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RESEARCH

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A comprehensive assessment method for the health status of bronzes unearthed at archaeological sites

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Abstract

As one of the common physical materials in Chinese archaeological excavations, ancient bronzes are an essential basis for studying the development of Chinese bronze culture, which is of great significance for exploring the development law of ancient human civilization and reconstructing ancient human society. As China's infrastructure advances, the number of bronzes unearthed by archaeological excavations continues to increase. However, environmental damage to artefacts is very complex, whether the buried environment of the artefacts or the above-ground environment when the artefacts are unearthed, leading to different health problems for the excavated bronzes. A scientific assessment of these bronzes needs to be carried out prior to extraction to inform staff how they should be extracted, moved, and transported and how they should be restored afterwards. In response to the above problems, this paper takes excavated bronzes from archaeological sites as the research object and, by analysing and studying the relevant industry standards and the disease characteristics of bronzes, establishes a three-tier indicator framework for assessing the health of bronzes in a layer-by-layer refinement and proposes quantitative indicators with typical correlations. Through extensive research and testing, we screened out efficient, non-destructive, convenient and reliable assessment and testing methods and assessment models that combine subjective and objective aspects suitable for archaeological sites. On this basis, the paper achieves a scientific and practical assessment of the health status of bronzes excavated from archaeological sites. After repeated experiments, a set of comprehensive methods for quickly and conveniently assessing the health status of excavated bronzes was proposed for the first time and successfully applied to the archaeological excavation site of Sanxingdui site in Guanghan City, Sichuan Province, China.

Keywords Archaeological site, Bronzes, Health assessment, Assessment methods, Sanxingdui site

Introduction

Ancient bronzes are essential physical materials for studying ancient societies. As China's infrastructure advanced, the number of unearthed bronzes increased, and most had health problems. In addition to physical extrusion deformation, cracking and damage, corrosion is the most significant damage during the long-term burial of bronze alloy artefacts. Numerous studies have shown that soil moisture, oxygen content, acid–base atmosphere, active anions and cations, and some microbial metabolism will cause varying degrees of corrosion to bronzes. As the buried environment stabilizes for a long time, the corrosion rate will gradually slow down. When the excavation process upsets this equilibrium environment, changes in the environment can lead to accelerated corrosion of bronzes and the emergence of other diseases. Therefore, before extracting the unearthed bronzes, it is necessary to conduct a health assessment first to grasp the health

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status of the artefacts in time. The current assessment of the state of health of excavated bronzes is still largely dependent on the subjective experience of individuals at the excavation site. This subjective experience carries considerable uncertainty and may lead to untargeted methods of extraction, packaging and transport by staff, resulting in damage to cultural objects. However, how to scientifically evaluate bronzes' health status has yet to form an effective assessment method. Therefore, there is an urgent need to construct an efficient and convenient method to assess the health status of bronzes unearthed at archaeological sites with the help of scientific detection methods. This method can better adapt to archaeological sites' complex and changeable environments, provide an essential basis for selecting artefacts extraction, packaging and transportation methods, and provide the necessary support for the emergency protection and long-term protection of ancient bronzes.

In recent years, with the continuous improvement of relevant industry standards and research results and the development of modern analytical and testing techniques, the bronze health assessment has been provided with new ideas and technical means. In 2014, the State Administration of Cultural Heritage of China issued industry standards such as 'Bronze and iron collection's disease and illustration' and 'Technical specification for evaluating disease of movable collection-Metal', which provided not only standard support for the definition of bronze diseases but also provided the necessary guidance for the identification, detection and measurement of bronze diseases. With the development of modern analytical and testing technology, CT scanning, metal ultrasonic detector, electron spectroscopy (EDAX), scanning electron microscopy, X-ray diffraction, non-destructive testing infrared technology and other come improved instruments [1–7] are widely used in qualitative or quantitative analysis of artefacts, providing technical support for bronze health assessment. Multidisciplinary exchanges are also becoming more frequent, and methods such as Grey Relation Analysis (GRA) and Analytic Hierarchy Process (AHP) have been gradually introduced into the field of heritage conservation, providing suitable assessment methods for further exploring the significance of data. All these provide a solid theoretical basis for us to study and propose the health assessment indicators, analysis methods, and assessment methods of unearthed bronzes from archaeological sites.

Given the lack of comprehensive assessment of the health status of unearthed bronze artefacts, this paper focuses on the health status of bronze artefacts in the complex environment of the excavation site, taking the bronze artefacts unearthed at the archaeological site as the research object, as shown in Fig 1. Based on existing research, combined with the relevant industry standards for the classification of artefacts diseases, according to the characteristics of artefacts materials and diseases, study the risk factors affecting the health status of artefacts after excavation, and determine the evaluation indicators. Under the premise of applying to archaeological excavation sites' complex and changeable environment, some rapid, in situ and non-destructive analysis methods are selected to identify and quantify the indicators. Combined with relevant systematic analysis and repeated experiments, scientific analysis of the influence degree of evaluation indicators, the correlation between assessment indicators and detection results, and the authenticity of evaluation models provide a set of scientific and practical health evaluation methods for bronzes unearthed at archaeological sites.

Research status of health assessment indicators of unearthed bronzes

Assessment indicators are essential to the health assessment methods of bronzes unearthed at archaeological sites. While little research on the health assessment indicators of bronzes is available, there is considerable research on the diseases of ancient bronzes. In 2014, the State Administration of Cultural Heritage of China issued 'Bronze and iron collection's disease and illustration', which listed ancient bronze diseases, including incomplete, fracture, crack, deformity, laminar deposit, perforation, surface encrustation, mineralization, pitting corrosion and damage by microorganism. 'Technical specification for evaluating disease of the movable collection-Metal' divides the diseases into three types according to the nature of disease activities, among which chlorine-containing corrosion products in active disease types can cause other diseases and damage artefacts under the influence of the environment.

In the past one hundred years, scholars have researched the corrosion products of bronzes. Results show that bronzes have various corrosion products, such as copper oxides, basic copper carbonate [8, 9], and basic copper chlorides [10]. The formation mechanism of these corrosion products was also studied by Scholars at home and abroad. At the beginning of the twentieth century, British scientist Vernon studied the connection between the composition of bronze corrosion products and the environment. Research by Bosi C & Garagnani GL [11], Robbila L et al. [12] and others have experimentally shown that bronze corrosion will lead to different metallographic structures. Some researchers also believe the alloy composition of the copper matrix significantly affects the surface morphology of corrosion products (e.g., Constantinides I [13]). At the end of the twentieth century, domestic research

Fig. 1 Bronzes excavated from the sacrificial pit K8 at the Sanxingdui site. a. K8-1 Bronze Mythological Beast. b. K8-4 Bronze Figurehead. c. K8-5 Bronze Zun (K8-5 青铜尊). d. K8-6 Bronze Zun

on the corrosion mechanism of bronzes showed that the formation of corrosion products of bronzes is not only related to the composition of the matrix itself but also under the influence of external environmental factors. Some studies suggest that the corrosion of bronzes is primarily the result of chloride, moisture and oxygen in the external environment (Xiao JX [14]), resulting in the appearance of native chloride-bearing bronze corrosions (bronze disease). Fan CZ et al. [15] artificially corroded copper samples by simulating natural conditions. The analysis of the experimental results showed that chloride ions, moisture, and oxygen were the basic elements of 'bronze disease' [16] and that chloride ions were the key elements. In addition, Fan CZ et al. [17] used hydrochloric acid to corrode the surface of copper samples and used instruments to analyze the occurrence and development of corrosion. The results showed that corrosion grew rapidly under acidic conditions.

Similarly, Afonso FS et al. [18] investigated the effects of chloride content, oxygen, and humidity in soil on copper corrosion and demonstrated a good correlation between the average corrosion rate and the soil aggressiveness based on gravimetric data. There is a correlation between the corrosion mechanism of unearthed bronzes from the archaeological sites and the soil characteristics [19]. In 2005, Nord AG et al. [20] indicated that acidic soils, large deposits of sulfur pollutants associated with critical loads, the presence of soot and soluble salts, and conditions in water and air all could accelerate the deterioration of bronzes. Zhou JH et al. [21] analyzed fifteen samples from the archaeological site and collections and believed that the unearthed bronzes did not have 'bronze disease' but formed lesions in the soil and gradually transformed into 'bronze disease' under suitable environmental conditions.

In recent years, research [22–26] has shown that many factors, such as water content, pH, oxygen content, acid–base substances, soluble salts, organic matter, and soil microorganisms, are directly related to the formation of corrosion products. Under high humidity, oxygen-containing, chlorine-containing, and acidic environments, 'bronze disease' can continually corrode bronzes, causing perforation, loosening, and festering. Suppose the preservation environment is not controlled in time. In that case, it constantly corrodes the bronze and infects other bronzes around it, thereby increasing the destruction.

Diseases' manifestation, characteristics and development trends are the basis for the health assessment of unearthed bronzes. It is also the key to determining the indicators of bronzes health assessment. The above research results provide a theoretical basis for establishing the framework of assessment indicators of bronzes excavated from archaeological sites.

Research status of a health assessment model of bronzes

According to the content of the unearthed bronze health assessment, screening the systematic analysis method suitable for bronze health assessment is the key to achieving scientific assessment. The method of system analysis refers to the methods and tools that use data and related management science techniques and methods to research to solve and optimize problems in decision-making. Research on the systematic analysis method of unearthed bronze health assessment is relatively rare. However, many excellent evaluation methods are worthy of reference, and the commonly used system analysis methods include Analytic Hierarchy Process, Grey Relation Analysis, et al.

Analytic Hierarchy Process (AHP) is a subjective assessment based on expert experience. It uses Professor Saaty T.L.'s fundamental 1–9 scale [27] to quantitatively describe the importance of pair-by-two comparisons of factors at the same level to evaluate the scores of each factor at the same two levels and obtain a judgment matrix. Grey correlation analysis (GRA) is an important method to study the correlation between factors within the system, which belongs to objective evaluation. It is a quantitative analysis of the dynamic development process of the system to examine whether the relationship between the factors of the system is close [28]. In terms of applied research, Analysis by Nachiappan S et al. [29] has revealed that a significant number of AHP applications are found when problems require considerations of both quantitative and qualitative factors. Vaidya OS et al. conducted a literature review of the applications of the Analytic Hierarchy Process (AHP) [30]. In 2022, Ing EB [31] proposed and verified that AHP processes could promote equity, diversity and inclusion. Scholars have also used the analytic hierarchy process and grey relational analysis method to evaluate Serbia's Saar Mountains [32], landslides [33], hybrid steel frame [34], electricity substitution projects [35], and social benefits of eco-tourism scenic areas [36], and obtain effective assessment results. These methods have also begun to be applied in heritage conservation in recent years. In 2016, Yao et al. [37] used the grey correlation method to quantify the degree of disease of twenty-nine buildings on the Great Wall from Niujialiang to Qinhe in Yuyang District, northern Shaanxi and provided a scientific basis for the protection and reinforcement measures of these single buildings. Ma YY [38] et al. used the grey correlation method to study the correlation coefficient between the main influencing factors and bronze corrosion when studying the influence of environmental factors on the corrosion of bronze.

The bronze health assessment model mainly uses systematic analysis methods to analyze quantitative data on indicators. Combining the AHP and GRA can form a comprehensive assessment, reducing the risks caused by subjective human assumptions. Both methods apply to the health assessment of excavated bronzes and enable quantitative data analysis on assessment indicators. Therefore, this paper draws on excellent evaluation cases, combines the AHP and GRA, systematically analyzes evaluation indicators, and calculates the total weight of assessment indicators.

Establishment of health assessment method for unearthed bronzes at archaeological sites

Health assessment of excavated bronzes refers to systematically collecting the health data of bronzes unearthed at archaeological sites and judging the value of the data, mainly based on the data source and systems. The health assessment methods of unearthed bronzes at the archaeological site include health assessment indicators, in-situ non-destructive analysis methods, and an assessment model. Establishing the framework of bronze health assessment indicators first involves identifying the risk factors affecting the extraction and preservation of bronzes from archaeological sites. And then analysing the extent to which the main factors are relevant to the health of excavated artefacts and how they can be quantified. According to the archaeological site environment and heritage conservation requirements, rapid, in-situ and non-destructive analysis methods are studied to support acquiring key information for health assessment. At the same time, bronze health assessment standards are formulated according to the degree of influence of different factors on the health status of bronzes. By analysing the state of preservation and health values of bronzes, the health levels of bronzes are distinguished. Then an effective assessment of the health status of bronzes is achieved through health levels.

Assessment indicators

The selection and identification of assessment indicators are crucial to constructing a health assessment methodology for bronze artefacts excavated from archaeological sites. According to previous studies and field investigations, the type and extent of disease of excavated artefacts can directly reflect the health status of the artefacts, and the environment in which the artefacts are located can further influence the development of the diseases. Therefore, the assessment indicators should contain two sub-systems: Bronze Health Assessment Indicators and Occurrence Environment Reference Indicators. The Bronzes Health Assessment Indicators (BHAI) are a focused representation of the characteristics and extent of bronze disease, which are critical to assessing the health of bronzes and can assist staff in adopting targeted methods of artefact extraction, packaging and transport. The Occurrence Environment Reference Indicators (OERI), which indicate the stability of the buried soil surrounding the artefact before extraction, can reflect the artefact's risk expectation and help conservators develop strategies for the long-term conservation of bronze artefacts.

Combined with the analysis of the state of conservation of the excavated bronzes, and based on the extraction, packaging, transport and emergency conservation treatment of the directly associated artefacts, the main factors affecting the deterioration of the bronzes thus identified are incomplete, crack, corrosion and mineralization. The diseases mentioned above can affect changes in the hardness of bronzes and thus directly affect the safe and stable condition of the bronzes. Measuring the hardness of bronzes can also reflect the health state of the bronzes to a certain extent and meet the demand for rapid, in-situ and non-destructive testing at archaeological sites. As a result, the main factors affecting the health status of the excavated bronzes were ultimately identified as mutilation, fracturing, corrosion, mineralization and hardness, which led to the conclusion that the secondary assessment indicators were completeness, degree of corrosion and mechanical properties.

In order to further quantify assessment indicators scientifically, the main factors need to be identified and measured and expressed using results such as quantity, area and length. The different sizes of the bronzes make it necessary to translate the quantitative results of some of the assessment indicators into percentages for comparisons of the same magnitude. Therefore, this paper uses the incomplete area ratio, crack length ratio, corrosion area ratio and corrosion thickness ratio to quantify the health status of excavated bronzes, which are quantified as follows.

Firstly, this paper uses the incomplete area ratio and the crack length ratio to characterise the completeness of the bronze. The incomplete area ratio refers to the ratio of the surface area of the incomplete part to the total surface area and the crack length ratio of the existing fissure length to the penetration length of the fissure development. Through many experimental analyses, the increase in incomplete area ratio and crack length ratio will directly reduce the stability of bronzes. Therefore, considering the safety of artefacts during archaeological excavation, incomplete area ratio and crack length ratio are used to characterise the completeness of the bronze. Secondly, this paper uses the corrosion area ratio and the corrosion thickness ratio to characterise the degree of bronze corrosion. The corrosion area ratio is the ratio of the sum of such corroded areas causing the bronze to be loose, brittle or with a corrosion thickness of more than 0.1 mm to the total area of bronze. In order to measure the corrosion thickness of bronze, we have tried various testing methods. Eventually, we proved through repeated experiments that only the resistance meter can meet the needs of fast, in-situ and non-destructive testing. The experimental results show that the corrosion thickness of bronze is positively correlated with the resistance in the same environment. Therefore, this paper uses resistance to characterise the corrosion thickness of bronze. Finally, to meet the need for scientific, efficient and convenient testing, the Shore hardness of the object will also be the primary way to characterise the mechanical properties of the bronze.

According to the study of the corrosion mechanism of bronzes, the environment in which the artefacts are preserved is an important external factor affecting the generation and development of disease. Characterization of soil corrosivity in archaeological sites is an important subject to understanding the conservation conditions of archaeological bronze collections and helps conservators to prepare a conservation strategy for the long-term preservation of bronze objects [24, 39–41]. According to the Technical specification for evaluating disease of movable collection-Metal, chlorine-containing corrosion products, as an active disease, will continue to corrode the substrate under the influence of the environment and lead to surface flaking and substrate decay of the bronze. Temperature, humidity, oxygen content, chloride ions and pH in the environment are the main factors in the emergence of 'bronze disease'. Therefore, humidity, temperature, salinity and conductivity can be selected as the main factors that characterize the burial environment's quality and reflect the excavated artefacts' risk assessment. A suitable preservation environment for bronzes is a temperature of around 20 °C and a humidity of 0–40%. According to the relevant definitions of soil conductivity, a conductivity of more than 166 ms/m is classified as saline soil. If the quality of the burial environment exceeds these normal ranges, the status of preservation of the bronze is likely to be at risk.

The indicators framework is shown in Fig. 2.

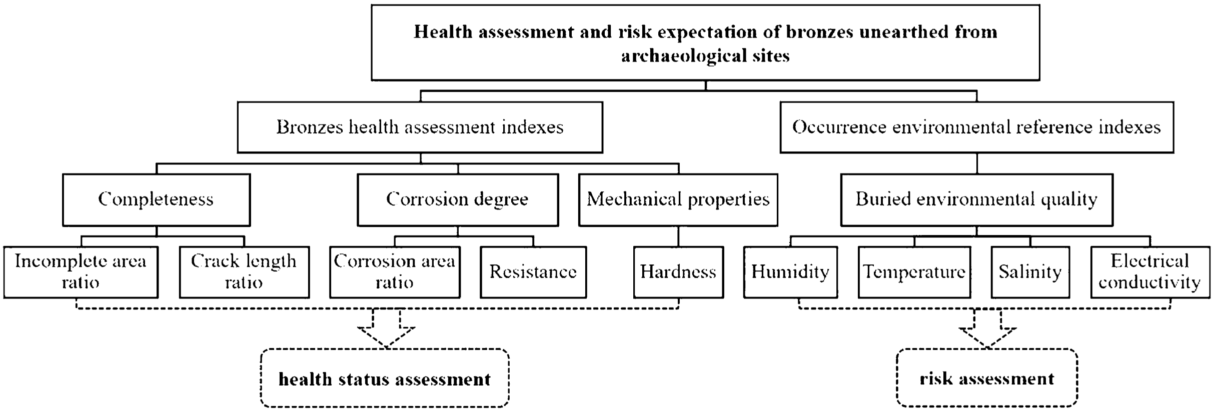

Fig. 2 Framework diagram of health assessment and risk assessment of bronzes unearthed from archaeological sites. The framework consists of two subsystems and three levels of indicators. Notably, the Health Assessment Indicators are crucial to assessing the health of bronzes, and the Occurrence Environment Reference Indicators reflect the artefacts' risk expectations

In-situ non-destructive analysis methods

Obtaining qualitative and quantitative results reflecting the ontology materials of artefacts by analytical means is a crucial way to effectively assess artefacts' health status. No systematic investigation and analysis methods exist for bronzes during the unearthed process. According to the content requirements of the health assessment of bronzes, this paper will study the in-situ non-destructive analysis methods to characterize the health status of bronzes effectively. Moreover, a systematic in-situ non-destructive analysis process will be developed by combining laboratory method research and field application validation.

In the process of identifying and quantifying the main influencing factors of bronze deterioration, the industrial grade DL9810 fibreglass tape measure offers the advantages of high accuracy and ease of operation for the measurement and calculation of incomplete area ratio, crack length ratio and corrosion area ratio of the health assessment indicator factors.

During the study, various characterisation methods have also been tried to characterise the corrosion thickness of bronze. Such as eddy current pulse thermography, ultrasonic testing, infrared thermography [42–44] and the high resistance method. The experimental results show that only the high-resistance method meets the detection needs, and the test results are promising. It is feasible to use the high-resistance method to characterise the corrosion thickness of bronze. The resistance instrument is easy to operate, enables non-destructive testing of artefacts and gives rapid results, meeting the requirements of the complex environment of the archaeological site and the protection of artefacts. Therefore, through the experiments and field analysis of various instruments, the resistance instrument was finally chosen to characterise the corrosion thickness of the bronze.

To characterise the mechanical properties of bronzes, we have tested the effectiveness of the metal hardness tester on archaeological excavation sites. However, the test results showed that the measuring probe of the metal hardness tester is of high strength and unsuitable for use with valuable artefacts such as bronze. For this reason, a Shore hardness tester with a relatively low measurement intensity was selected and successfully applied to the excavation site of the Sanxingdui site. There are three types of Shore hardness testers: D, A and C. All three types of hardness testers can effectively measure the surface hardness of bronze. The LXD-D hardness tester has relatively high strength and is suitable for excavated bronzes of high hardness. The LXD-A hardness tester has relatively low strength and is suitable for low to medium-hardness bronzes. The LXD-C hardness tester is suitable for measuring fragile bronze's hardness. The LXD- D, A and C hardness tester is capable of unit conversion and conversion with other hardness units. Therefore, according to the bronze's preservation state, we can choose the right type of Shore hardness tester at archaeological excavation sites.

Characterisation of the environment is an essential tool for understanding and assessing the state of the environment in which artefacts are buried. It helps conservators to develop plans for the long-term conservation of bronzes. In this paper, the TR-6D soil detector was selected to quantify the Occurrence Environment Reference Indicators, which can detect soil temperature, moisture, salinity and conductivity. Moreover, it can indicate the state of the buried environment of artefacts and guide for determining the environmental parameters for their later preservation.

Assessment model

Explore constructing a health assessment model for bronze artefacts, including an assessment indicator framework and an analytical methodology. The indicator framework is based on quantifying indicators and classifying health levels; the analytical method supports acquiring crucial information for the health assessment. The subjective and objective weights of the assessment indicators are calculated using the Analytic Hierarchy Process and Grey Relation Analysis; the weight formula calculates the total weight of each assessment indicator, and the health value formula calculates the health value of the excavated bronze.

On this basis, the rationality of the classification of bronze health levels is verified according to the on-site judgment of archaeological sites and the calculation results of bronze health value. Finally, scientific and practical assessment of the excavated bronzes is achieved through the health levels.

In addition, the quantitative results of the Occurrence Environment Reference Indicators can reflect the environmental quality of the soil in which the bronzes were buried and guide the preservation of the bronzes.

The arithmetic process of the assessment model is detailed in the methods section.

Materials and methods

Materials

Based on the constructed comprehensive assessment method for the health status of excavated bronzes, an applied study was carried out using bronzes excavated from the Sanxingdui site. Twelve bronzes are selected from those unearthed at the sacrificial pits K7 and K8 in the sacrificial area of Sanxingdui site, including the K7-1 Bronze Figurehead, K7-2 Bronze, K7-3 Bronze Bird, K7-4 Bronze Human Mask, K7-5 Bronze Fragment, K8-1 Bronze Beast, K8-2 Bronze Lei (青铜罍), K8-3 Bronze Beast, K8-4 Bronze Human Figurehead, K8-5 Bronze Zun (青铜尊), K8-6 Bronze Zun and K8-7 Bronze Human Figurehead.

Methods

Quantitative methods for assessment indicators

Based on ten types of bronze disease (incomplete, fracture, crack, deformity, laminar deposit, perforation, surface encrustation, mineralization, pitting corrosion, damage by microorganism), this paper counts the type and quantity of disease for each bronze. The bronze health assessment indicators were also quantified using the DL9810 fibreglass tape measure, LXD-A hardness tester, and 6517B high-resistance meter. Table 1 shows the quantitative results of each assessment indicator.

The DL9810 fibreglass tape measure was used to measure and calculate the incomplete area ratio, crack length ratio and corrosion area ratio.

The resistance measurement method is to select 10–15 resistance values and calculate the average. The resistance is measured by the 6517B high-resistance meter. The instrument measurement parameters: measurement function: two-wire resistance; range: 2MΩ,20MΩ,2GΩ,20GΩ; NPLC (cycle multiple of sampling power): 1; DC voltage value: 100 V; Meter Connect (select it); acquisition: measurement delay: 1.00 s; the number of measurement points: 5; the measurement length: 1 cm.

The measurement method of the LXD-A hardness tester is to evenly take 10–12 points on the surface of bronzes for testing, select the 3–5 lowest values from the results, and calculate the average value.

Table 1 Quantitative results of assessment indicators

Artefact number	Number of diseases	Incomplete area ratio (%)	Crack length ratio (%)	Corrosion area ratio (%)	Resistan-ce (GΩ)	Hardness (HA)
K7-1	4	2.0	100	100	480.83	84.88
K7-2	3	0.1	0.1	20.0	70.00	96.75
K7-3	1	0.1	0.1	80.0	495.80	84.33
K7-4	3	0.1	6.6	10.0	102.35	85.17
K7-5	3	90.0	100	100	289.04	44.00
K8-1	2	0.1	0.1	10.0	38.24	95.80
K8-2	4	12.7	40.0	80.0	183.79	83.17
K8-3	1	0.1	0.1	32.0	473.97	94.90
K8-4	1	0.1	0.1	15.0	44.60	94.50
K8-5	4	1.1	22.8	10.0	146.42	86.00
K8-6	4	49.9	10.0	100	211.08	93.00
K8-7	2	16.1	0.1	100	297.19	93.00

Follow the measurement method of the TR-6D soil detector, then evenly select 5–10 points at the buried location of bronzes for detection and calculate the average value to obtain the data of the occurrence environment reference indicator of the bronzes.

The subjective weights calculation method of the assessment indicators

According to Analytic Hierarchy Process, the subjective weights of the assessment indicator are calculated to determine its impact on the bronze's health status. According to the fundamental 1–9 scale table [45, 46] of Table 2, a judgment matrix was created.

Calculate the eigenvectors of the assessment indicator. The approximate value of the indicator's eigenvector is calculated using the root method.

Calculate the nth root of the product of the elements in each row of the assessment indicator. M_i is calculated according to the following formula.

$$M_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{1}$$

where a_{ij} represents the comparison of objective i th relative to objective j, which is given using Professor Saaty's fundamental 1–9 scale.

Normalize the M_i and calculate the subjective weights of the indicators. W_i is calculated according to the following formula.

$$W_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{2}$$

The objective weights calculation method of the assessment indicators

Normalizing the data on the number of diseases and assessment indicators for bronzes allows the assessment indicators to be converted to values within the interval [0,1]. The normalization formula is shown in the equation below.

$$X_{ij} = \frac{x_{ij} - x_{j_{min}}}{x_{j_{max}} - x_{j_{min}}} \tag{3}$$

where x_{ij} is respective specific value corresponding to the first and second sets of data, i is the i th indicator, which in this paper refers to the number of diseases, incomplete area ratio, crack length ratio, corrosion area ratio, resistance and hardness data, respectively. j is j th evaluation object, which in this paper refers to the j th bronze; X_{ij} is the j th data corresponding to the i th set of data; $x_{j_{min}}$ and $x_{j_{max}}$ are the minimum and maximum values in the i th set of data, respectively.

The correlation coefficients of each assessment indicator are calculated according to the Grey Relation Analysis. The reference series is the number of diseases, and the comparison series is the incomplete area ratio, the crack length ratio, the corrosion area ratio, the resistance and the hardness. The correlation coefficients are calculated as follows:

$$\xi_{ij} = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{ij} + \rho\Delta_{max}} \tag{4}$$

where i is the i th indicator; j is j th evaluation object; $\Delta_{ij} = \left|X_{ij} - X_{0j}\right|$, X_{0j} is the value of the reference number, X_{ij} is the value of the comparison numbers; Δ_{min} and Δ_{max} are the minimum and maximum values of the Q_{ij}, respectively; Q_{ij} is the absolute value of the value in i th column and the X_{0j} corresponding to the same row, respectively, $\rho = 0.5$.

The objective weights are obtained by weighting the grey correlation coefficient of each indicator, i.e. calculating the average of the correlation coefficients of each health assessment indicator and obtaining five values. The ratio of these five values to the sum of the five values is the objective weight of each health assessment indicator.

Table 2 The fundamental 1–9 scale

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	For a compromise between the above values
Reciprocals of above	If objective *i* has one of the above non-zero numbers assigned to it when compared with objective *j*, then *j* has the reciprocal value when compared with *i*
1.1–1.9	If the activities are very close

Methodology for calculating the combined weight of the assessment indicators

The combined weights are calculated from the formula:

$$W_i = aW_i' + bW_i'' \tag{5}$$

In this formula: W_i' and W_i'' are the subjective weight and the objective weight; a and b respectively represent the relative importance of the subjective weight and the objective weight, $a + b = 1, a = 0.5, b = 0.5$.

Bronzes health value calculation

All assessment indicators are to be positively correlated with the degree of health, so the data for incomplete area ratio, crack length ratio, corrosion area ratio and resistance need to be divided by 1. The new data is then normalised to the hardness data. The normalisation equation is shown below.

$$X_{ij} = \frac{x_{ij} - x_{j_{min}}}{x_{j_{max}} - x_{j_{min}}} \tag{6}$$

where X_{ij} is respective specific value corresponding to the first and second set of data, i is the i th indicator, j is j th evaluation object. X_{ij} is the j th data corresponding to the i th set of data. $x_{j_{min}}$ and $x_{j_{max}}$ are the minimum and maximum values of the i th set of data, respectively.

The following formula calculates the health value of each bronze:

$$JKZ = (ax_1 + bx_2 + cx_3 + dx_4 + ex_5) \times 100 \tag{7}$$

where JKZ is the health value of each bronze; a,b,c,d and e are the combined weights of the incomplete area ratio, crack length ratio, corrosion area ratio, resistance and hardness of each bronze, respectively. x_1 、x_2 、x_3 、x_4 、x_5 are the normalised data corresponding to the incomplete area ratio, crack length ratio, corrosion area ratio, resistance and hardness of each bronze, respectively.

Results

Subjective weight calculation results

A judgement matrix has been created in Table 3 based on 'the fundamental 1–9' in Table 2.

Calculate the square root value of the assessment indicators. According to Eq. (1), M_i = (1.201, 2.141, 0.339, 0.644, 1.783).

M_i was normalized, and the subjective weights of the assessment indicators were calculated. According to Eq. (2), W_i = (0.20, 0.35, 0.06, 0.11, 0.29.

Objective weight calculation results

The correlation coefficients of each assessment indicator were calculated according to the Grey Relation Analysis, and the results are shown in Table 4.

The objective weights of each assessment indicator were calculated according to the objective weight calculation method, and the results are shown in Table 5.

Combination weights calculation results

The combination weights of the assessment indicators were calculated according to Eq. (5), and the results are shown in Table 5.

Bronzes health value calculation results

The results of normalised calculations are shown in Table 6.

The health values of the 12 bronzes are shown in Table 7. The range of health values is [0.00–100.00]. The higher the health value, the healthier the bronze.

Results of the bronzes health level assessment

As there is currently no standard for the health level of excavated bronzes, this paper uses 25 as a tolerance, classifies them according to an equivocal series, and delineates the health grades as I, II, III and IV. The results are shown in Table 8. Among them, I indicates that the bronze is in a dangerous health state; II indicates that the bronze is in a relatively dangerous state; III indicates that the bronze is in a good state; and IV indicates that the bronze is in an excellent health state.

On this basis, the results of the archaeological site judgements and the health values of the 12 bronzes were compared to verify the reasonableness of the initial classification of the health levels. The results of the health class assessment of the 12 bronzes are shown in Table 9.

Table 3 Judgment matrix of assessment indicators

Health assessment indicators	Incomplete area ratio	Crack length ratio	Corrosion area ratio	Resistance	Hardness
Incompletearea ratio	1	1/3	5	3	1/2
Crack length ratio	3	1	5	3	1
Corrosion area ratio	1/5	1/5	1	1/3	1/3
Resistance	1/3	1/3	3	1	1/3
Hardness	2	1	3	3	1

Table 4 Correlation coefficient of assessment indicators

Artefact number	Incomplete area ratio	Crack length ratio	Corrosion area ratio	Resistance	Hardness
K7-1 Bronze Figurehead	0.3381	1.0000	1.0000	0.9386	0.6896
K7-2 Bronze	0.4286	0.4286	0.4737	0.4557	0.6000
K7-3 Bronze Bird	1.0000	1.0000	0.3913	0.3333	0.3954
K7-4 Bronze Human Mask	0.4323	0.4540	0.4286	0.4871	0.8146
K7-5 Bronze Fragment	0.6000	0.6000	0.6000	0.8084	0.4286
K8-1 Bronze Beast	0.6000	0.6000	0.6000	0.6000	0.4353
K8-2 Bronze Lei	0.3678	0.4543	0.6923	0.4230	0.6601
K8-3 Bronze Beast	1.0000	1.0000	0.6716	0.3443	0.3413
K8-4 Bronze Figurehead	1.0000	1.0000	0.9000	0.9730	0.3431
K8-5 Bronze Zun	0.3359	0.3928	0.3333	0.3957	0.7104
K8-6 Bronze Zun	0.5288	0.3569	1.0000	0.4455	0.8755
K8-7 Bronze Figurehead	0.7629	0.6000	0.4286	0.6825	0.4564
Average value	0.6162	0.6572	0.6266	0.5739	0.5625

Table 5 Combined weights of assessment indicators

Weights	Incomplete area ratio	Crack length ratio	Corrosion area ratio	Resistance	Hardness
Subjective weights	0.20	0.35	0.06	0.11	0.29
Objective weights	0.20	0.22	0.21	0.19	0.19
Combined weights	0.20	0.28	0.13	0.15	0.24

Table 6 Normalized processing results

Artefact number	Incomplete area ratio	Crack length ratio	Corrosion area ratio	Resistance	Hardness
K7-1 Bronze Figurehead	0.0489	0.0000	0.0000	0.0026	0.7750
K7-2 Bronze	1.0000	1.0000	0.4444	0.5084	1.0000
K7-3 Bronze Bird	1.0000	1.0000	0.0278	0.0000	0.7645
K7-4 Bronze Human Mask	0.0990	0.0141	1.0000	0.3213	0.7805
K7-5 Bronze Fragment	0.0000	0.0000	0.0000	0.0598	0.0000
K8-1 Bronze Beast	1.0000	1.0000	1.0000	1.0000	0.9820
K8-2 Bronze Lei	0.0067	0.0015	0.0278	0.1419	0.7426
K8-3 Bronze Beast	1.0000	1.0000	0.2361	0.0038	0.9649
K8-4 Bronze Figurehead	1.0000	1.0000	0.6296	0.8455	0.9573
K8-5 Bronze Zun	0.0883	0.0034	1.0000	0.1994	0.7962
K8-6 Bronze Zun	0.0009	0.0090	0.0000	0.1127	0.9289
K8-7 Bronze Figurehead	0.0051	1.0000	0.0000	0.0559	0.9289

Quantification results of the occurrence environment reference indicators

Quantification results of the Occurrence Environment Reference Indicators were obtained using the TR-6D soil detector. The quantification results of each reference indicator are shown in Table 10.

Intuitive analysis results

The radar chart can visually analyse the bronzes' health status, helping staff understand the defects in the excavated bronzes and providing an essential basis for targeted extraction, packaging and transport. Before drawing the radar chart, all the hardness data in Table 1

Table 7 Calculation of bronzes health values

Artefact number	Health value	Artefact number	Health value
K7-1 Bronze Figurehead	19.62	K8-2 Bronze Lei	20.49
K7-2 Bronze	85.40	K8-3 Bronze Beast	74.29
K7-3 Bronze Bird	66.71	K8-4 Bronze Figurehead	91.84
K7-4 Bronze Human Mask	38.93	K8-5 Bronze Zun	36.96
K7-5 Bronze Fragment	0.90	K8-6 Bronze Zun	24.25
K8-1 Bronze Beast	99.57	K8-7 Bronze Figurehead	51.23

Table 8 Correspondence between health values and health levels

Range of health	Health level
[0.00–25.00)	I
[25.00–50.00)	II
[50.00–75.00)	III
[75.00–100.00)	IV

is divided by one to obtain the 'low hardness' data set, and this allows the five indicators to show the same correlation (negative correlation) with the bronze's health to demonstrate the excavated bronze's defects and facilitate graphical data analysis. Then we normalised the data from Table 1 (incomplete area ratio, crack length ratio, corrosion area ratio and resistance) and the 'low hardness' data. The normalised data was finally used to create a radar chart, as shown in Fig. 3. The smaller the area of the radar chart, the better the health status of the bronze.

Analysis of results

Analysis of health assessment results

The results of the assessment show that the bronzes in Health Level I are K7-1 Bronze Figurehead, K7-5 Bronze Fragment, K8-2 Bronze Lei (qingtong lei) and K8-6 Bronze Zun (qingtong zun). The bronzes in Health Level II are K7-4 Bronze Human Mask, K8-5 Bronze Zun. The bronzes in Health Level III are K7-3 Bronze Bird, K8-3 Bronze Beast, and K8-7 Bronze Figurehead. The bronzes in Health Level IV include K7-2 Bronze, K8-1 Bronze Beast, and K8-4 Bronze Figurehead.

The extremely poor state of health of K7-1 Bronze Figurehead, K7-5 Bronze Fragment, K8-2 Bronze Lei and K8-6 Bronze Zun has resulted in the potential need for temporary reinforcement during the extraction of the artefacts and extra care in their packaging and transportation. In addition, by combining the health values of the 12 bronzes and the results of on-site judgement, the reasonableness of the health class classification was initially verified, and it is of some guiding significance. With the expansion of the assessment objects and the amount of data, the range of health values and health class correspondence will continue to be corrected.

Buried environmental impact analysis

The quantification results of the Occurrence Environment Reference Indicators in Table 10 and the normal parameters of the bronze preservation environment indicate that the temperature and humidity in K7 and K8 were within normal limits. Based on the data on salinity and conductivity of K7 and K8 sacrificial pits and the criteria for judging soil salinity, and with reference to the soil resources of Guanghan City, Sichuan Province, it indicates that the soils of K7 and K8 sacrificial pits are predominantly slightly acidic and neutral. However, the fact that most of the bronzes excavated from the K7 and K8 ritual pits are thickly patinated may be related to the manner of burial in the K7, and K8 ritual pits, i.e.

Table 9 Health level results for 12 bronzes

Artefact number	Health level	Artefact number	Health level
K7-1 Bronze Figurehead	I	K8-2 Bronze Lei	I
K7-2 Bronze	IV	K8-3 Bronze Beast	III
K7-3 Bronze Bird	III	K8-4 Bronze Figurehead	IV
K7-4 Bronze Human Mask	II	K8-5 Bronze Zun	II
K7-5 Bronze Fragment	I	K8-6 Bronze Zun	I
K8-1 Bronze Beast	IV	K8-7 Bronze Figurehead	III

Table 10 Quantification results of the occurrence environment reference indicator

Measuring position	Humidity (%)	Temperature (℃)	Salinity (mg/L)	Conductivity (us/cm)
K7	20.5	19.5	117	213
K8	24.5	18.3	165	301

the bronzes in both ritual pits are covered with a layer of organic artefacts. When preserving this group of bronzes indoors, care should be taken to control the temperature and humidity in the environment and acidity and maintain a dry environment to prevent further corrosion.

Discussion

In the twenty-first century, the protection of cultural heritage has become a worldwide consensus. In order to meet the needs of domestic archaeological excavation site conservation studies of excavated bronzes, a scientific and systematic health assessment method needs to be established. In the face of the current lack of research on excavated bronze health assessment methods in the industry, this paper takes excavated bronze artefacts from archaeological sites as the research object and, by combing through relevant research results and national standards, establishes a three-tier framework of bronzes health assessment indicators refined layer by layer, and proposes quantitative indicators with typical correlations. Through extensive research and testing, we screened out efficient, non-destructive, convenient and reliable assessment and testing methods and assessment models that combine subjective and objective aspects suitable for archaeological sites. On this basis, a comprehensive method for assessing the health of bronzes at archaeological sites that combines heritage health assessment

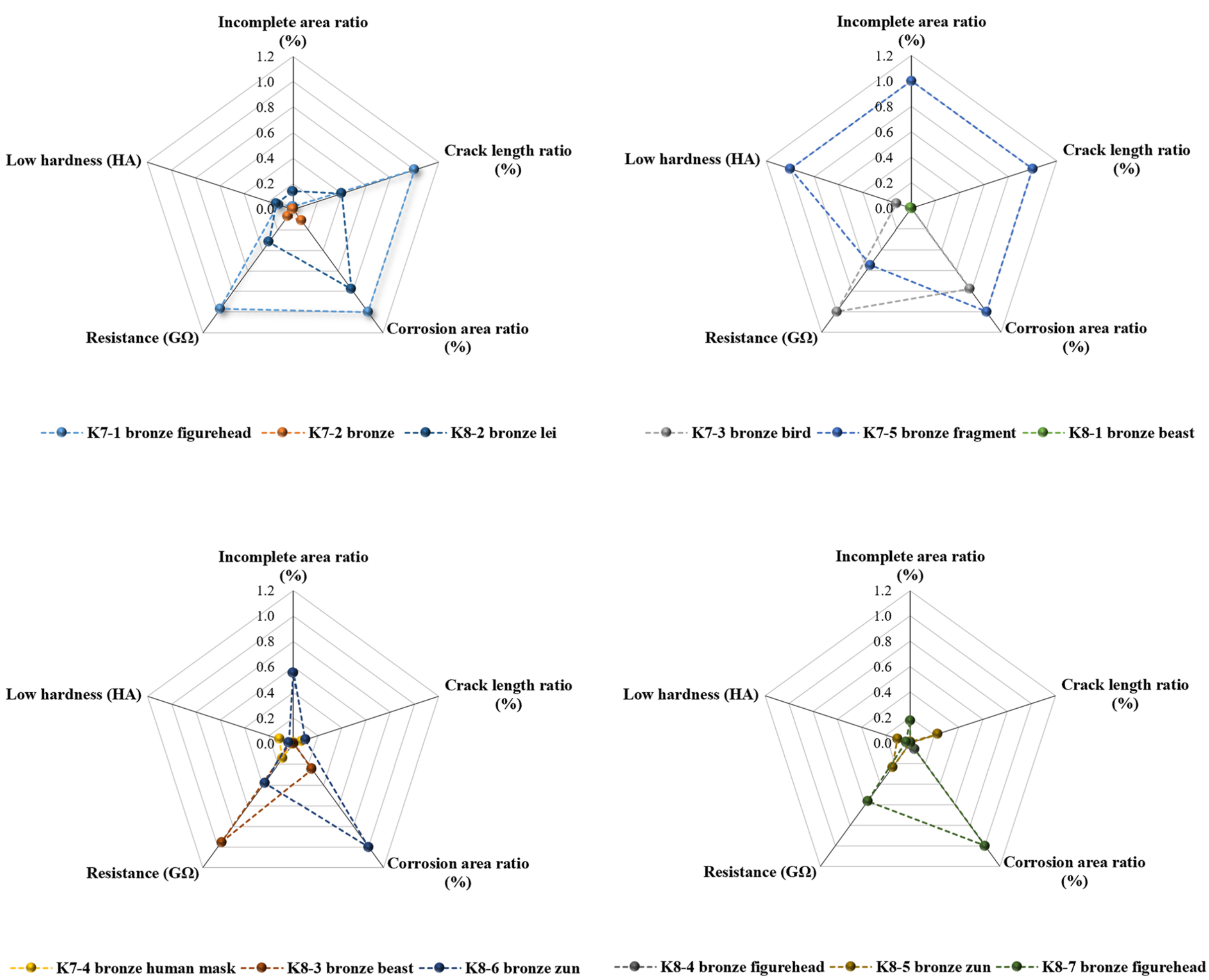

Fig. 3 Radar chart analysis results of 12 bronzes. Figures a, b, c and d visualise the health status and defects of the 12 bronzes. The figures show that the radar areas of K7-1, K7-5, K8-2 and K8-6 are relatively large, and more care should be taken when extracting these four bronzes

and environmental risk expectation has been established, and the health assessment process is shown in Fig. 4. Demonstration applications were completed at several archaeological sites. For the first time, the constructed health assessment method has been applied to the unearthed bronzes at the Sanxingdui site, verifying the assessment method's feasibility and also providing a significant reference value for future related research. The method also facilitates the development of more targeted on-site conservation work while providing scientific support for developing different conservation methods for developing sets of technologies for emergency conservation, on-site extraction and packaging and transportation of bronze artefacts. In addition, this paper provides insight into developing a standardised framework for bronzes, which can serve as a case study for establishing a standardised framework for bronze health assessment and risk expectation.

Quantify assessment indicators through in-situ non-destructive analysis methods

We have also tried to use 3D scanning to extract bronze surface information as a technical means to assess the completeness degree. Still, the problems of complex burial relationships in archaeological sites, the processing of the amount of data collected and the cost of the information collection have become the primary considerations that the researchers did not use. After many attempts, it was finally decided to use the DL9810 fibreglass tape measure to measure the incomplete area, crack length, and corrosion area. The DL9810 fibreglass tape measure has high accuracy, easy operation, non-destructive measurement, and fast results. The results in the Materials and

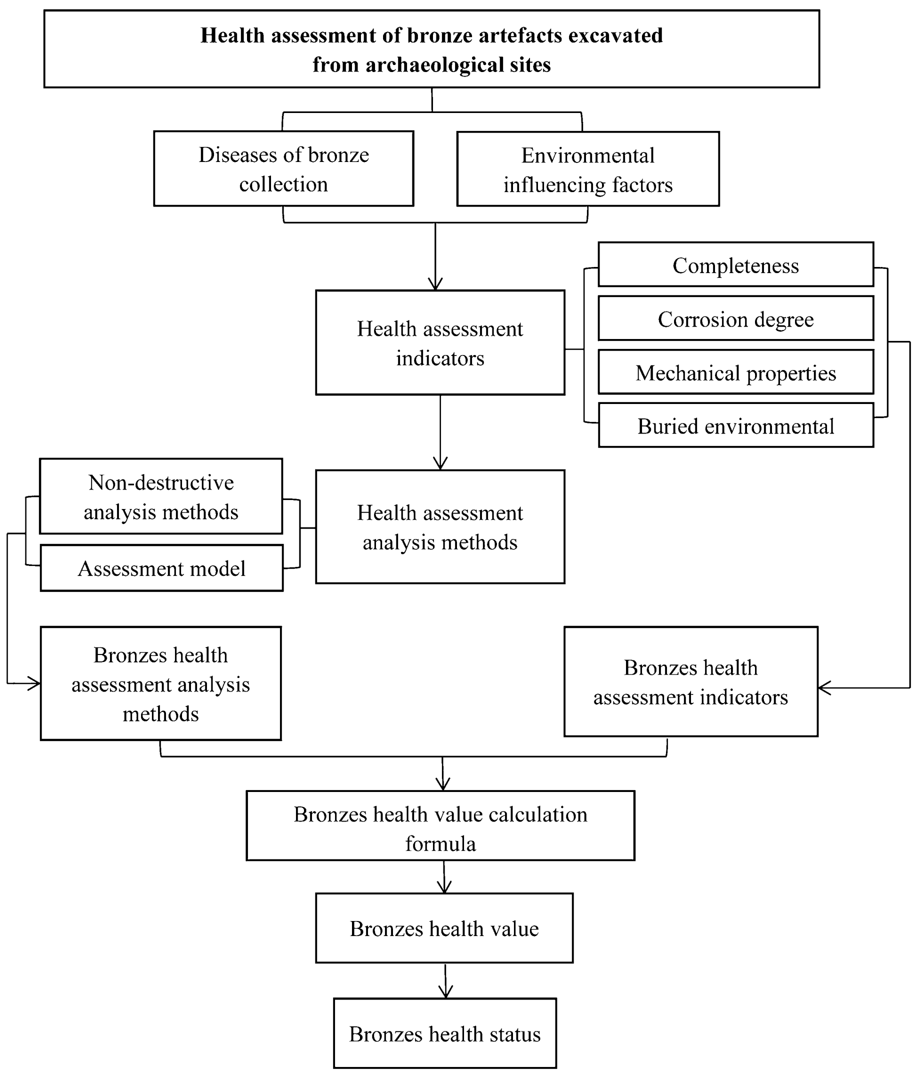

Fig. 4 Flow chart of the health assessment of bronzes excavated from archaeological sites

Methods section show that it is feasible to use DL9810 fibreglass tape to measure the incomplete area, crack length, and corrosion area.

The method of measuring the corrosion thickness of bronzes excavated at archaeological sites is one of this study's key points and difficulties. This study tested eddy current pulse thermography (ECPT), ultrasonic testing (UT), infrared thermography, and resistance analysis methods. The experimental results show that the eddy current pulse imaging results can characterise a certain corrosion thickness of bronzes but have the disadvantage of being a large instrument that cannot meet the needs of the archaeological site. Ultrasonic inspection and infrared thermography are only capable of qualitative analysis and are inadequate in characterising the extent of corrosion. In addition, infrared thermal wave inspection techniques, although capable of non-contact and in-situ inspection of the structure and internal damage of the artefacts, are complex in their post-processing data and limited by the background of expertise.

Theoretically, bronzes have good electrical conductivity, and the thicker the corrosion of the bronze, the less conductive it is. In this study, resistance experiments were carried out on 15 ancient bronze coins with varying degrees of corrosion. During the experiments, 1 cm long sections of the edges of the bronze coins were polished to observe the thickness of the bronze corrosion. The thickness of corrosion at the polished locations was then calculated using an ultra-deep field microscope, and the resistance of these bronzes was measured using a high resistance meter. Repeated experiments showed a positive correlation between the bronze's corrosion thickness and resistance in the same environment ($r = 0.42$ correlation coefficient between bronze corrosion thickness and resistance using Pearson's correlation coefficient). The experimental results also showed that the high-resistance method allows semi-quantitative analysis of the corrosion thickness of bronze. Moreover, the instrument's small size allows for in-situ inspection of artefacts, making it suitable for use in scenarios such as museums and archaeological sites. It is also easy to operate, non-destructive and provides fast access to results, which meets the requirements of bronze conservation in complex environments and archaeological sites.

However, several issues with these in-situ, non-destructive analytical methods need to be addressed. Due to the irregular shape of the bronze, more accurate measurement of these indicators using DL9810 fibreglass tape measure remains an issue. In addition, resistance may be influenced by temperature and humidity in the environment, making comparing data from different environments impossible. Therefore, the quantitative relationship between resistance, temperature, and humidity in bronze is also essential to be studied in depth. The quantitative relationship between corrosion thickness and resistance in bronze is also an essential research element. Moreover, we are currently researching all three of these issues.

The strengths and weaknesses of the assessment model

Regarding assessment methods, the Analytic Hierarchy Process (AHP) and Grey Relation Analysis (GRA) are frequently used in assessment cases both inside and outside the industry. Both AHP and GRA are equally applicable to the health assessment of excavated bronzes. The simultaneous use of these two methods allows for a combination of subjective and objective assessments, resulting in more scientific and objective results.

Ultimately, a practical assessment of the health of bronzes is achieved through the formulae for bronze health values and the correspondence between the health values and health levels of bronzes. The entire calculation process can be carried out with the help of a computer, which saves time and effectively avoids the difficulties of identifying corrosion patterns, operating analytical equipment and carrying out systematic analysis due to a lack of relevant expertise. In addition, to improve the scientific assessment of the health status of bronzes, we need to improve the analysis methods and optimise the assessment models continuously.

Practical significance of the study

In the face of the current lack of research on the health assessment methods of excavated bronzes, this paper presents for the first time a comprehensive method for quickly and conveniently assessing the health status of excavated bronzes in the environment of the archaeological site. The method has been tested on several archaeological excavations, proving its applicability and guiding significance. In terms of heritage assessment, the method helps to assess the health status of excavated bronzes scientifically and gives a quantifiable assessment of the health grade of the artefacts. It can therefore provide a basis for the emergency conservation, on-site extraction and packaging and transportation of excavated bronzes, aiding archaeological work. In heritage conservation, the method can effectively assess the health status of excavated bronzes and contribute to the scientific conservation, value elaboration and effective use of excavated bronzes, playing a role in the deep integration of technology and culture. Moreover, the research on the health assessment of excavated bronzes is essential to support the construction of a health assessment system for excavated bronze objects in archaeological sites.

By accumulating a large amount of data later, we will also further optimise the indicators, train and calibrate the assessment model, and eventually, form a scientific and complete set of comprehensive analysis methods for the health assessment of bronzes excavated from archaeological sites. A more scientific code of practice for assessing bronzes at archaeological excavation sites will also be established.

Conclusions

For the first time, a set of comprehensive evaluation methods for the health assessment of unearthed bronzes at archaeological sites are proposed, including the establishment of a three-level indicator framework for health assessment indicators and risk expectation of bronzes, a systematic in-situ non-destructive analysis method for bronzes, and a health assessment model based on Analytic Hierarchy Process and the Grey Relational Analysis.

By illustrating the comprehensive method of bronze health assessment, we verify the feasibility of a comprehensive analysis method for the health assessment of unearthed bronzes at archaeological sites. In this case, we assessed the health status of 12 unearthed bronzes from the K7 and K8 sacrifice pits at the Sanxingdui sites. This assessment showed that the health status of the K7-1 Figurehead, K7-5 Bronze Fragment, K8-2 Bronze Lei and K8-6 Bronze Zun was determined to be in level I, an abysmal state of preservation. This assessment result can further help us determine each bronze's health status and keep abreast of its defects, providing an essential basis for selecting excavated bronze's emergency conservation, on-site extraction, packaging, and transportation methods.

Nowadays, scientific preventive conservation is becoming increasingly important for cultural heritage. The study of the health assessment methods of bronzes excavated from archaeological sites is a valuable exploration. The established assessment methodology will provide a methodological reference and case study for the scientific assessment of the health status of bronzes and provide methodological support for the emergency and long-term conservation of excavated bronzes.

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Author contributions
LL, JX, and JL designed the study. LL, JX, and JL conducted the research. LL, JX, JL, ZX and QX prepared all the data. LL and JL analyzed the data. JL wrote the main manuscript. XL, LL, and XZ revised the main manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
In this work, the original data are shown in the main manuscript, and any other further data are available upon request from the authors.

Declarations

Competing interests
The authors declare that they have no competing interests. We declare that we do not have any commercial or associative interest that represents a competing interest in connection with the work submitted.

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