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CityGML Grotto ADE for modelling niches in 3D with semantic information

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Abstract

The regions of East Asia, as well as South Asia and the Middle East are rich in cultural heritage of grottoes where a large number of Buddhist niches exist. Three-dimensional (3D) semantic modelling enriches 3D geometric models with an understanding of the historical and cultural value of cultural heritage, facilitating interoperability and analysis beyond mere visualization. 3D models with semantic information act as essential digital infrastructure for heritage management, knowledge dissemination and simulation analysis in cultural heritage. However, due to the lack of standardized data model for the grotto domain, it is difficult to exchange information, share knowledge and the advancement of spatial analysis and simulation. In order to fill the above-mentioned gap, this study develops a data model for niches as a CityGML Application Domain Extension (ADE) based on the CityGML 3.0 standard. In this ADE, niche components and their attributes are defined on two semantic levels, i.e., niche structural component and niche component member. A famous niche in China belonging to the World Heritage was selected as a case study to demonstrate the integration of geometries, semantics and attributes, illustrating that the extended ADE module complies with the CityGML 3.0 standard. This study provides novel insights into the 3D semantic modelling of niches as well as expands the applications scope of CityGML standard within the cultural heritage sector.

Keywords CityGML, ADE, Grotto, Niche, 3D modelling, Semantic modelling

Introduction

Grottoes, as an important form of immovable cultural heritages worldwide, have garnered significant attention due to their distinctive artistic value and deep historical significance. There are many stone niches in the cultural heritage of Buddhist grottoes, which have a profound impact not only in the realms of religion, art, and culture, but also demonstrate extraordinary skills architectural and sculptural skills [1–3]. Advancements in three-dimensional (3D) digital technologies have made it possible to create geometric models of niches with accurate and realistic surface qualities for 3D digital documentation [4–6]. The integrated representation of thematic information and geometric models of cultural heritage in an interoperable and comprehensible manner significantly enhances public understanding and appreciation of cultural heritage, while providing professional guidelines for heritage interpretation [7]. With regard to facilitating multi-source information management and cultural heritage knowledge sharing, it presents significant challenges for integrating comprehensive semantic information (e.g., heritage value, cultural meanings, and interpretative knowledge) with 3D models in a data model [8–10]. In existing studies, Poux et al. [11] proposed a smart point cloud framework for storing and providing services to high dimensional point clouds while integrating semantics. Yang et al. [12] generated a smart point cloud information model in the field of cultural heritage. Park et al. [13] achieved the integration

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of point clouds with semantic information through an object-oriented hierarchical data structure, enriching the semantic depth while preserving the geometric and visual authenticity of the objects. Existing methods are mostly for visualization purposes, and the use of 3D models are great restricted for computation and simulations across various applications. Although some information models enable the integration of point clouds or 3D mesh models with semantic information, they lack standardized data model and exchange protocols for optimal integration of semantic and attribute information. This greatly limits standardized knowledge sharing and information exchange across platforms or applications, such as Geographic Information Systems (GIS) and Building Information Models (BIM). Therefore, this study aims to provide a new standardized data model that integrates geometrics and semantic expressions for niches as geographic elements, advancing the 3D semantic modelling of grottoes.

The City Geography Markup Language (CityGML) [14] has achieved significant success in 3D semantic urban modelling. CityGML has offered a set of basic modules (e.g., building, bridge, land use, etc.) designed to fulfill a broad spectrum of 3D semantic modelling requirements in various geographic environments. However, the current CityGML modules cannot support the description of the structure and detailed components of niches, as well as their related attributes, leading to CityGML inability to be used for 3D semantic modelling of niches. To solve similar problems, CityGML has designed an extension mechanism, namely CityGML Application Domain Extension (ADE), enabling users to enrich the data model by adding new feature classes and attributes while preserving the encoding standard specification [15, 16]. Adhering to semantic encoding specifications of CityGML, users can customize data models to their specific needs by integrating extension modules through CityGML ADE. Consequently, CityGML ADE can be utilized to standardize the 3D semantic modelling of niches, offering a flexible and adaptable framework that effectively encapsulate the intricate details and properties of these historic stone structures. Given the fact that there are different types of features in the domain of cultural heritage, different types of features are inherent with their own conceptual models in the hierarch of semantics. In this case, each type of cultural heritage needs to have its own ADE for the 3D semantic modelling. Therefore, it is necessary to develop a specific ADE for the 3D semantic modelling of niches, in case that the 3D models are not only needed for visualization but also required for important interactions, calculation and simulation tasks in various applications, as well as for the purpose of data management and information exchange.

In this work, we developed a specialized CityGML ADE for 3D semantic modelling of niches, named CityGML Grotto ADE, filling the gap in semantic encoding for grottoes. Based on the CityGML 3.0 standard, this study defines the structural component and component member of niches, and their related attributes. Through adopting the CityGML ADE mechanism, a specialized CityGML extension module for niches was constructed, which provides standardized semantic encoding rules for niches and complements the existing CityGML extension modules. To validate the effectiveness of the proposed CityGML Grotto ADE, we conducted a case study focusing on the 3D semantic modelling of the HuaYanSan-Sheng niche, a prominent niche located within the Dazu grotto group in Chongqing, China. The results exemplify the successful integration of complex geometric forms representative of Buddhist grottoes into the CityGML framework through standardized methods.

The remainder of this paper are organized as follows. Sect. "Related work" reviews the related work. Sect. "Development and implementation steps" describes the implementation steps of this work. Sect. "CityGML Grotto ADE" details the terminology, conceptual model, logical model, and physical model involved in constructing CityGML Grotto ADE. Sect. "Case study" validates the effectiveness of the proposed approach through a case study. The future work is discussed in Sect. "Discussion" and some significant conclusions are drawn in Sect. "Conclusion".

Related work

CityGML standard defines a conceptual model and exchange format for the representation, storage and exchange of virtual 3D city models [14]. It encodes the 3D geometric shape, topological structure, semantics, and appearance of important urban geographical objects [17], which not only realizes the standard geometric expression and visualization of the scene but also integrates rich structured semantic information with multi-level detailed geometric graphics. Versatility of CityGML is demonstrated by its applications in many fields such as energy-related applications [18], indoor navigation [19], detailed street space modelling [20], emergency rescue applications [21], urban flood simulation [22], 3D smart city, and digital twins [23]. As an application schema for the Geography Markup Language (GML, ISO 19136-1:2020 [24]), CityGML aligns with the international standards for spatial data exchange set by the Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO) Technical Committee 211 (ISO/TC 211) [25]. This ensures its extendibility and interoperability in a global context. Therefore, the implementation of CityGML standard is supported by a number of well-known software and platforms through standardized interfaces and extension plugins, including the Feature Manipulation Engine by Safe Software, 3D City Database, QGIS, ArcGIS and CityEngine by Esri, and Autodesk Revit [26–30]. The standardization of CityGML, coupled with its excellent interoperability for data exchange, significantly enhances the efficiency and effectiveness of data storage, sharing, and interaction across a myriad of applications. This not only facilitates the accurate and detailed representation of urban environments but also promotes the seamless integration of 3D city models into various analytical and operational frameworks.

Over the last two decades, CityGML has undergone continuous development, reaching a significant milestone with the release of version 3.0. Kutzner et al. [31] made a summary of the new features and revisions in CityGML 3.0, which are designed to enhance its usability in a variety of applications. Compared with the previous versions, the CityGML 3.0 version includes innovative elements such as a novel space concept, an updated Levels of Detail (LOD) framework, and mechanisms for representing time-dependent attributes. These modules include CityGML Core for foundational elements, Appearance for visual attributes, Generics for flexible attribute definition, Dynamizer for dynamic properties, Versioning for historical changes, and PointCloud for integrating point cloud data. Additionally, it encompasses specific modules for detailed urban elements such as Construction, Building, Bridge, Tunnel, CityFurniture, CityObjectGroup, LandUse, Relief, Transportation, Vegetation, and WaterBody, ensuring a comprehensive framework for 3D urban modelling.

Due to CityGML encoding a large number of thematic data models, it has significantly facilitated urban management, spatial analysis, and simulation efforts. For instance, Liamis et al. [32] developed GRextADE for the 3D modelling of Greek urban environments, tackling the challenges of incomplete cadastral data management and enhancing infrastructure visualization. Saeidian et al. built [33] the VicULA ADE to create a legal-physical integrated 3D model at the urban scale, aimed at improving underground data management. Rossknecht et al. [34] utilized the CityGML Energy ADE to incorporate the energy and climate atlas of Helsinki, Finland, into a comprehensive 3D urban model. This integration facilitated emission predictions leveraging the CityGML 3D city model. Kumar et al. [35] utilized CityGML to refine standards for modelling industrial and road traffic noise, employing 3D urban models to simulate noise pollution generated by road traffic and industrial activities, thereby aiding in urban noise management.

In the cultural heritage field, CityGML has demonstrated multifunctionality and effectiveness in various innovative ways. CityGML has been integrated with the Industry Foundation Classes (IFC) standard, enhancing the handling of historical buildings [36, 37]. For instance, Eudave et al. [38] proposed a general framework with regard to the convergences of GIS-BIM-Historical building information modelling(HBIM) technologies. Colucci et al. [39] further investigated the incorporation of HBIM models into 3D GIS frameworks using CityGML, aiming to provide comprehensive documentation vital for analyzing sites prone to risks. Additionally, there has been a significant amount of research on the mutual conversion between the IFC and CityGML standards [40–42]. In the area of historic urban district planning and management, Dore et al. [43] employed parametric CAD modelling and 3D GIS to improve the documentation and analysis of heritage sites. Pepe et al. [44] developed CityGML models at different Level of Details (LoDs) specifically for the ancient city of Taranto, which included a detailed LoD 3D model of a historic bridge. Such models are instrumental in aiding spatial planning and the conservation of urban heritage sites. Eriksson et al. [45] created a specialized ADE named CityGML Sve-Test that was tailored to assist in the creation of 3D city models, promote the integration with BIM, and guarantee linkage with national registries. Cantatore et al. [46] examined and evaluated a streamlined Digital Model using the CityGML standard with the aim of developing a virtual restoration plan for historical districts. Moreover, CityGML has defines LoDs for enhanced visualization. José et al. [47] utilized CityGML within a visualization platform, which was adopted for instructing on conservation tasks related to architectural cultural heritage. Ergun et al. [48] enhanced the visual performance of cultural heritage buildings using the LoDs feature in the CityGML standard, reducing the geometric complexity of the objects and enabling users to view models at the desired level of detail in a computerized environment. With regard to data management and information retrieval, Hidalgo-Sánchez et al. [49] demonstrated the application of 3D models in GIS for managing architectural heritage, focusing on a comprehensive study of 115 municipal heritage buildings across various dimensions and functions.

In order to meet the requirements of a more diverse range of cultural relic types and attributes, Gkadolou et al. [50] developed a CityGML ADE to detail cultural heritage monuments, particularly focusing on ancient theatres. Li et al. [51] adopted a semantic approach using CityGML ADEs for modelling roofs in traditional Chinese architecture, employing a two-level semantic decomposition that distinguishes between structural and decorative elements. Mohd et al. [52] used CityGML to monitor issues of damage in historical houses. Egusquiza et al. [53] developed a method leveraging a CityGML-based urban model to assess Energy Conservation Measures (ECMs) in historic districts, demonstrating the framework's utility in energy demand reduction analysis.

Development and implementation steps

Figure 1 illustrates the development and implementation process of the CityGML Grotto ADE proposed in this study. The process begins with the identifying of niche structural components and component members as new feature classes and their attributes, progressively integrating these semantic themes into standard framework of CityGML. Implementing the data model of CityGML ADE involves five steps: defining terminology table, designing conceptual model, constructing logical model, physical model implementation, and validating the CityGML file. In the aforementioned process, the semantic encoding of the CityGML Grotto ADE was implemented from Step 1 to Step 5. However, due to the diversity of Buddhist niche types and the abundance of structural components and component members, it is difficult to achieve a perfect abstraction expression of the niche at once. With regard to practical applications, the development of the semantic model is often an iterative process. In other words, once users find the data model proposed after running Step 1 to Step 5 once cannot meet some specific needs, it is necessary to enrich the terminology table again (i.e., staring from the Step 1 again), continuously expanding new versions to accommodate the diverse niches until all needs meet.

Step1: Defining terminology table

The terminology table is used to clarify the structural components of niches and their subdivisions, together with their attributes. This method provides standardized terminology for new feature classes and attributes within CityGML Grotto ADE. The terminology table is essential for the accurate definition of concepts, preventing misunderstandings among diverse stakeholders. Periodic updates and optimizations of the table are recommended to reflect the various of niches within CityGML Grotto ADE.

Step2: Designing conceptual model

The conceptual model functions as a high-level abstraction of niche entities and their complex structures in the real world, acting as the fundamental blueprint for logical and physical models. By employing vocabulary from the terminology table, this conceptual model represents entities and defines their inheritance and compositional relationships, thereby providing a clear logical framework for the ADE.

Step3: Constructing logical model

This step effectively translates the abstract classes in the conceptual model into a more tangible logical model through using Unified Modelling Language (UML) class diagrams, which offers extensive capabilities for software modelling. The logical model details new feature classes, their attributes (including data types and value range), and interrelations. It also

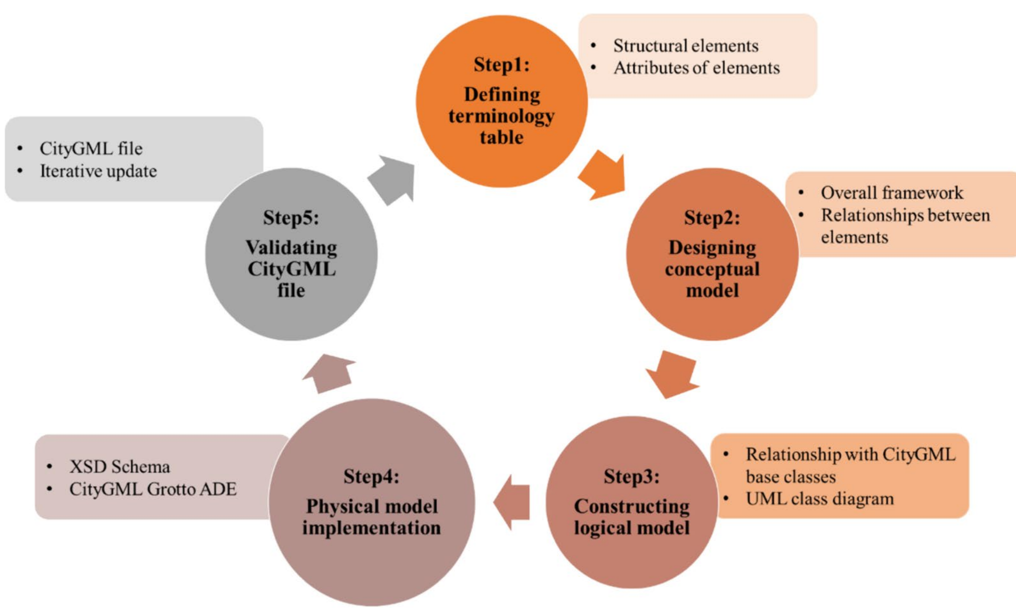

Fig. 1 The development and implementation process of CityGML Grotto ADE

clarifies the inheritance and associative connections between these feature classes and CityGML standard classes.

Step4: Physical model implementation

Physical model implementation is represented in the form of XML Schema Definition (XSD) files, which structurally express and store the logical model. The XSD file for CityGML Grotto ADE includes all newly added feature classes and attributes, adheres to XML Schema syntax rules, and complies with CityGML 3.0 encoding standards. This ensures its broad applicability and compatibility. Conversion of the UML logical model into an XSD file can be done manually or automatically through tools such as commercial software Enterprise Architect. The content defined in the resulting XSD file needs to be parsed by the CityGML standard.

Step5: Validating CityGML file

This step involves verifying that the encoding specifications of CityGML Grotto ADE align with the CityGML 3.0 standard. CityGML files (*.gml or *.xml files), which incorporate ADE encoding with specific niche semantics and geometric features, serve as test cases for this purpose. This process ensures the accuracy and effectiveness of the model in practical application.

CityGML Grotto ADE

Terminology table of CityGML Grotto ADE

In the terminology table of CityGML Grotto ADE, new feature classes and attributes of niches are specified to capture their distinctive construction structure and semantic themes. The terminology table in this paper builds upon the research by Yang et al. [9] on the structure components and attributes of niches, making a series of adjustments and optimizations. This study categorizes the semantic themes of niches into two levels. The first level consists of niche structural components to express the spatial structure. The second level describes patterns of stone carving art (e.g., Buddhas and decorations) carved on the surface of structural components, called niche component members. Niche component members can be affixed to any niche structural components.

Niche structural components are composed of niche eave, cliff wall, cliff wall footing and ground. Niche component members include the primary Buddha statues (The largest one or group of Buddha statues in the niche), other Buddha statues (smaller than the primary Buddha statues, usually their guards or disciples, there are also some decorative circular or square shape of small Buddha statues), pedestals (the Buddha statue usually stands or sits on a pedestal), decorations (objects with Buddhist

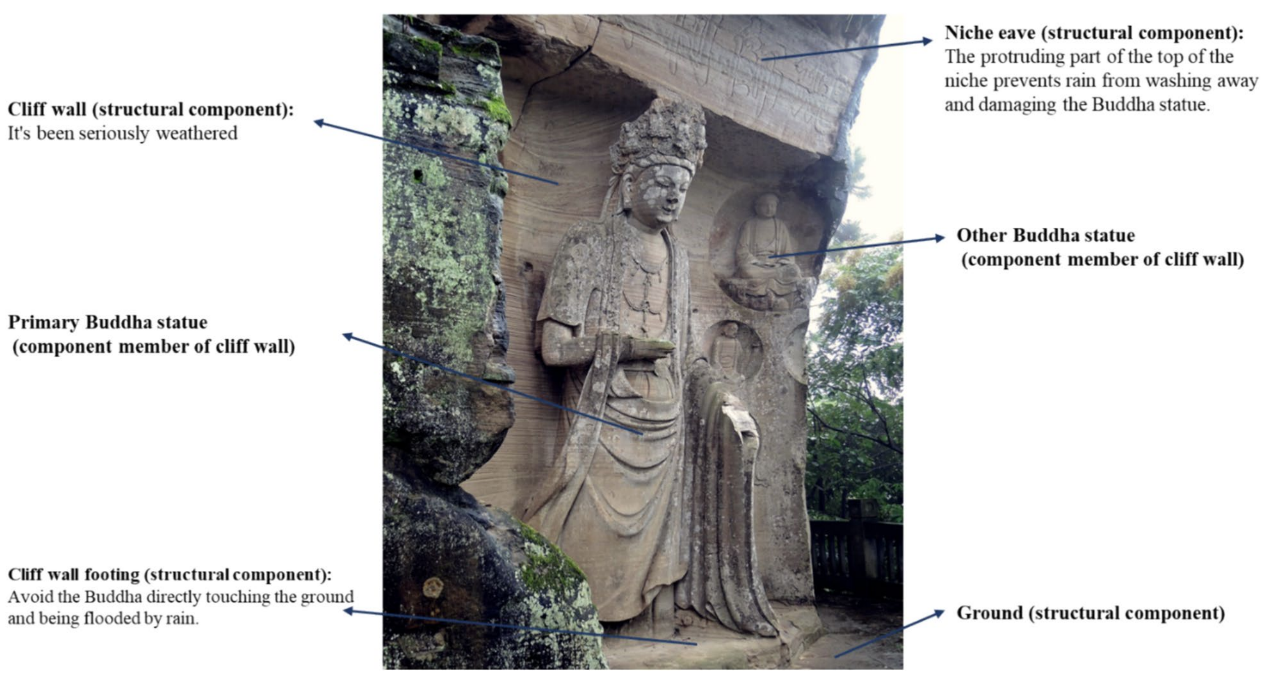

Fig. 2 The structural components and component members of a niche

meanings), and inscriptions (engraved with text). Additionally, niches also contain various appendant items, such as plaques and stone tablet. Figure 2 shows the partial structural components and component members of a niche. With the aim of demonstrating the components defined above at a finer scale, we show some other common niche structural components and their component members in Fig. 3.

The attributes serve as abstract semantic descriptions capturing the characteristics of niches. For instance, the attributes of the primary Buddha statue include name, id, hairstyle, headwear, face feature, shoulder

Fig. 3 Some of the component members and appendant item from various grottoes

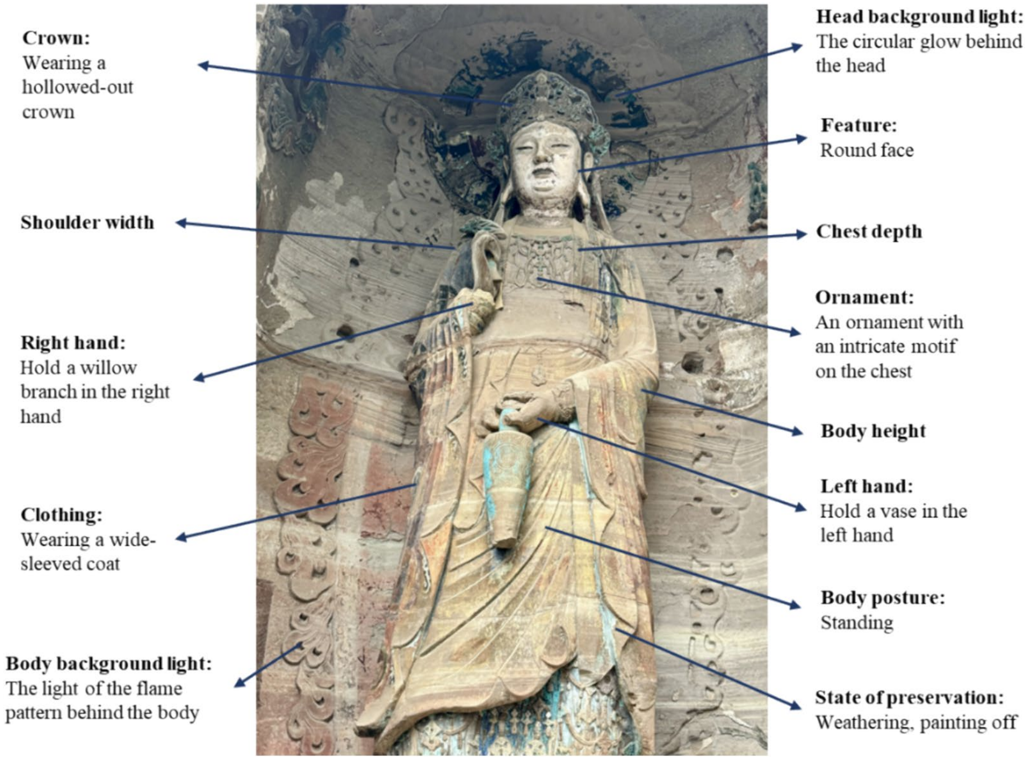

Fig. 4 An explanation of the important attributes of a primary Buddha statue

width, chest thickness, statues height, body posture, left hand, right hand, clothing, accessories, head background light, body background light, state of preservation, maintenance records, description, and surface area. Figure 4 elaborately explains the important attributes of the primary Buddha statue, assisting the understanding of each attribute.

Table 1 lists the niche structural components, niche component members and their attributes defined in the CityGML Grotto ADE. The five basic attributes including name, id, maintenance record, state of preservation, and description, are common to all classes and are not repetitively listed in the table. Any subclass automatically inherits all the attributes of its superclass. This inheritance mechanism enhances the flexibility and extensibility of CityGML Grotto ADE.

Conceptual model of CityGML Grotto ADE

Based on the terminology table, a graphical method was employed to construct the conceptual model, which outlines the niche structural components, niche component members, and their complex interrelationships and inheritance patterns. This conceptual model is depicted in Fig. 5. The class *Abstract Niche* includes two distinct subclasses: class *Niche* and *Niche Part*. Together with class *Appendant* and class *Abstract Niche Structural Component*, collectively forge a comprehensive structural framework. The class *Abstract Niche Structural Component* are further divided into four subclasses: *Niche Eave*, *Cliff Wall*, *Cliff Wall Footing* and *Ground*. Simultaneously, the class *Abstract Niche Component Member* are segregated into five subclasses: *Primary Buddha Statue*, *Other Buddha Statue*, *Pedestal*, *Decoration*, and *Inscription*. These structural components are intricately populated and detailed by component members, ensuring a thorough and cohesive representation.

UML class diagram of CityGML Grotto ADE

To achieve the integration of CityGML grotto ADE into the existing CityGML data model, the new feature classes defined in this study within UML all inherit from the standard modules of CityGML. CityGML Grotto ADE specifies a unique namespace "chg" to prevent conflicts with the names of existing classes and attributes in CityGML. In terms of designing the logical model, the extended new feature classes mainly referenced the Building and Construction modules in CityGML 3.0.

Within the standard modules of CityGML, the class *AbstractBuilding* inherits from class *AbstractConstruction*, which is defined as the abstract superclass for objects that are manufactured by humans from construction materials, are connected to earth, and are intended

Table 1 The terminology table of CityGML Grotto ADE

Class name	Superclass	Attribute and interpretation
Abstract Niche	–	Abstract class of niches
Niche	Abstract Niche	Period (e.g. Tang Dynasty, Song Dynasty etc.), theme (e.g. Buddhism, Taoism etc.), location (geographical position), belong to (belongs to the grotto group), lithology (e.g. Quartz sandstone, red sandstone, granite rock), type, length, height, depth
Niche Part	Abstract Niche	A niche may consist of several niche parts. The attributes of the niche part are the same as niche
Appendant	–	Surface area
Stone Tablet	Appendant	Content (the content of the inscription carved on the stone tablet), length, height, width, type
Abstract Niche Structural Component	–	The basic class of all the structural component of niches
Niche Eave	Abstract Niche Structural Component	Type (for example, natural rock niche eaves, carved stone imitation wood niche eaves, etc.), length, thickness, depth, surface area
Cliff Wall	Abstract Niche Structural Component	Length, height, surface area
Cliff Wall Footing	Abstract Niche Structural Component	Length, height, depth, surface area
Ground	Abstract Niche Structural Component	Length, width
Abstract Niche Component Member	–	The basic class of all the component member of niche structural component
Primary Buddha Statue	Abstract Niche Component Member	hair style, headwear, face feature, shoulder width, chest thickness, status height, status posture, left hand, right hand, clothing, accessories, surface Area, head background light, body background light
Other Buddha Statue	Abstract Niche Component Member	Type (such as guards, disciples and flying Apsaras)
Quadrate Small Buddha Statue	Other Buddha Statue	Length, height, depth
Circular Small Buddha Statue	Other Buddha Statue	Major axis radius, minor axis radius
Pedestal	Abstract Niche Component Member	Type (such as lotus platform, Kong Kim platform), length, height, width,
Decoration	Abstract Niche Component Member	Type (such as pavilions, auspicious clouds, auspicious animals and bodhi trees)
Inscription	Abstract Niche Component Member	Length, height, width, content

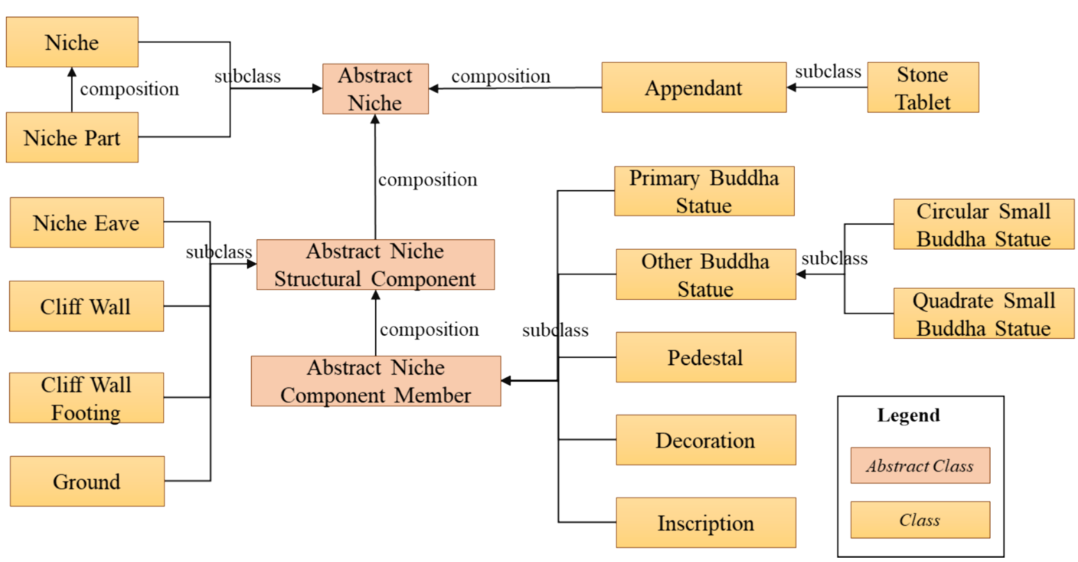

Fig. 5 The conceptual model of CityGML Grotto ADE

to be permanent. With reference to the class *AbstractBuilding*, we have also defined the *AbstractNiche* as a subclass of *AbstractConstruction* and designed the classes *Niche* and *NichePart* to inherit from the class *AbstractNiche*. Additionally, the appendant items refer to the class *AbstractBuildingInstallation* in the CityGML Building module, which inherits from *AbstractInstallation*. The class *AbstractAppendant* was designed as the appendant items of the niche. Stone tablet, as a type of appendant, are defined as its subclass. The attributes of the new feature class are defined in the module of the class. The UML model of the niches and its appendants is shown in Fig. 6, which was created from the conceptual model using Enterprise Architect software.

Niches are composed of structural components, which are filled with component members. As Niche structural components refer to architectural structure, we defined the class *AbstractNicheStructuralComponent* as inheriting from *AbstractConstructionSurface* in the Construction module. Similarly, niche structural components, such as doors, windows, were defined in the class *AbstractNicheComponentMember*, inheriting from *AbstractFillingSurface*. The UML class diagram is shown in Fig. 7, aligning with CityGML standards to serve as the logical model for CityGML Grotto ADE. This approach not only clarifies new feature classes and their attributes but also ensures the inheritance and compositional relationships among these new feature classes.

Physical model of CityGML Grotto ADE

The physical model is regarded as the meta-model for CityGML Grotto ADE, designed to be parsed and loaded by applications that comply with the CityGML 3.0 standard. In the transition from UML class diagrams to the physical model, classes, attributes, and relationships defined in the UML diagrams, are translated to GML schemas. Utilizing the specialized function provided by the Enterprise Architect software, the CityGML 3.0 UML model was transformed into GML application schemas. The CityGML Grotto ADE was structurally preserved in XSD files, characterized by specific XML structures. These XSD files conform to predetermined structures and constraints, thereby ensuring that the ADE files facilitate

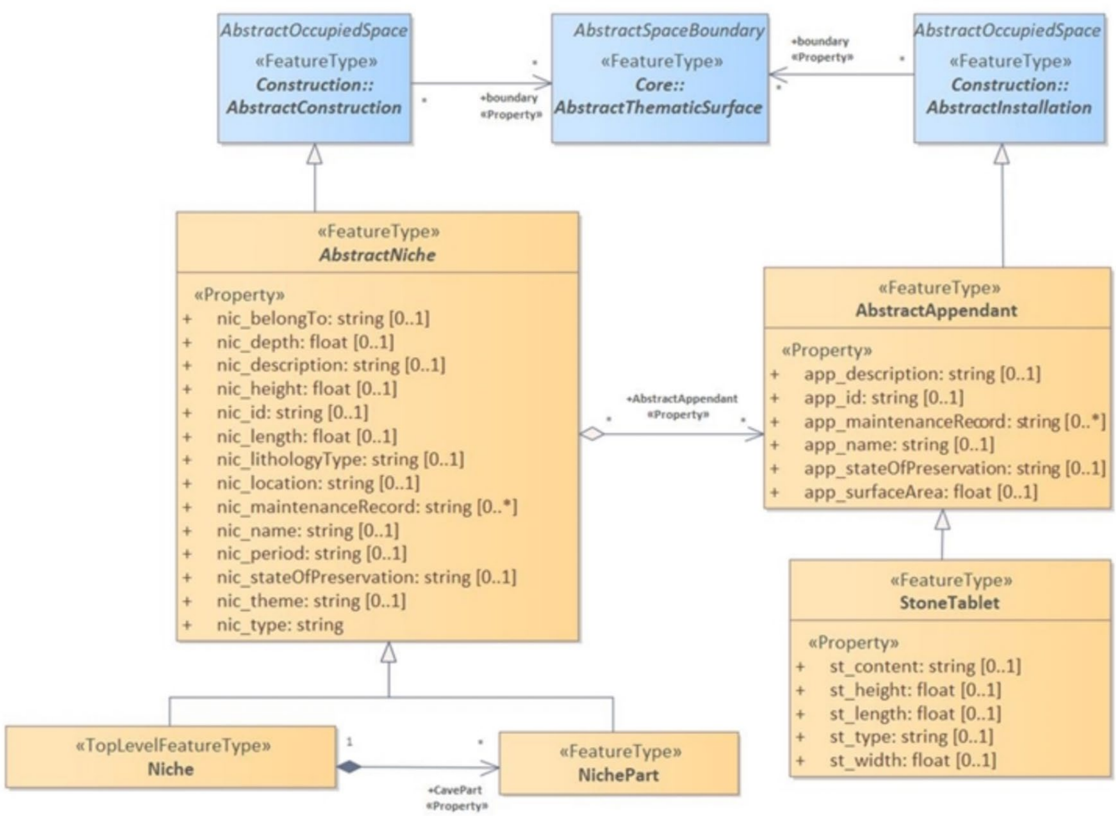

Fig. 6 UML class diagram of the niche and appendant (the orange represent the new feature classes and attributes defined in this paper; other colors are consistent with the UML class diagram in CityGML 3.0 standard)

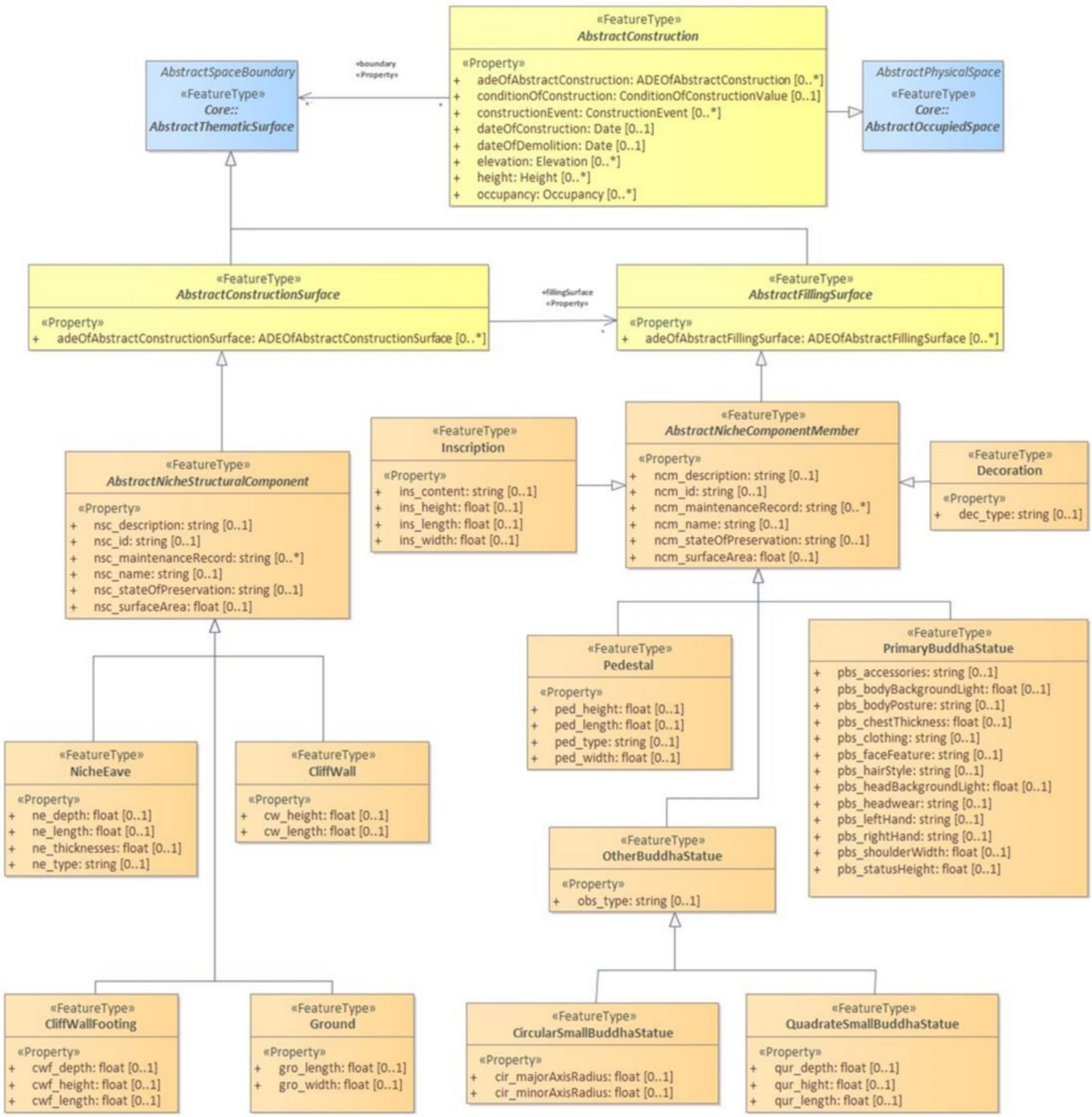

Fig. 7 UML class diagram of the niche structural component and niche component member (the orange represent the new feature classes and attributes defined in this paper; other colors are consistent with the UML class diagram in CityGML 3.0 standard)

effective information sharing and data interchange in the semantic modelling of grottoes. Figure 8 illustrates the detailed encoding results of converting the class *AbstractNiche* and class *PrimaryBuddhaStatue* from UML class diagram.

Case study

Experimental area

The case study selects the HuaYanSanSheng (华严三圣, Huayan Three Saints) niche (Fig. 9) in the Baodingshan Grotto group of Dazu, Chongqing, China, as the test area to validate the effectiveness of the proposed CityGML Grotto ADE module. There are three structural components in this niche, which are the niche eaves,

```xml
▼<element name="AbstractNiche" type="chg:AbstractNicheType" substitutionGroup="con:AbstractConstruction" abstract="true">
  ▼<annotation>
     <documentation>AbstractNiche is an abstract superclass representing the common attributes and associations of the classes Niche and NichePart.</documentation>
   </annotation>
 </element>
▼<complexType name="AbstractNicheType" abstract="true">
  ▼<complexContent>
    ▼<extension base="con:AbstractConstructionType">
      ▼<sequence>
         <element name="nic_name" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_length" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="nic_id" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_location" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_belongTo" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_theme" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_period" type="string" minOccurs="0" maxOccurs="1"/>
        ▼<element name="AbstractAppendant" type="bldg:AbstractAppendantPropertyType" minOccurs="0" maxOccurs="unbounded">
          ▼<annotation>
             <documentation>Relates the installation objects to the Niche or NichePart.</documentation>
           </annotation>
         </element>
         <element name="nic_depth" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="nic_description" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_height" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="nic_lithologyType" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_maintenanceRecord" type="string" minOccurs="0" maxOccurs="unbounded"/>
         <element name="nic_stateOfPreservation" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="nic_type" type="string"/>
       </sequence>
     </extension>
   </complexContent>
 </complexType>
▼<complexType name="AbstractNichePropertyType">
  ▼<sequence minOccurs="0">
     <element ref="chg:AbstractNiche"/>
   </sequence>
   <attributeGroup ref="gml:AssociationAttributeGroup"/>
   <attributeGroup ref="gml:OwnershipAttributeGroup"/>
 </complexType>
```

(a) Converting the class *AbstractNiche* from UML class diagram

```xml
▼<element name="PrimaryBuddhaStatue" type="chg:PrimaryBuddhaStatueType" substitutionGroup="chg:AbstractNicheComponentMember">
  ▼<annotation>
     <documentation>A PrimaryBuddhaStatue is a boundary surface of AbstractNicheComponentMember.</documentation>
   </annotation>
 </element>
▼<complexType name="PrimaryBuddhaStatueType">
  ▼<complexContent>
    ▼<extension base="chg:AbstractNicheComponentMemberType">
      ▼<sequence>
         <element name="pbs_accessories" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_bodyBackgroundLight" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_bodyPosture" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_chestThickness" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_clothing" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_faceFeature" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_hairStyle" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_headBackgroundLight" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_headwear" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_leftHand" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_rightHand" type="string" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_shoulderWidth" type="float" minOccurs="0" maxOccurs="1"/>
         <element name="pbs_statusHeight" type="float" minOccurs="0" maxOccurs="1"/>
       </sequence>
     </extension>
   </complexContent>
 </complexType>
▼<complexType name="PrimaryBuddhaStatuePropertyType">
  ▼<sequence minOccurs="0">
     <element ref="chg:PrimaryBuddhaStatue"/>
   </sequence>
   <attributeGroup ref="gml:AssociationAttributeGroup"/>
   <attributeGroup ref="gml:OwnershipAttributeGroup"/>
 </complexType>
```

(b) Converting the class *PrimaryBuddhaStatue* from UML class diagram

Fig. 8 The encoding results of the CityGML Grotto ADE

Fig. 9 The HuaYanSanSheng niche in the Baodingshan grotto group of Dazu, Chongqing, China

the cliff wall, and the cliff wall footing. The cliff wall comprises three primary Buddha statues, three pedestals, and 81 circular small Buddha statues. In addition, there are two stone tablets preserved in the niche as appendant items.

CityGML geometric features represented by 3D mesh model

With the aim of accurately capturing geometric characteristics of the niche, we used 3D mesh model to express geometric features by taking the rich geometric texture details on the niche surface into consideration. The original point cloud data was acquired using a terrestrial 3D laser scanner (TSL), i.e., the Faro Laser Scanner LS 420. The color texture of the model was derived from photos taken at the niche site. Subsequently, the commercial software Geomagic Wrap 2021 was used to encapsulate the point clouds into a 3D mesh model, which is further textured with the collected photos. The mesh model consists of 12,899,441 vertices and 25,504,486 faces. Finally, the textured 3D mesh model was manually segmented into various structural components and component members to generate a set of mesh models. Following the semantic hierarchy of a niche, it consists of normally several parts, namely, cliff wall, niche eave, cliff wall footing, primary Buddha statue etc., as depicted in Fig. 5. In the 3D modelling process, cliff wall and niche eave are modelled by using solid representation formed by polygons, because their surfaces are much homogenous and can be represented by a set of polygons. However, Buddha statues and other decoration objects are very finely sculptured and must be modelled by using triangular meshes so that the geometrical details can be well represented. The coloured 3D model of this niche is illustrated in Fig. 10. The 3D model was processed with individualization, meaning that each components was manual segmented from the mesh model based on defined structural components and component members.

3D integrated niche model

Based on the summarization of the niche structural components and niche component members of the HuaYanSanSheng niche in the real world, semantic encoding was performed using the new feature classes and attributes within the CityGML Grotto ADE to generate a semantic 3D niche model. This model integrates the geometric features represented by 3D mesh model with semantics and is stored in the form of CityGML file. In this work, the compatibility of the CityGML Grotto ADE module with CityGML 3.0 was confirmed using the KITModelViewer software. This software facilitates the support of the grotto ADE by pre-loading its XSD schemas and then processes the CityGML file for analysis and visualization of the integrated model.

As shown in Fig. 11, the KITModelViewer software successfully and accurately parsed the niche structural components, niche component members and their attributes of the HuaYanSanSheng niche. The tree structure on the left side shows that the structural components are composed of niche eave, cliff wall, and cliff wall footing. And there are two stone tablets as appendages to this niche. The cliff wall contains three primary Buddha statues and their pedestals, surrounded by 81 circular small Buddha statues. Those structural components are consistent with the definitions and expected results in the proposed ADE. This figure also displays the attributes of the niche parsed by the software, and the corresponding semantic encoding in the GML file. This geometric and semantic integrated 3D model provides basic information and dimensions of the niche, which can be used for the routine management, recording the current state of cultural relic preservation and maintenance information over time, and offering knowledge for those who are unfamiliar with the background of HuaYanSanSheng niche. Figure 12 shows the semantic encoding in the CityGML file and the attributes parsed for a primary Buddha statue named "PiLuZheNa Buddha (毗卢遮那佛)" within HuaYanSanSheng niche. The Buddha statue features a round face, is dressed in a U-neck coat, adorned with a YingLuo (璎珞) necklace as an accessory, and has two rays above its head. The left hand is placed flat in front of the chest, while the right hand is extended forward, palm facing up. This statue affected by weathering and the deterioration of paint. Additionally, some difficult-to-quantify geometric statistics are provided, such as the Buddha statue

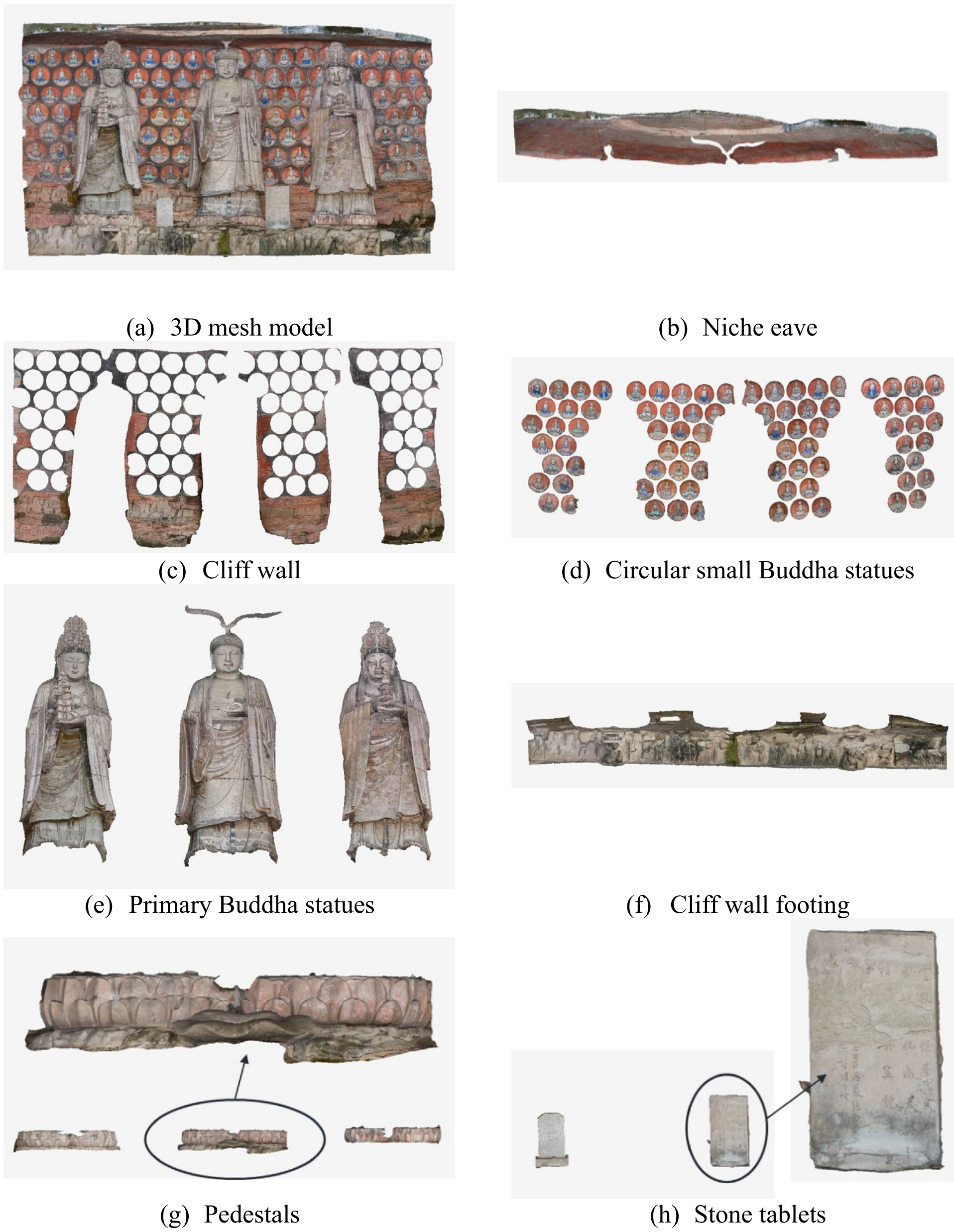

Fig. 10 3D Mesh model of The HuaYanSanSheng niche segmented according to structural components and component members

having a height of 6.36 m, a shoulder width of 2.03 m, a chest depth of 0.53 m, and a surface area of 39.06 square meters. These semantic details provide a comprehensive description for users who are not come from cultural heritage fields. Those attributes offer fine-provide knowledge of cultural heritage, enhancing understanding beyond mere visualization. Figure 13 illustrates a specific case of a circular small Buddha statue. From the semantic information of the 3D model, we can determine that this small circular sculpture has a radius of 0.33 m, a surface area of 0.51 square meters, and is similarly affected by weathering and the deterioration of paint.

The integrated 3D niche model that integrates the geometric features represented by 3D mesh model with semantics also supports friendly user interaction. Based on the abstract data model provided by the CityGML grotto ADE, the sematic encoding of niche is implemented to generate the CityGML files (i.e., the XML-based encoding in CityGML file in Figs. 11, 12 and 13). Accordingly, the tools such as KITModelViewer and FME

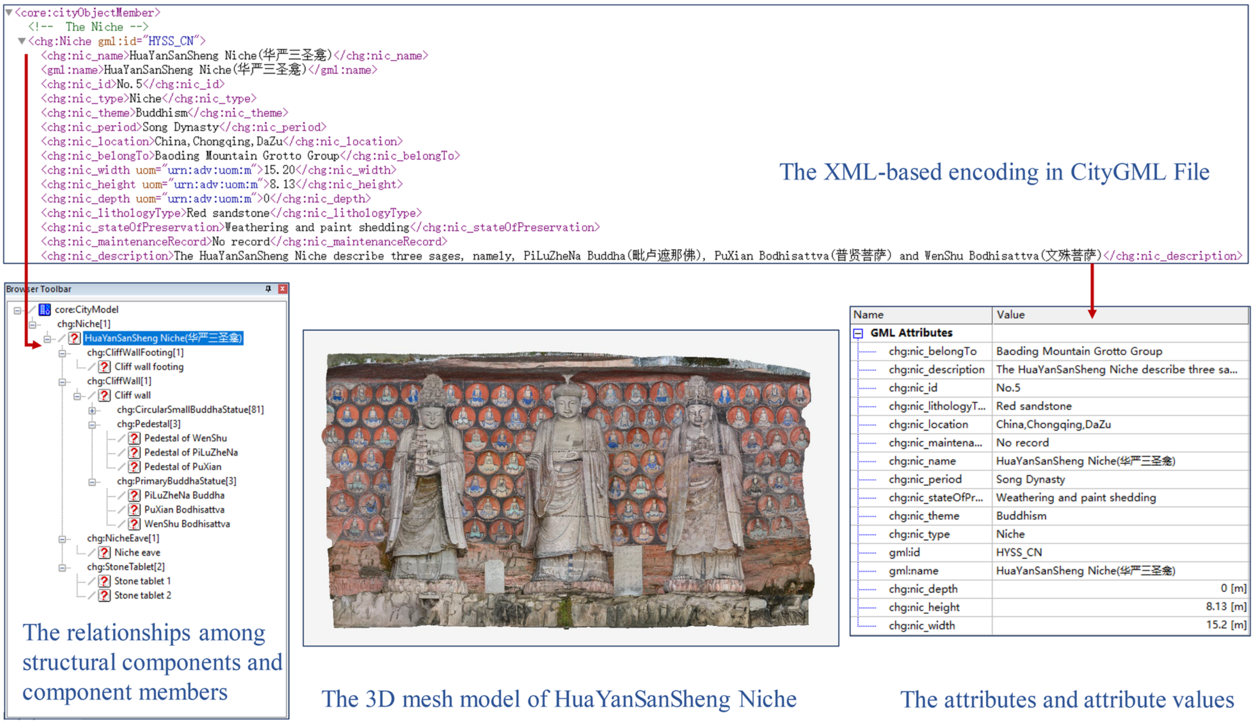

Fig. 11 The geometric and semantic integrated 3D model of HuaYanSanSheng niche

by Safe Software are used to parse the semantic encoding through referring to the attributes defined in the CityGML grotto ADE. In this way, the relationships between structural components and component members (i.e., the relation table in Figs. 11, 12 and 13) as well as the attributes and attribute values (i.e., the attribute table in Figs. 11, 12 and 13) can be parsed. The parsed results indicating the semantic information of geometric primitives are returned to the users in a user-friendly way. As users select or click a specific geometric primitive (e.g., a niche, a structural component or a component member) on the front end of visualization, the semantic information related to the selected geometric primitive can be returned by tables (e.g., the relationship tables and attribute tables in Figs. 11, 12 and 13). Based on the user interaction with the integrated 3D mesh model, it benefits users to clearly capture which structures and members are included and to understand the abundant attributes of each element, further serving the information management of cultural heritage, offering relevant knowledge about artifacts to cultural heritage enthusiasts while visualizing them, and can be widely used for semantic retrieval as well as semantic-based spatial analysis.

Discussion

Despite the achievements obtained in this study, there still exist certain space for improvement, such as enhancing the grotto domain vocabulary, introducing LoDs specifications tailored specifically to niches, and improving the efficiency of extracting geometric primitives. The details of each research endeavor are elaborated as follows:

(1) Enhancing the grotto domain vocabulary

Expanding the CityGML schema with the ADE mechanism involves the crucial process of accurately defining new feature classes and attributes within the extended domain. Given the diversity and vast number of grottoes, this task necessitates high-level generalization and abstraction of a large number of niches. For example, when engaging in more extensive semantic modelling of the CityGML Grotto ADE, one might encounter elements and attributes that lack full support, highlighting the need for prompt ADE updates. Therefore, this task requires close collaboration not only from cultural heritage experts but also from geographic information data modelling experts.

(2) Clarifying LoDs definitions for grottoes

The LoDs concept plays a pivotal role in depicting objects with varied degrees of complexity and detail.

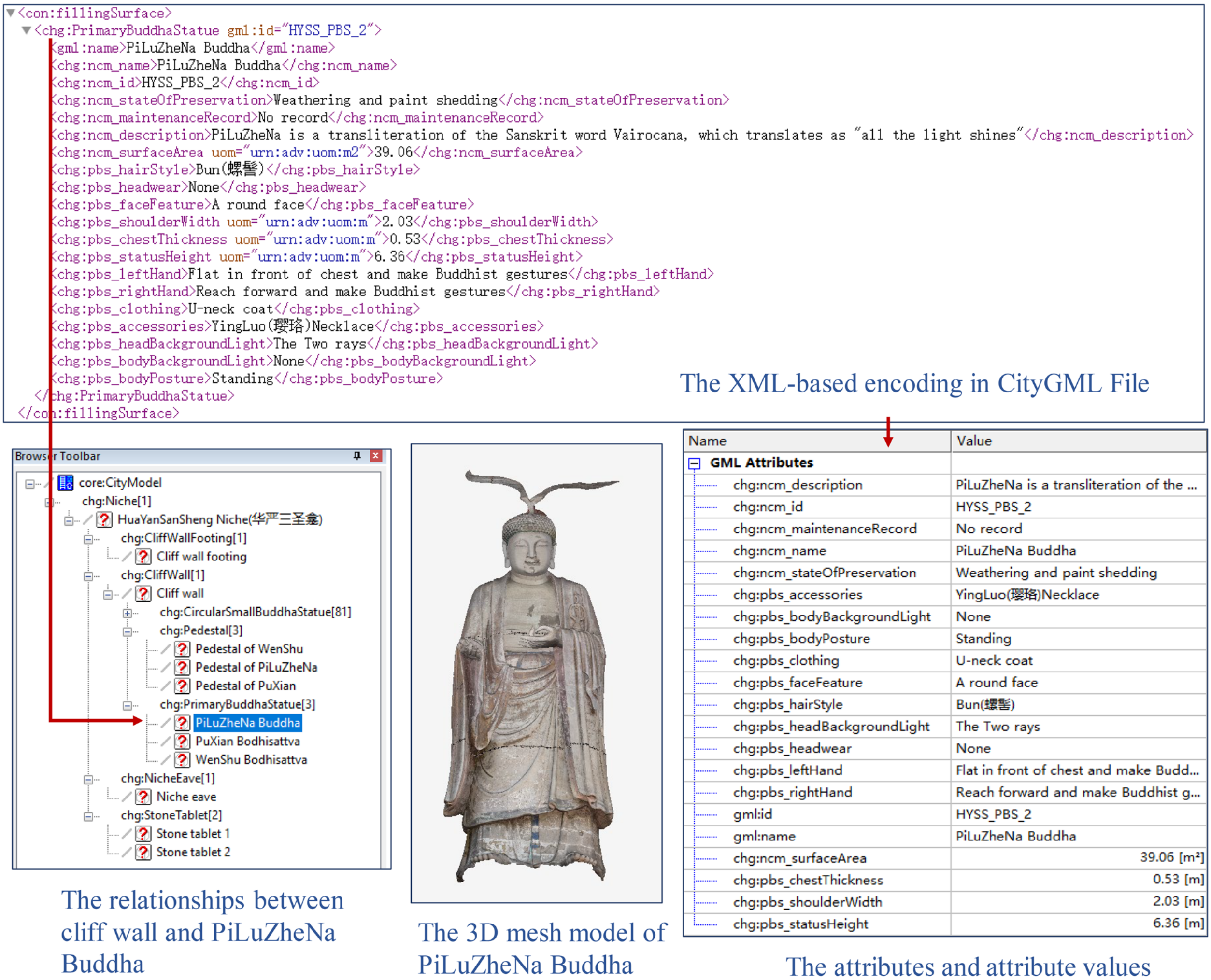

Fig. 12 The geometric and semantic integrated 3D model of PiLuZheNa Buddha

For example, in the context of buildings, different LoDs showcase a spectrum of detail from the most basic to the most intricate. Specifically, at LoD 0, a building is depicted solely by its 2D boundary, omitting any height data. Progressing at LoD 1, the building is represented as a basic volume with a consistent height but without intricate architectural details. At LoD 2, the model introduces variations in roof structures. Advancing to LoD 3, the model incorporates more detailed architectural elements such as doors, windows, and balconies. At LoD 4, the representation extends to interior elements, including rooms, staircases, and furnishings. Nevertheless, the precise delineation of LoDs is subject to the specific needs of the application. Consequently, establishing appropriate LoDs for niches, with their unique structural and historical complexities, remains a challenge yet to be fully addressed.

(3) Improving the efficiency of individualization of grottoes geometric primitives

In comparison to the previous 3D modelling of niches, we need to semantically separate the niche components before the 3D modelling process. This means that we need to develop smart algorithms to detect niche components automatically from 3D point clouds and then set up optimal parameters to mesh model every component in detail. This increase, of course, additional cost in computation and time. The technical challenges remain hardly to be solved. But this is very essential to obtaining semantic information from 3D point clouds. Otherwise, the 3D models do not contain any semantic information and can only be used for visualization purposes.

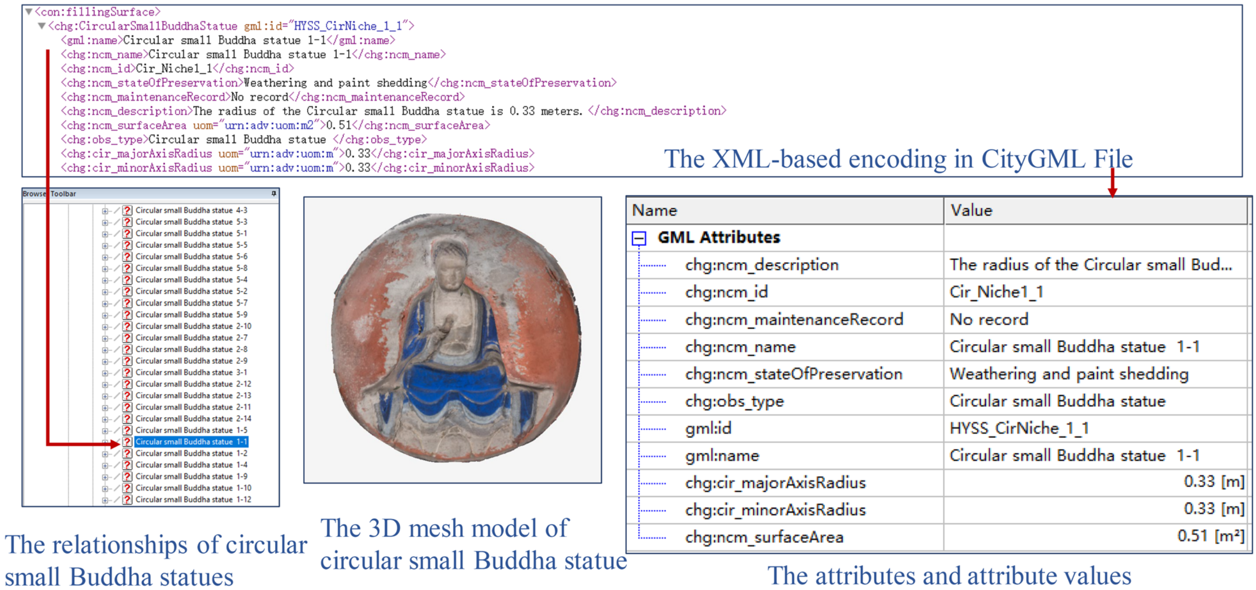

Fig. 13 The geometric and semantic integrated 3D model of one circular small Buddha statue

Conclusion

In this study, under the framework of the CityGML 3.0 standard, the ADE mechanism was employed to successfully develop the CityGML Grotto ADE suitable for 3D niche semantic modelling. During the definition process, niches were decomposed into structural components, component members, appendants, and their related attributes. Through following the stages of conceptual model design, logical model construction, and physical model conversion, a complete CityGML Grotto ADE was established. To verify the effectiveness and practicality of this extension model, this study selected the HuaYanSan-Sheng niche in the Dazu Rock Carvings in Chongqing, China, as a case study, confirming the consistency of CityGML Grotto ADE in building 3D semantic models of niches with its semantic encoding standards. In terms of geometric expression, the model adopted the point cloud encoding method newly supported in the CityGML 3.0 standard. Although this experiment was limited to a specific cultural relic in the Dazu Rock Carvings, the construction of abstract classes for niche structural components and niche component members ensures that the model can be generally applied to grottoes with complex geometrics.

In a word, our main contribution is application contribution through following a typical process of extending the modules for semantic expression shown in Fig. 1. Since the research of extending the sematic expression module that is defined in the CityGML 3.0 standard to accommodate the requirements for the standardization of the semantic information of niche application had been empty, our work filled this research gap. The standardized semantic information of niche can be further deployed for the 3D semantic modeling.

Grottoes are primarily categorized into two categories. The first category is a “niche”, more similar to the exterior wall of modern buildings, composed of cliff walls and niche eaves. The second categorized is a “cave”, which resembles a room with a certain depth, consisting of floor, ceiling, and surrounding walls, showcasing carved art on the cliff walls. It is usually spacious enough to accommodate visitors inside. Both “cave” and “niche” are composed of a common foundational structure, with the primary difference being that a “cave” has a cave ceiling (i.e., a type of cave eaves) and it consists of three or four cliff walls. Therefore, the ADE proposed in this study can be easily applied in caves. Future efforts can be engaged in extending the modules in the CityGML 3.0 standard based on the implementation process shown in Fig. 1 to meet the requirements of other practical applications.

CityGML Grotto ADE effectively integrates geometric models represented by 3D mesh model lacking semantic information with rich semantics. As such, it not only enhances the interpretability of geometric models but also provides new perspectives for knowledge dissemination, conservation management, and public services of cultural heritage, and provides the possibility for more simulation and analysis. In the future, we plan to further expand the vocabulary of the grotto domain during continuous application, iteratively improve new versions of CityGML Grotto ADE, develop LoDs standards specific to grottoes, and enhance the semantic segmentation efficiency of geometric primitives, to promote the sustainable development of cultural heritage.

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Author contributions
SY, MH, HF conceived the presented idea. SY conducted the analysis process and wrote the manuscript. MH and HF revised and supervised the manuscript. All authors approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

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

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