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From Recording to Communication: A Three-Layer Framework for the Digitalization of Cave Temples and the Gaps Between Layers

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Abstract

Digital work on cave temples has moved beyond data capture into exhibition and public communication, yet most studies describe technologies one by one and rarely ask how the stages connect. This paper proposes a three-layer framework—recording, representation, communication—treating cave temple digitalization as a value chain from permanent preservation to cultural diffusion. Drawing on Yungang, Longmen, Dunhuang and the Zhangye Great Buddha Temple, it examines the technical features, cost structures and limits of each layer. The recording layer is relatively mature, but high-precision data are poorly converted into public-facing content; the representation layer is interpretively strong yet costly and hard to replicate; the communication layer reaches widely but stays shallow. The three form a structural gap—abundant data, thin content, superficial communication—rooted not in single-layer technology but in the absence of mechanisms that move work between layers. The paper proposes a data–content–channel conversion chain, tiered authorization and institutional safeguards, and an evaluation shift toward the conversion end.

Keywords

cave temples, digital exhibition, three-layer framework, interlayer transformation, cultural heritage communication

1. Introduction

Cave temples combine architecture, sculpture and mural painting in one complex, and carry historical,

artistic and cultural value that cannot be replaced. China has 5,986 cave temple and cliff-carving sites, widely distributed and irreplaceable, and they face a double threat from natural weathering and human damage. Digital technology has opened new possibilities: 3D laser scanning and close-range photogrammetry can record their form precisely, while VR/AR and digital platforms can bring them to people beyond the limits of time and place. Digitalization is therefore widely seen as a key path for preserving and passing on cave temples.

Existing research, however, is weak in three respects. First, there is much description of technology and little assessment of effect: many studies detail capture accuracy and modeling methods, but few ask what protection or communication outcomes these investments actually produce. Second, single-case accounts outnumber cross-case comparisons: Yungang, Longmen and Dunhuang are each written about repeatedly, yet rarely placed within one framework to compare their technical choices and results. Third, capture is studied far more than the later stages: digitalization is often assumed complete once data are collected, while how data become content the public can understand, and how that content becomes effective communication, remains the weakest part of the chain. In short, the field lacks a framework that connects capture, exhibition and communication.

This paper proposes a three-layer framework—recording, representation, communication—and treats cave temple digitalization as a layered value chain. The recording layer aims at permanent preservation and condition monitoring, using 3D laser scanning, close-range photogrammetry and multi-source data fusion. The representation layer aims at restoration research and immersive exhibition, built on painted-surface reconstruction, 3D modeling and VR/AR. The communication layer aims at cultural diffusion and public participation, through digital platforms, social media, online exhibitions and international collaboration. The three are related by progression—foundation, value-added, amplification—not by parallel listing. The question this paper asks is therefore not “which technologies are used” but where each layer reaches its limit, and why work fails to move between layers.

The paper draws on literature review and case analysis. Cases were chosen for their representativeness at each layer: Yungang leans toward recording, Longmen toward representation, and Dunhuang and the Zhangye Great Buddha Temple toward communication—together covering all three. The analysis does not describe technologies layer by layer; it identifies the limits of each layer and diagnoses the gaps between them.

2. Foundations and Framework

2.1 Cave Temples and the Need for Digitalization

Cave temples are Buddhist temple sites carved into cliffs. They combine buildings, sculptures and wall paintings in one place, and they cannot be replaced once lost. China has a large number of these sites, spread widely and mostly found in provinces such as Henan, Shanxi, Gansu and Sichuan. Their value lies in three areas. Artistically, the sculptures and murals are fine examples of ancient art. Historically, they offer physical evidence of how people once lived, worshipped and governed. Culturally, they show

how different traditions mixed and influenced each other. However, natural weathering, water damage, micro-organisms and human destruction continue to threaten them. Traditional ways of protecting them have limits—it is hard to record them with perfect accuracy, every physical visit causes some wear, and monitoring their condition is difficult. Because of this, digitalization has become a necessary choice.

2.2 The Three-layer Framework: Recording, Representation and Communication

Most existing studies introduce digital technologies one by one—scanning, modeling, VR, social media and so on. This is easy to follow, but it hides an important point: different technologies serve different purposes, cost different amounts, and build on each other in a certain order. As a result, there is no clear framework that links data capture, exhibition and public communication together. Luo Xiaohong, in a study of museum digitalization, proposed a three-layer structure of "recording, display and communication". She argued that digital recording, display and communication make up the basic workflow, and that they move forward step by step (Luo, 2017). This paper borrows that structure but makes two changes. First, the middle layer is renamed "representation" instead of "display". This is because restoring paintings or rebuilding a cave in VR is not just showing an object; it is a careful reconstruction based on scientific study, and its value depends on whether it is accurate and believable. Second, this paper shifts the focus from simply dividing the three layers to asking how work moves from one layer to the next—in other words, why the connections break down and how they can be fixed. Based on this, the paper proposes the three-layer framework of recording, representation and communication, as shown in the table below.

Table 1. The Three-layer Framework of Cave Temple Digitalization

Layer	Goal	Core technology	Evaluation criteria	Cost structure
Recording	Permanent preservation, condition monitoring	3D laser scanning, close-range photogrammetry, multi-source data fusion	Accuracy, completeness	High one-off investment
Representation	Restoration research, immersive exhibition	Painted-surface reconstruction, 3D modeling, 3D printing, VR/AR	Interpretive strength, credibility	High investment, low frequency
Communication	Cultural diffusion, public participation	Digital platforms, social media, online exhibitions, international	Reach, participation	Ongoing operational cost

collaboration

These three layers are connected step by step, not placed side by side. Recording is the base: without accurate data, representation and communication have nothing to stand on. Representation adds value: it turns cold data into something people can understand and experience. Communication spreads the value: it decides whether the results stay inside the institution or actually reach the public. The standards for judging each layer are also different. The recording layer is judged by millimetre accuracy, the representation layer by how believable and clear it is, and the communication layer by how many people it reaches and how deeply they engage. It is a mistake to judge the communication layer by the standards of the recording layer, or the other way around.

The value of this framework is that it turns "digitalization" from a vague technical label into three clear stages with different goals and limits. This makes it possible to ask which stage is weak and why they fail to connect. Chapters 3 to 5 look at the three layers one by one, and Chapter 6 examines the gaps between them.

2. The Recording Layer: A Mature Technology and Its Limits

2.1 The Technology

Three technologies make up the recording layer. 3D laser scanning collects point-cloud data from many angles and stitches them into an accurate three-dimensional form; it is fast, comprehensive and accurate to the millimetre, and can capture details such as facial expression and the lines of drapery. Close-range photogrammetry measures without contact, using photographic imaging; it is particularly good at surface texture and colour, and has the advantages of high information capacity, high accuracy, low cost and no damage to the object. Multi-source data fusion addresses the limits of each single method—laser scanning is strong on geometry but weak on fine texture, while photogrammetry is strong on texture but less reliable when reconstructing complex structures—by combining data from several sources to improve the completeness and accuracy of the model and provide a better base for later display. Together the three form a complete recording chain: geometry, texture, fusion.

2.2 Yungang: A Mature Case of the Recording Layer

Yungang is a representative case of a recording layer that has reached maturity. Working with several research institutions, the Yungang Research Institute has used high-precision 3D laser scanning to record cave form at the millimetre level, close-range photogrammetry to recover surface texture, and multispectral techniques to detect chemical composition and material properties. For Cave 13, the team collected 283,400 high-resolution images and built a 3D model with an error of less than 0.1 mm, achieving for the first time millimetre-level recovery of sandstone carving details such as the main Buddha's robe folds and the arms of the supporting figures (Tian et al., 2014). The institute also worked with Beijing Jiangong Jianfang Technology to complete digital records of Caves 1–4 and 9–13 and the Yungang upper fort, and established a point-cloud archive that allows adjustable viewing angles,

measurement and millimetre accuracy.

These results serve both conservation and research. In the reinforcement of the Wuhua Cave rock mass and the construction of cave eaves, orthophotos and section drawings derived from 3D laser scanning provided accurate references for design and construction; on the basis of the digital record, researchers have been able to analyse the evolution of Buddhist sculptural style, carving techniques and cultural meaning. The value of the recording layer is clear here: it supplies data for conservation and a base text for scholarship.

2.3 The Limits of the Recording Layer

Maturity, however, also exposes limits. First, the main destination of high-precision data is conservation and research, not public display. Millimetre point clouds and vast image sets are valuable to specialists but hard for ordinary visitors to read. Second, data formats vary and storage pressure is high: different devices and software produce different formats, which obstructs integration and sharing, and long-term secure preservation requires continuing investment. Third, the recording layer tends to stop once a project is accepted—after acceptance, data often sit unused in the archive, and there is no institutional arrangement for moving them toward representation and communication. This is the source of the data-to-content gap diagnosed in Chapter 5.

3. The Representation Layer: High-Threshold Value-Added Work

3.1 The Technology

The representation layer turns data into content that can be understood and experienced. Four technologies matter here. Painted-surface reconstruction uses portable microscopes, X-ray fluorescence and Raman spectroscopy to analyse pigment composition and technique, and rebuilds the original appearance on a scientific basis. 3D modeling and 3D printing convert captured data into visual models and can produce full-scale replicas, making immovable heritage movable and tour-able. VR creates a fully virtual cave environment that visitors can enter with a headset. AR overlays virtual information onto the real scene, presenting interpretation, narration and animation through a phone, tablet or smart glasses. What these four share is that none is a simple copy of the original; each is a form of representation, carrying interpretation and reconstruction.

3.2 Longmen: The Technical Depth of the Representation Layer

The reconstruction of the lotus caisson ceiling in the Middle Binyang Cave at Longmen is a model case of technical depth in this layer. The ceiling had suffered more than 1,500 years of erosion; its painted surface was badly flaked and its colours and outlines blurred. In January 2021 the team began with high-precision 3D data capture to obtain accurate spatial information. Because the damage was severe, they used a portable microscope to observe traces of yellow, blue, pink and white pigment, gaining initial colour clues; they then used X-ray fluorescence and Raman spectroscopy to sample and analyse pigment residue from different positions, identifying the pigments and the overall pattern of colour. In the end they recovered the painting technique used when the cave was built under the Northern

Wei—pigments made from minerals mixed with animal glue. The work took more than a year, and the ceiling was successfully reconstructed on a flat plane.

The case shows that representation is not a stack of technologies but a scientific reconstruction requiring several disciplines: 3D capture supplies the spatial base, microscopy supplies colour clues, spectroscopy supplies compositional evidence, and craft research supplies the logic of making. All four are necessary, and this is what sets the threshold of the layer.

3.3 Yungang 3D Printing and VR: The Experiential Dimension

On the experiential side, Zhejiang University and the Yungang Research Institute have worked together on high-fidelity 3D modeling of the site and on 1:1 replication through 3D printing, allowing an immovable site to travel; the digital protection centre at Yungang also uses VR to let visitors experience the scale of the caves through a headset. The Dazu Rock Carvings digital project goes further, combining VR and AR: visitors can walk freely through a virtual cave and observe carving details from different angles, or use AR to overlay virtual figures, historical episodes and interpretation onto the real scene, choosing their own route and the content they want. If Longmen shows the technical depth of the layer—how accurately the original can be recovered—Dazu shows its experiential breadth: whether visitors can actually enter it.

3.4 The Limits of the Representation Layer

The layer is interpretively strong, but its limits are just as clear. First, it is costly, infrequent and hard to replicate. The Longmen ceiling took more than a year and drew on several precision instruments and a multidisciplinary team; that level of input means it can only be applied to a small number of key caves, not at scale. Second, representation is interpretive reconstruction, not the original. A reconstruction on a flat plane, a 3D-printed replica and a virtual cave are none of them the original object; their value lies in carrying display functions the original cannot, but their status as representation must be made clear to visitors, or the result is the mistaken belief that the virtual is the real. Third, the experience technologies still have weaknesses: headset comfort, image fluency and the naturalness of interaction all need improvement. The representation layer is therefore a high-threshold value-added stage—high in value, but also high in the cost of conversion.

4. The Communication Layer: Wider Channels, Shallow Reach

4.1 Platform-based Communication

Digital exhibition platforms bring scattered resources together and give visitors easier access, freeing cave temples from the limits of place and time. The “Digital Dunhuang” platform is a successful example: it presents high-resolution murals, 3D models and descriptive text from many Mogao caves, so that viewers can see every line and colour clearly and can also move through a virtual environment to take in the layout and atmosphere of a cave. The platform also supports research, since its high-resolution images and models serve as source material for work on artistic style, historical change and Buddhist culture, and it allows online exchange and collaboration. Its value lies in turning

dispersed digital output into a searchable, accessible public resource—the basic infrastructure of the communication layer (Wu, 2022).

4.2 Social Media

Social media is the main channel through which the communication layer reaches the public, and the key is differentiated operation across platforms rather than copying the same content everywhere. Yungang offers a clear example. On Weibo, attractive images, short videos and interpretive articles broaden visibility. On WeChat, longer essays on history, artistic style, Buddhist culture and conservation deepen engagement, supported by quizzes and photography contests that strengthen reader loyalty. On Douyin, short videos present panoramic views, close-ups of carving, VR experiences and cultural commentary, drawing in younger audiences. The three platforms have different roles and different content, and together they form a communication matrix. It should be noted, however, that this is still largely a one-way model of institutional publication and public viewing; deep participation and user re-creation remain limited.

4.3 Online Exhibitions and International Collaboration

Online exhibitions and events break the limits of time and place. The "Cloud Tour of Dunhuang" exhibition, built on the Digital Dunhuang results, presents murals and sculpture as high-resolution images and 3D models that visitors can browse freely and enlarge for detail (Zhao & Wang, 2021); a live-streamed event at Dazu brought an interpreter and a scholar into the Baodingshan precinct to explain the carving technique and Buddhist meaning of the Thousand-Hand Guanyin and the Huayan Three Saints. Internationally, according to public reports, the "Digital Silk Road Cultural Tracing Initiative" has brought together research institutions from China, the UK, the US, Italy and elsewhere to carry out digital capture, conservation research and exhibition along the Silk Road, and to bring cave temple culture to a global audience through touring exhibitions and online displays.

4.4 Zhangye Great Buddha Temple: Communication and Local Tourism

In 2023 the Zhangye Great Buddha Temple began its "Immovable Cultural Relics Digital Protection Project", using 3D laser scanning and digital photogrammetry to build a digital twin of its buildings, murals and painted sculpture, and planning a 350-square-metre digital gallery that reconstructs the temple's layout in different periods and presents its sutras, murals and Buddhist stories. According to public reports, visitor numbers rose after the gallery opened, and the surrounding food, accommodation and transport sectors benefited. The case shows that the communication layer can produce direct economic and social returns, and that it is the final amplification stage of the digital value chain (He, 2026).

4.5 The Limits of the Communication Layer

The effect of the layer, however, remains shallow. Wider reach does not mean deeper understanding, and growth in traffic does not mean growth in participation. Content is still mostly published one-way by institutions, leaving little room for public involvement or re-creation; at the same time, unclear ownership of digital output, blurred boundaries for commercial use and cross-border data security all

act as institutional bottlenecks on sustained operation.

5. Gaps Between Layers and the Mechanisms of Conversion

5.1 Comparing the Three Layers: Abundant Data, Thin Content, Shallow Reach

Placing the findings of Chapters 2 to 4 side by side reveals a structural imbalance. The recording layer has the largest input and the highest maturity: Yungang completed full capture of Cave 13 at millimetre accuracy (see 2.2), and the technology is now well established. The representation layer carries the highest value and the highest threshold: the Longmen ceiling reconstruction took more than a year and a multidisciplinary team, and though interpretively strong it is hard to replicate at scale. The communication layer reaches the widest audience with the least depth: the social media matrix has widened visibility, but publication remains one-way and public participation is limited. The result is that data accumulate, content stays thin, and communication remains superficial. Most investment settles in the recording layer, while the representation and communication layers—the ones that actually shape cultural influence—are underfunded and poorly converted.

5.2 Diagnosing the Gaps: The Bottleneck is not Single-layer Technology but Movement between Layers

Three gaps appear in sequence. The first is the data-to-content gap: high-precision point clouds and images lack narrative and visual translation, so professional data never become content the public can understand, and much of the recording layer's output sits unused in archives. The second is the content-to-product gap: reconstruction and 3D-printed replicas mostly appear in one-off exhibitions and do not become reusable, iterable content products, so high input is hard to spread. The third is the product-to-channel gap: channel operation is separated from content production, and social media stays at the level of posting images and short videos, without deep planning or public participation built on digital content. Behind all three is a common cause: digitalization is organized around capture projects rather than around content conversion. Once a project is accepted, the work is considered finished, and no one is responsible for conversion.

5.3 Proposals for Conversion Mechanisms

Three proposals follow from the gaps above. First, build a data–content–channel conversion chain. Digital projects should include a content translation stage, staffed by a team with both heritage knowledge and narrative skill, that turns captured data into exhibition narratives, educational courses and interactive products, and connects them to channel operation, so that conversion becomes a necessary part of the project rather than an add-on. Second, strengthen tiered authorization and institutional safeguards. As one study notes, clear determination and management of rights over digital heritage resources is a precondition for sustainable digital protection (Yang, 2025). Where ownership is unclear, contracts at project start should specify the data rights of the managing institution, the technology company and the research institute; where commercial boundaries are blurred, a tiered classification standard for cave temple digital resources should be promoted, with authorized access to high-precision core data and open sharing of public-facing data; where cross-border data security is at

stake, review and authorization mechanisms should be built into international collaboration; and for long-term preservation, open formats, off-site backup and periodic migration should be adopted, with a clear maintenance body. Third, shift funding and talent toward the conversion end. Investment currently concentrates on capture equipment and technical development; special funds for content conversion and communication operation should be added, and combined talents who understand both heritage protection and digital narrative and communication should be trained.

5.4 A Supplementary Indicator for Evaluation

Evaluation needs to change along with the mechanisms. At present, digitalization is judged mainly by capture scale (number of caves, number of images) and accuracy (millimetre level), which in effect applies the recording layer's standard to the whole chain. A conversion rate should be introduced as a supplementary indicator: the public reach, understanding and participation produced per unit of capture investment. This does not replace accuracy and scale but sits alongside them, pushing digital work from "capture completed" toward "value realized".

6. Conclusion

This paper proposes a three-layer framework—recording, representation, communication—and treats cave temple digitalization as a value chain running from permanent preservation to cultural diffusion. Drawing on Yungang, Longmen, Dunhuang and the Zhangye Great Buddha Temple, it has examined the technical features, cost structures and limits of each layer. The recording layer is relatively mature, but high-precision data are poorly converted into public-facing content. The representation layer is interpretively strong yet costly, infrequent and hard to replicate. The communication layer reaches widely but stays shallow. Together the three form a structural gap—abundant data, thin content, superficial communication—whose cause lies not in weak technology at any single layer but in the absence of mechanisms that move work between layers.

The paper accordingly proposes a data–content–channel conversion chain, stronger tiered authorization and institutional safeguards, a shift of funding and talent toward the conversion end, and a conversion-rate indicator as a supplement to existing evaluation. The next step for cave temple digitalization is not simply higher capture accuracy or more channels. It is to open the passage between layers: to let recorded data become content people can understand, to let represented content become products that can travel, and to let those products reach and move the public. This is a technical question, but also an organizational and institutional one, and it requires conservation bodies, technical teams and communication operators to work together.

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