself is small; thus, the weights of indicators R and W represented by PC2 based on the objective weight method are smaller than those of the other indicators. In fact, indicators R and W generally develop quickly at the early stage of desiccation cracking formation. Therefore, this conclusion is the result of data collection at a specific time.

Regarding the correlation analysis of soil properties and DOC, this study indicates that for the purpose of site conservation, there are four soil properties that should be focused on, among which moisture content must be emphasized. Although the correlation of moisture content with DOC is negative, this does not mean that more water is better for site preservation. Based on the basic knowledge of geological engineering, the shear strength of soil decreases with increasing moisture content, since the internal friction angle (c) and soil cohesion (φ) decrease. Consequently, the risk of collapse increases. Accompanying the increasing moisture content, soluble salt in the soil dissolves and crystallizes repeatedly; then, the strength of the soil decreases, and the surface of the soil is weathered. The secondary deterioration caused by water also affects the conservation of earthen sites. Thus, to control the development speed of desiccation cracking once excavation begins, environmental control measures should be focused on. It is necessary and important to slow desiccation cracking by maintaining moisture rather than adding more water.

Additionally, although the fitting line is drawn in Fig. 6 in this research, it does not mean that quantitative relationships between the four soil properties and DOC are obtained. The desiccation cracking of the site is essentially a problem caused by the expansion and shrinkage of soil, which is the result of the synergistic influence of various factors. It is still not clear how this synergy works and how the quantitative relationship between the various factors reflect the formation mechanism in the geotechnical field. The scatter plots in Fig. 6 illustrate the closeness between the four soil properties and DOC, which lays a foundation for exploring the quantitative relationships between multiple factors and DOC.

Based on existing research [37–39], the influence of organic content in desiccation cracking is not clear and needs to be explored. In this research, the organic content is weakly related to DOC, which is consistent with previous literature.

Generally, dry density has a negative effect on DOC [9, 12], but in this study, the correlation between the two is not strong. Since the ten monitoring areas in this study are located at the same archaeological excavation site, the fluctuation range of dry density data is not large. Limited by the amount of data, the relationship between them is not clear, and more data are needed.

There are some deficiencies in this research. Another important aspect is that environmental factors also play a crucial role in the process of desiccation cracking. The generation of desiccation cracking is a complicated process involving the soil properties, atmospheric conditions, geological conditions, and groundwater conditions. Desiccation cracking forms under all these factors. This research aims to explore the effect of site soil properties on shrinkage cracking. This is a preliminary study on the formation mechanism of shrinkage cracking at a site of archaeological excavations. The influence of environmental factors will be studied in future studies.

Conclusions

According to in situ monitoring, geotechnical testing, PCA and LCA, the following conclusions were drawn:

1. The weights of seven indicators characterizing desiccation cracking were calculated by the PCA method, and the weights in descending order are K (0.179) > Na (0.176) > L (0.166) > Nn (0.144) > Ns (0.143) > R (0.138) > W (0.053). The damage effect of desiccation cracking on soil is reflected in two aspects. The comprehensive indicator can reflect the DOC in terms of both aspects. For the Sanxingdui archaeological site, the indicators of K, Na, and L should be focused on in the next monitoring stage. Once these three indicators change significantly, shrinkage cracking develops and accelerates.
2. Clay particle content, clay mineral content, and plasticity index closely impact the DOC positively, while moisture content shows a strong negative correlation. At the Sanxingdui archaeological excavation site, these four parameters are the main internal factors influencing desiccation cracking, and maintaining the initial moisture content of the site soil is essential for controlling the development of desiccation cracking. For other archaeological excavation sites, to prevent desiccation cracking, these three soil properties should be taken into consideration first; if these three parameters are high, desiccation cracking easily develops quickly, and environmental control will be a crucial factor.

Abbreviations

DOC	Development degree of desiccation cracking
PCA	Principal component analysis
LCA	Linear correlation analysis
R	Surface fissure ratio
L	Total length of the fissures
W	Average fissure width
Nn	Number of fissure nodes
Ns	Number of fissures
Na	Number of soil blocks
K	Fractal dimension
KMO	Kaiser–Meyer–Olkin

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Author contributions
XY and FZ designed the research project; FZ was responsible for the investigation, data collection, and analysis; XY wrote this publication. All authors read and approved the final manuscript.

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Availability of data and materials
The data used in this research are published in this paper, and they are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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