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The Role of Survey in Evidence-Based Interpretive Scenarios †

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Abstract

This study presents the critical contribution of digital survey and representation to the interdisciplinary SCORPiò-NIDI research project. By adopting a reverse analytical sequence—from measurable impact effects to mechanically and historically compatible causes—the investigation integrates high-resolution 3D survey, morphometric characterization, reverse modeling, and numerical simulation within a structured Information System, together with the reconstruction of experimental demonstrators calibrated on the obtained datasets. Rather than proposing a definitive reconstruction of the Sullan siege, the study establishes a reproducible and transferable workflow for the analysis of ancient siege evidence, grounded in metrically reliable data and integrated within a shared digital research environment designed to manage evidence-based interpretive scenarios.

Keywords: ancient siege warfare; Roman artillery; ballistic impact analysis of anti-personnel dart weapons; reality-based 3D modeling; reverse engineering; finite element modeling; digital twin; information systems; experimental archaeology; Pompeii fortifications

1. Introduction

The study of ancient Roman artillery has long been grounded in the critical interpretation of five Hellenistic treatises, not all of which have survived in their entirety [1], together with the limited archaeological remains that have been identified as components of elastic-torsion engines only after a clear understanding of the operational principles governing these machines had been established [2]. Many of the most influential historical reconstructions of weapons and battlefield scenarios are based on these sources [3–6].

While these approaches have significantly expanded the analytical and communicative scope of archaeological research, they have also raised methodological concerns regarding the balance between narrative coherence and scientific verifiability within a graded system of historical and archaeological evidence for virtual reconstructions [7]. In many cases, reconstructed scenarios remain predominantly inferential, often calibrated on typological comparisons or isolated finds rather than on verifiable empirical data, largely as a consequence of the limited survival of direct material evidence.

Within this context, the systematic documentation of impact traces unearthed along the northern fortifications of Pompeii (Figure 1), attributed by archaeologists to the Republican period, provides a decisive alternative evidentiary basis for assessing the artillery machines employed in 89 BC during the siege led by Lucius Cornelius Sulla [8–12]. These traces therefore provide an indirect confirmation of siege dynamics, based on quantifiable terminal ballistic parameters rather than solely on comparative typologies.

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Figure 1. Aerial view of the northern fortifications of the city with the research area highlighted between the Vesuvio (above left) and Ercolano (bottom right) Gates. Archaeological Park of Pompeii, Google Maps satellite imagery (accessed on 10 March 2026).

The archaeological context of Pompeii provides an exceptional opportunity to address these issues from an inverse perspective to that adopted until now. Between the Vesuvio and Ercolano Gates (Figure 2), a distinct and well-defined concentration of ballistic imprints attributable to different types of projectiles and weapons from the Republican period can be observed, some of which were already documented in the early twentieth century. These traces, preserved for centuries beneath volcanic deposits following the eruption of Mount Vesuvius in AD 79 and brought to light only in the modern era, constitute a remarkably well-preserved record of the destructive effects of such weapons [13]. The extrados of the stone ashlars functions as a material record of the interaction between artillery, inflicted damage, and target, thereby recording key elements for reconstructing the siege context. Unlike war machines reconstructed from surviving components or hypothetical battle layouts, these surface alterations represent direct physical evidence of impact events, whose geometry, depth, and spatial distribution can be measured through high-resolution digital survey techniques used by specialized technical surveyors for acquisition, processing, and analysis [14] (Figure 3).



Figure 2. Equirectangular projection derived from a spherical panorama showing the city walls between Towers X and XI. Photo by V. Casadei (SCORPiò-NIDI Project Team).

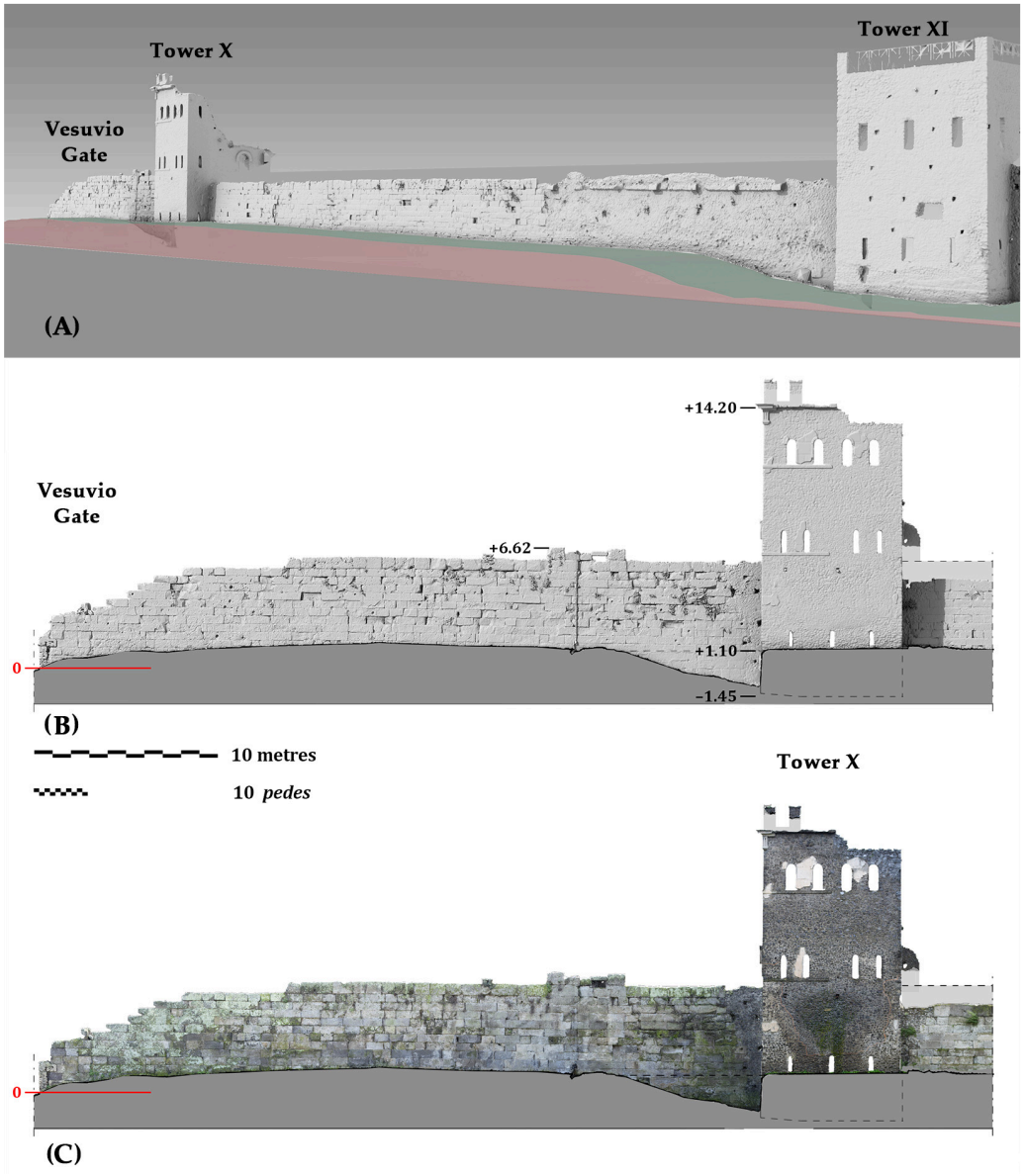


Figure 3. (**A**) Perspective view of the 3D model of a section of the northern wall sector used as general reference (Terrestrial Laser Scanner—TLS data), from Vesuvio Gate to the stretch between Towers X and XI (Tower of Mercurio), where most ballistic imprints have been identified. (**B**) First wall sector with a general graphic scale and indication of the elevation above the local origin, showing the actual level below ground level and the access to the tower postern. (**C**) Textured model of the corresponding area. Model and rendering by S.B.

The combined use of no-contact range-based and image-based acquisition and modeling techniques, together with calibrated post-processing and mesh optimization procedures [15,16], enables the production of geometrically accurate and analytically usable models through the transformation of raw discrete measurements into continuous geometric models suitable for computational analysis [17]. While the primary datasets consist of objectively recorded point clouds, subsequent processing stages generate continuous surface representations whose parameters and processing settings must be explicitly defined in order to preserve data reliability [18]. Dedicated software environments enable high-resolution 3D documentation, morphometric inspection, volumetric estimation, and spatial analysis of ballistic traces [19], providing the empirical basis for mechanical reasoning and numerical simulation [20] (Figure 4).

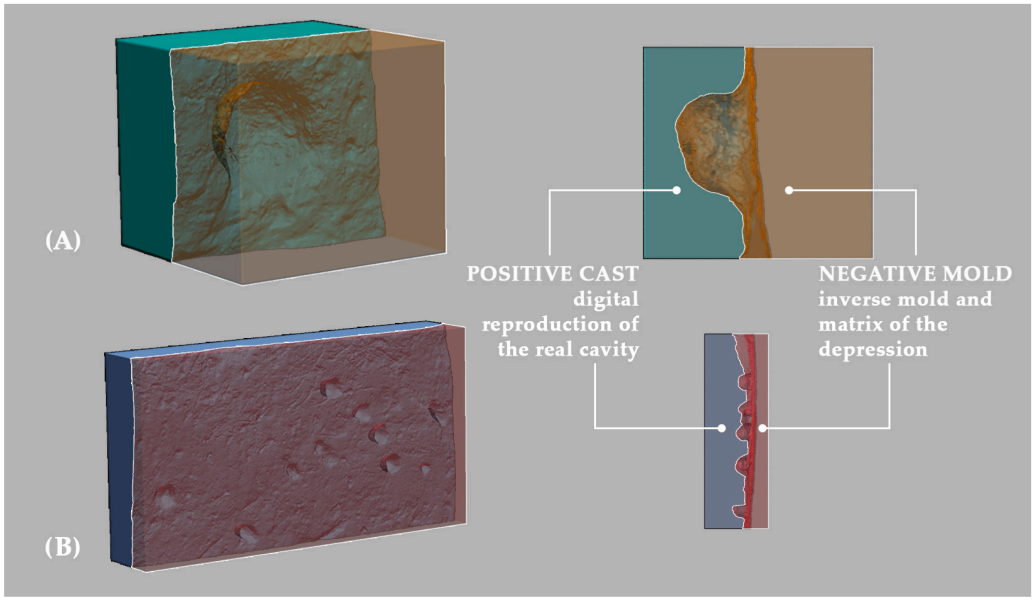


Figure 4. Virtual positive casts and corresponding negative molds used for the documentation and subsequent analysis of the two different kinds of ballistic imprints: (**A**) axonometric view of a virtual model of a ballistic imprint produced by a stone projectile, with the corresponding inverse cast virtually generated from the digital survey shown in transparency; (**B**) ballistic imprints produced by metal-tipped darts, with the corresponding inverse cast virtually generated from the digital survey shown in transparency. The 3D models on the right show lateral cross-sectional views, highlighting the different depths of the cavities. Models by S.B.

At the conclusion of a two-year research phase (1 November 2023–28 February 2026) [21], this contribution presents the principal contributions developed by the ERC SH5_12 specialists within the SCORPiò-NIDI project, framing the results within a coherent methodological framework aligned with the interdisciplinary objectives of the research. Further developments and potential findings can already be envisaged beyond the objectives originally defined for the project.

Rather than following what until recently was considered the conventional sequence, the present premise allows the analytical process to be inverted, extending analytical knowledge beyond what traditional techniques alone could achieve. Instead of starting from reconstructed weapons to verify their lethality, the analysis begins with the digital survey of ballistic impacts preserved along the northern sector of the city walls and proceeds toward the quantification of mechanically compatible causes and their historical verification [21] (pp. 1–22). Confident in the chronological attribution suggested by the singular history of Pompeii, this study deliberately departs from narrative-driven reconstructions. It instead assembles the results derived from reliable digital survey conducted on material evidence, together with analytical calculations and comparisons with Reverse-Engineering (RE) processes, in order to construct scenarios that leave no room for purely illustrative improvisation (Figure 5).

Within this multidisciplinary framework, the proposed interpretations are formulated as degrees of compatibility and verifiability instead of definitive identifications [22], ultimately aimed at establishing a reproducible and transferable methodological framework for the investigation of ancient siege evidence.

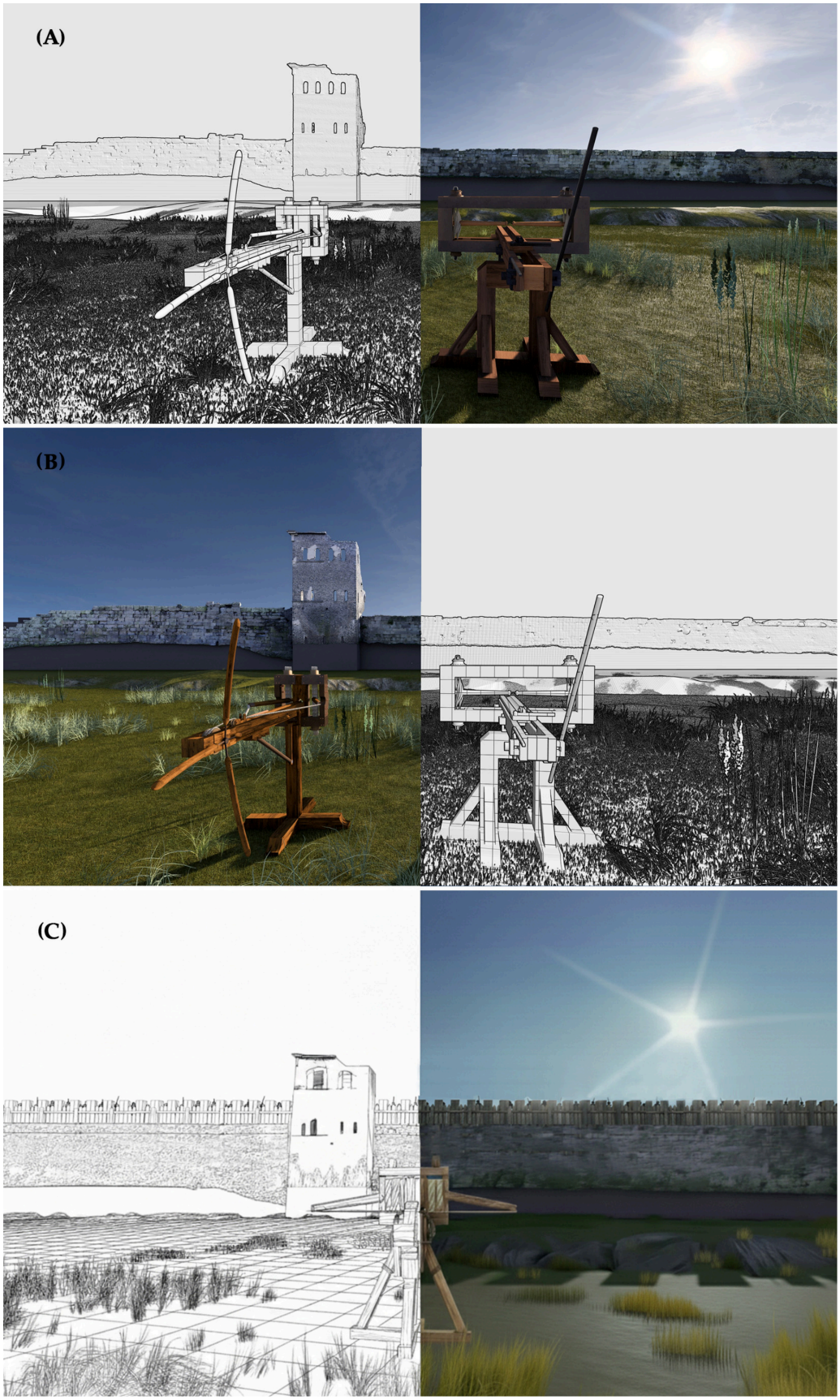


Figure 5. (**A**–**C**) Siege scenarios with reconstructed Roman artillery. Reality-based 3D assets derived from TLS survey data by S.B.; Roman weapons 3D reconstructions by C. Formicola (SCORPiò-NIDI Project Team); siege scenario layout, rendering and animation (Lumion Pro Student 2024) by V. Casadei (SCORPiò-NIDI Project Team). Supervisor: A.R.

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2. Materials and Methods

The methodological approach adopted in this research was structured as a multi-stage pipeline. The sequence illustrated in Figure 6 reflects the logical transition between intermediate outcomes necessary to ensure metrically controlled documentation that can subsequently be verified through inductive analysis. At the same time, a cyclical and interactive process influences the investigation towards unforeseen results and previously unformulated insights, discoveries, and interpretations that scientific analyses further explore within a digital environment.

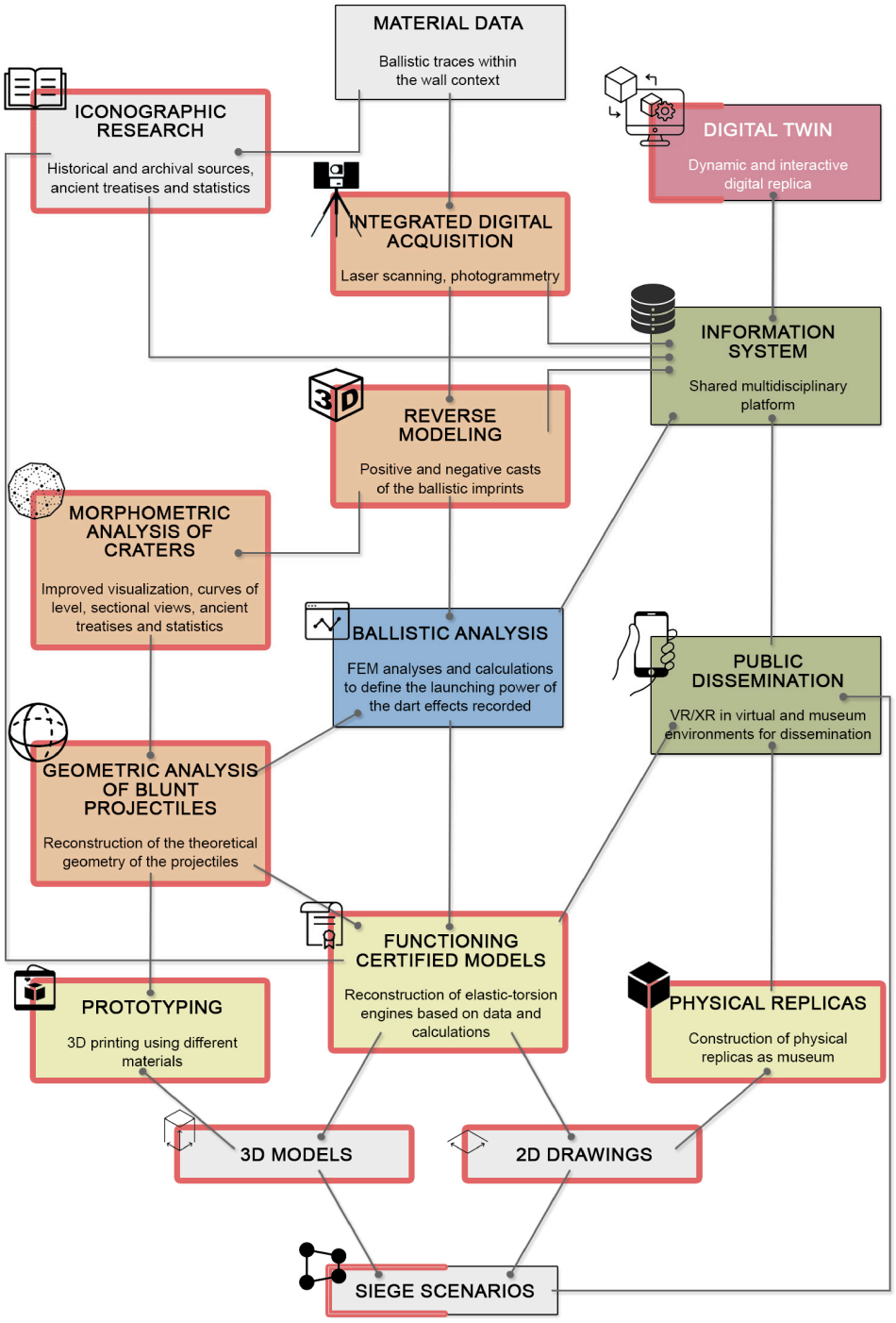


Figure 6. SCORPiò-NIDI project workflow with the research activities carried out by the Vanvitelli team (in red). Scheme by S.B.

Under this approach, phases that were once linearly distinct and sequential prove instead to be mutually interconnected, supporting research activities that share models, information, and results through procedures capable of transforming the way archaeological evidence is constructed and interpreted.

Data acquisition (the culture of survey) and the hermeneutic and critical interpretation of the results (the culture of design) together outline a palimpsest of material and immaterial data. The organization of the Information System (IS) makes it possible to modify, implement, record, and monitor this dataset over time.

At the origin of the workflow lies the digital survey of the material evidence, understood in the present study as the set of ballistic traces identified on the northern fortification walls, considered as measurable outcomes of impact events within a well-dated stratigraphic and historiographical context [23–26].

Among the various ballistic traces attributable to specific siege tactics, the survey focused on two different groups of ballistic imprints (Figure 7): (i) distinct circular impact marks caused by spheroidal stone projectiles, already discovered in the mid-1920s [27,28]; (ii) small quadrangular indentations arranged in fan-shaped groupings, configurations identified band selected by Adriana Rossi as potential evidence of impacts produced by bolts fired from repeating catapults. This hypothesis was scientifically discussed during the two-year research phase [19,22,29], but nevertheless requires further investigation in future studies. From this, the investigation proceeded through integrated digital acquisition, morphometric characterization, Reverse-Modeling (RM), and mechanical evaluation, progressively transforming localized surface alterations into structured analytical datasets for subsequent analysis.

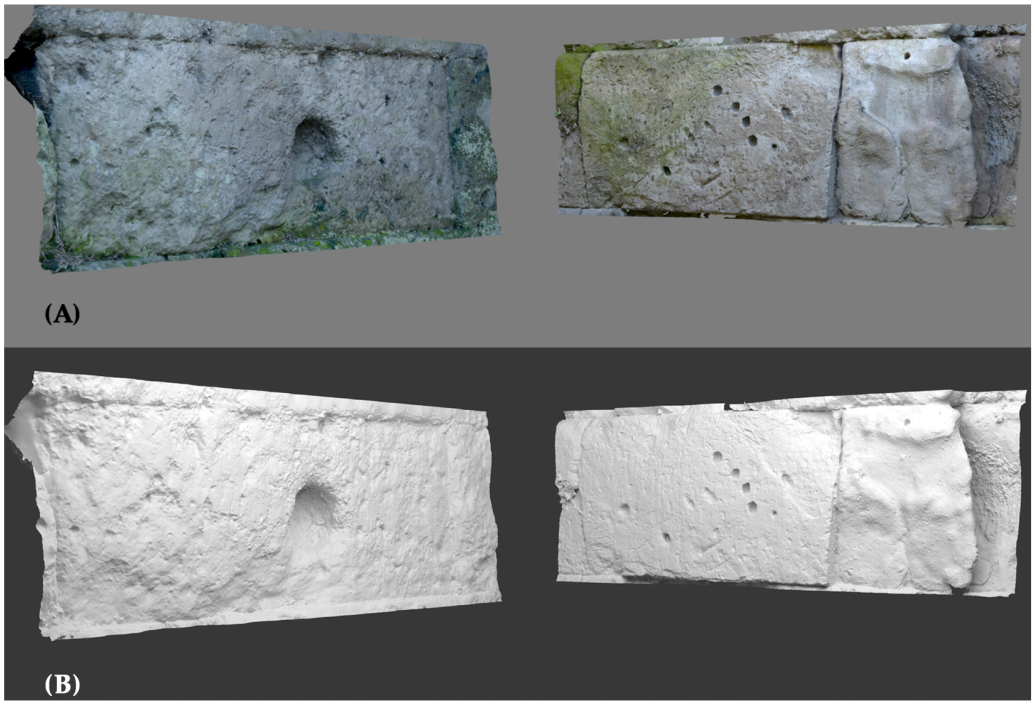


Figure 7. Virtual casts of the two types of traces analyzed obtained through digital photogrammetry: (**A**) with apparent color texture and (**B**) without. On the left, impact produced by a stone ball; on the right, darts with metallic tips. Photogrammetry by S. Gonizzi Barsanti (SCORPiò-NIDI Project Team); models and renderings by S. Bertacchi.

Non-contact recording strategies were adopted to ensure metric reliability and complete surface coverage of the small-scale and irregular morphologies of many preserved ballistic imprints, without interfering with the stone ashlars. An integrated approach based

on close-range photogrammetry and range-based Terrestrial Laser Scanning (TLS) was employed to capture both local geometric detail and broader spatial relationships within the wall sector, and to generate high-resolution three-dimensional models of selected wall sections and individual impact marks.

The resulting point clouds were processed through calibrated alignment and filtering procedures, leading to the generation of high-resolution polygonal meshes. These 3D models allow for quantitative assessment of cavity geometry, including depth, diameter, volumetric displacement, and orientation relative to the wall surface, particularly in deeper cavities. Particular attention was devoted to documenting material heterogeneity and construction techniques, since the mechanical response of the local materials used in the city walls (tufa, limestone, and volcanic inclusions in irregular masonry) [30] directly influences fracture propagation and energy dissipation during impact events, thus enabling reliable ballistic assessment [20].

In addition to metric extraction, the three-dimensional models were interrogated within digital modeling environments to enhance the visual perception of subtle surface discontinuities (Figure 8). Controlled lighting simulations, sectional slicing, and curvature-based visualization tools were employed to distinguish impact-generated indentations from erosion patterns and restoration interfaces. Particular attention was devoted to identifying degrees of circularity and edge regularity, allowing for repeatable classification of marks tending toward spheroidal impact morphology. This enhancement phase supported a more reliable discrimination between anthropogenic ballistic imprints and irregular surface degradation [14].

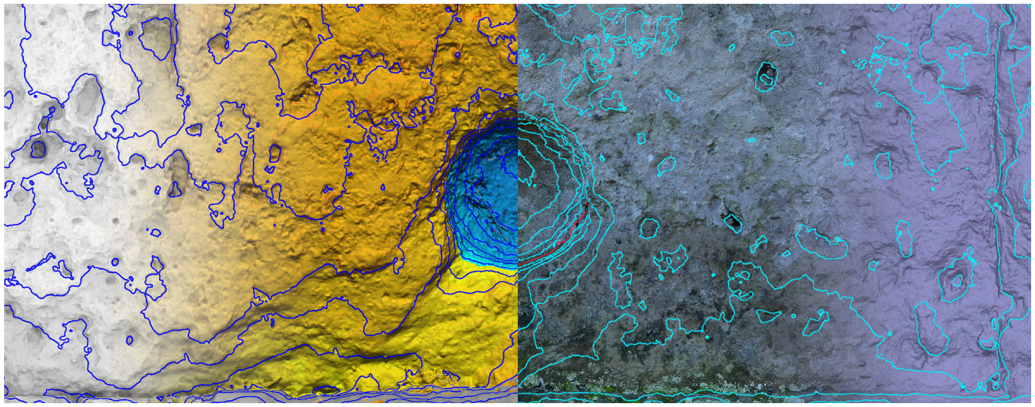


Figure 8. Comparative visualizations of the 3D digital model of a cavity in the fortification wall obtained through photogrammetry. From left to right, the applied maps emphasize surface morphology, false-color deviation from a vertical reference plane, the apparent color texture mapped onto the polygonal mesh, and contour lines intersecting the model at 1 cm intervals. Model by S.B.

On the basis of these morphometric datasets, RM procedures were implemented to infer the most plausible characteristics of the impacting projectiles. Digital positive casts of the cavities were generated to estimate the original impact geometry, enabling the corresponding negative molds to support projectile hypotheses within constrained morphological ranges. Geometric range estimation of the impacting projectiles was conducted through constrained shape-fitting procedures applied to reconstructed cavity volumes. For spheroidal stone projectiles, primitive geometric fitting techniques were used to approximate admissible diameter ranges consistent with measured concavities. In the case of quadrangular imprints, comparative geometric analysis focused on pyramidal and sub-pyramidal bolt-tip morphologies, evaluating dimensional compatibility between reconstructed cavity edges and historically documented projectile forms [21] (pp. 47–62) (Figure 9).

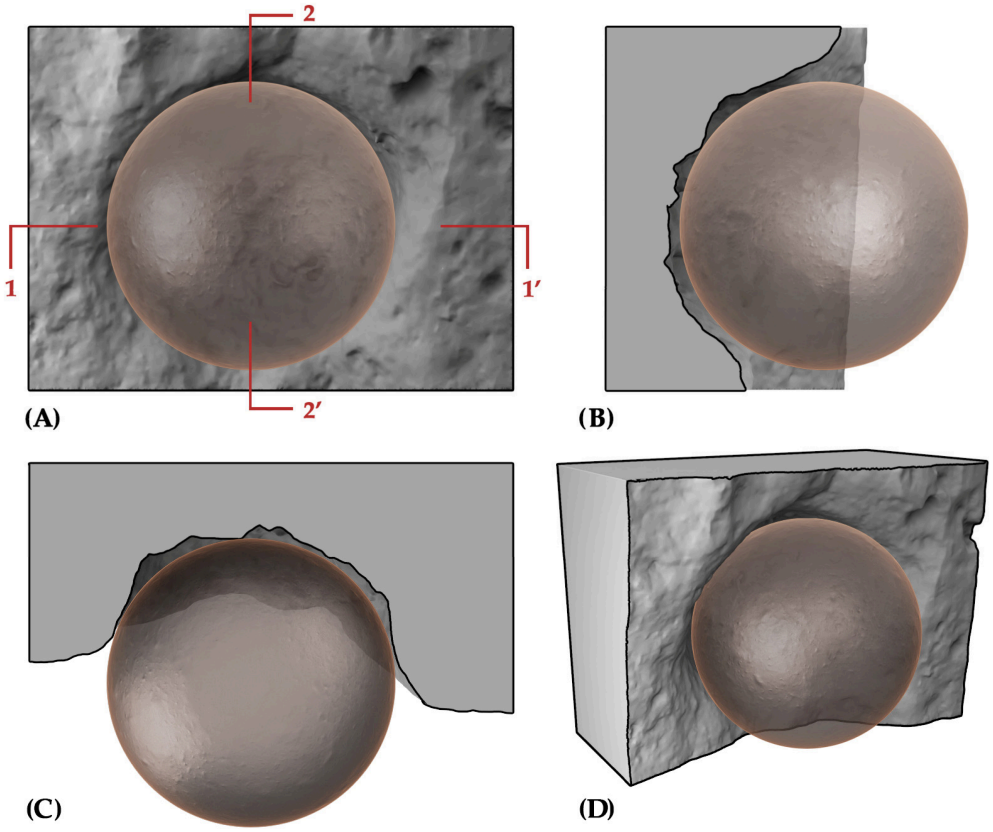


Figure 9. Virtual replica of the existing wall surface (impact cavity). From the high-resolution digital model, it is possible to hypothesize solid geometries that may correspond to the impacting object responsible for the cavity and the associated material loss: (**A**) front view; (**B**) lateral view of cross-section 2–2′; (**C**) top view of cross-section 1–1′; (**D**) perspective view of the reconstruction. Model and geometric reconstruction of the stone ball by S.B.

This step does not aim at the exact replication of lost objects, but to define bounded morphological intervals within which plausible projectiles could be situated and mechanically compatible geometries that can be tested against the recorded evidence, as supported by stone balls still preserved at the site today [21] (pp. 36–46).

Several difficulties therefore had to be critically addressed in order to resolve issues that fall outside any standard procedural logic or manual guidelines, while still respecting established protocols. The reconstructed geometries currently available reflect post-siege restorations, volcanic infill deposits, weathering damage, and modern conservation interventions. These factors introduce unavoidable sources of uncertainty in the reconstruction, which are explicitly acknowledged and incorporated into the analytical framework [31].

Mechanical evaluation constitutes the subsequent phase of the pipeline. Analytical reasoning and numerical simulation tools, including Finite-Element Modeling (FEM) [32], were applied to estimate the mechanical energy required to produce the observed damage on the basis of the estimated density of the stone materials. Different projectile types and firing configurations were examined within historically and technically plausible ranges, ensuring that mechanical plausibility remained grounded in the archaeological context [33].

Ancient technical treatises on artillery [34] were integrated at this stage as comparative guides for the numerical simulations preceding the experimental reconstructions. It should be recalled that the machines under investigation date to the pre-Christian period and were progressively optimized through experimental verification processes, which resulted in calibration systems used to proportion their structural components and to predict their destructive effectiveness.

3. Results

All generated datasets—including raw survey data, processed meshes, sectional analyses, mechanical outputs, and interpretive metadata—were organized within a structured IS. This system was designed to ensure traceability, interoperability, and multidisciplinary accessibility. Information System approaches have been widely adopted in recent decades within the Cultural Heritage (CH) domain and function not merely as a repository, but as an operational environment in which different categories of assets can be cross-referenced and progressively updated as new analyses are performed, particularly in complex sites where multiple teams operate simultaneously [35–37].

Reality-based models constitute the foundational layer for the development of a digital twin of the investigated wall stretch. The digital twin does not represent a purely illustrative reconstruction, but a dynamic framework capable of integrating metric documentation, analytical results, and interpretive hypotheses into a coherent and verifiable structure. This architecture enables the controlled generation of derivative outputs, including analytical 3D models, technical drawings, functional reconstructions, and scenario simulations, while preserving explicit links to the original measured evidence.

From this structured data environment, several categories of qualitative and interpretive results were produced during the phases of the project.

Three-dimensional prints of selected impact traces and reconstructed projectile geometries were produced at 1:1 scale to allow tactile examination and comparative assessment. Such outputs are particularly relevant for controlled experimental verification, inclusive dissemination contexts in which direct access to the archaeological site may be restricted (either visually or physically) [21] (pp. 127–140), and for advanced visualization strategies in digital heritage contexts [38–40].

Similarly, the parametric reconstruction of torsion-powered machines—calibrated on mechanically compatible projectile ranges—resulted in full-scale demonstrators of stone-ball and dart-throwing devices. These reconstructions were derived from metrically constrained digital models rather than from purely typological analogy.

Among the most significant results are the small, previously mentioned quadrangular indentations (2.5–2.8 cm per side), less than 2 cm deep, with an orientation approximately perpendicular to the wall, occurring at short intervals along a curved trajectory. These features, attributable to projectiles with metallic tips launched by torsion-powered engines and previously associated with small-caliber ballista projectiles [41] (p. 6), have been further validated through numerical simulations based on selected examples [32], despite the lack of metallic tips identified in situ until now. Their absence is plausibly explained by corrosion processes, material loss over time, and the difficulty of distinguishing possible metallic fragments from lithic inclusions embedded within the indentations without invasive analytical procedures. Even in the absence of this limited direct material evidence, the reconstructed geometries provide clearer indications.

Particularly noteworthy are clusters of small marks, previously overlooked or not considered worthy of detailed analysis, which—on the basis of their highly distinctive geometric configurations and polemological and hoplological considerations related to projectile weapons—have been recorded as potential evidence of impacts produced by bolts fired from repeating catapults [22]. The exegetical analysis conducted by the Principal Investigator (P.I.), Adriana Rossi, confirms the morphometric similarity between the cavities forming the fan-shaped arrangement within the cluster (Figure 10). Indeed, it has been observed that the slight rotation of each cavity relative to the next by a few degrees, occurring at short and regular intervals, would be difficult to achieve with weapons loaded at different times or fired from different positions. From a hoplological perspective, these short and regular intervals are more plausibly associated with repeated firing trajectories

from a single position. Further philological examination strengthens this interpretation [29]. The reconstructed patterns display formal similarities to the effects expected from an automatic weapon such as the *polybolos*, described in detail by Philo of Byzantium in his treatise on artillery [34]. Although historical coincidences alone cannot be considered conclusive evidence, the convergence of archaeological, mechanical, and textual indications suggests that the hypothesis represents more than a simple intuitive interpretation.

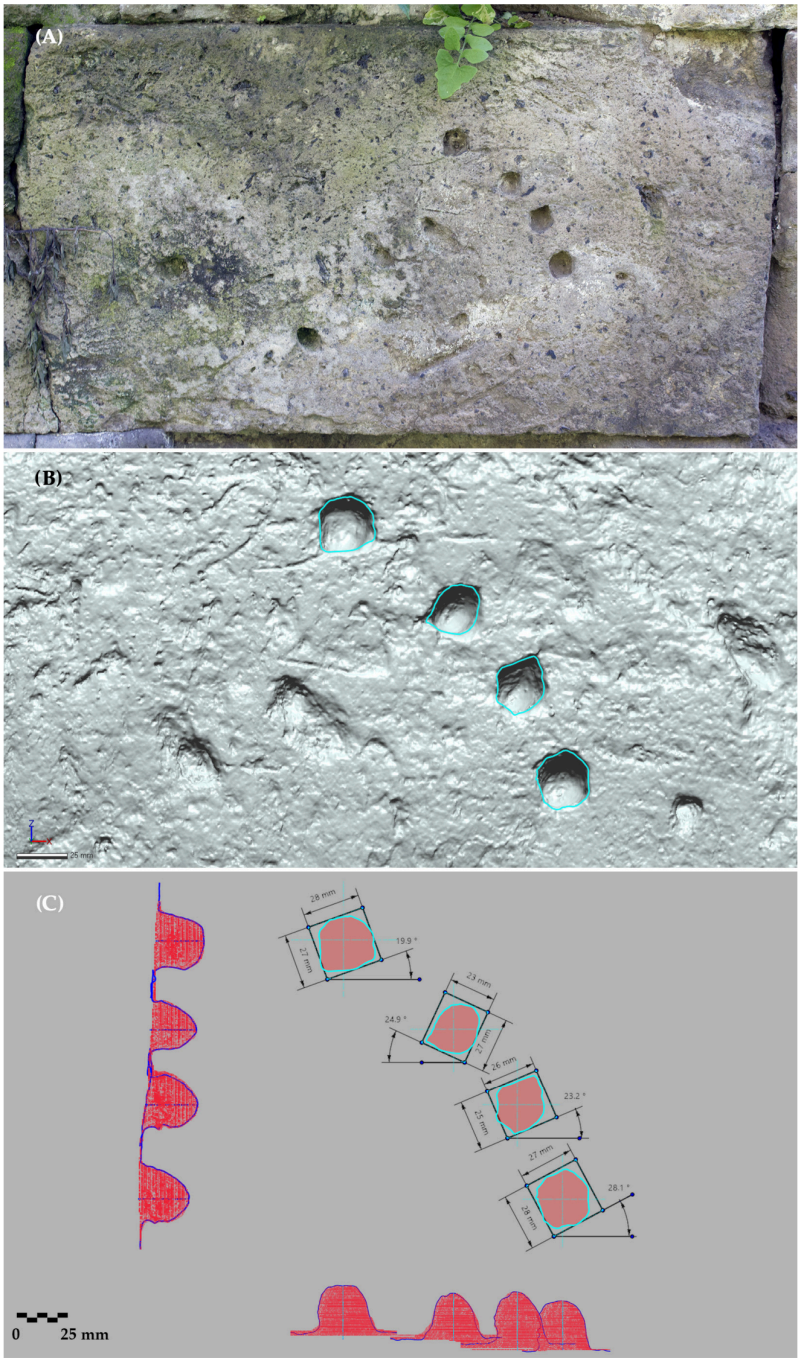


Figure 10. (**A**) Identification of square-hole configurations along curved alignments on the stone ashlar (photographic survey by A. Rossi, 2016). (**B**) Quadrangular impact marks with the external outline highlighted. (**C**) Measurements in millimeters and angular values in degrees, with corresponding horizontal and vertical cross-sections. The slight angular deviation of the cavity profiles relative to the horizontal reference suggests that the arrowheads did not strike the surface in perfectly aligned trajectories but instead with small rotational variations. This pattern is more consistent with repeated firing mechanisms such as a *polybolos* than with a single-shot scorpio. Model by S.B.

Additional support derives from reverse reasoning based on the calculated volume of pulverized material. Using the measured dimensions and recurring configurations of the imprints, and considering the density of the tuff masonry, it becomes possible to apply calibration formulas and derive the dimensional module through inverse calculation on which families of certified *scorpiones* were reconstructed. These include both virtual and physical demonstrators—fabrication-ready models suitable for additive manufacturing and full-scale reconstruction [21] (pp. 63–74)—as well as an ongoing reconstruction of a *polybolos* calibrated on the measurements provided by Philo (see Rossi–Formicola in the same proceedings) [21] (pp. 112–125).

4. Discussion

The implications of these findings extend beyond the specific case of Pompeii, touching upon broader methodological issues in the study of ancient warfare and digital heritage. Traditional reconstructions of ancient artillery have often proceeded from surviving components or textual descriptions, using them as the primary drivers of interpretive narratives. While such approaches have yielded valuable insights, they risk introducing circular reasoning when material effects are retrofitted to preconceived models.

By contrast, the approach adopted here prioritizes observable effects as the starting point of analysis. This inversion—from effects to causes—repositions digital reconstruction as an analytical instrument instead of a narrative device. The resulting scenarios are not intended as immersive storytelling environments designed to persuade or entertain audiences, but as active interpretive spaces in which hypotheses remain open to scrutiny and revision [42]. In this sense, reality-based digital assets function as controlled analytical datasets, whose metric reliability constrains subsequent modeling and interpretative elaboration.

Within this framework, the proposal that an automatic repeating dart-thrower may have been employed during the siege of Pompeii should be understood as a reasoned inference rather than a definitive conclusion. Ancient authors themselves expressed ambivalence toward such machines, emphasizing both their mechanical ingenuity and their tactical limitations. The concentration of closely spaced impacts observed at Pompeii corresponds to descriptions of weapons capable of firing multiple projectiles along a confined trajectory—a feature repeatedly highlighted in discussions of repeating artillery. However, the compatibility observed between impact configurations and historically documented mechanisms is treated here as a graded analytical correspondence, not as direct evidence of specific technological deployment.

The historical plausibility of this hypothesis is further supported by the broader geopolitical context of the late second and early first centuries BC, during which technological innovations circulated across the Mediterranean. The Roman appropriation and adaptation of Hellenistic artillery traditions is well documented, and the potential transfer of advanced mechanisms cannot be dismissed a priori. Nonetheless, the present study deliberately refrains from asserting direct lines of transmission, focusing instead on functional compatibility and contextual feasibility.

Beyond the specific hypothesis advanced, the study highlights the operative value of a structured Information System in archaeological interpretation. By integrating raw survey data, morphometric classifications, mechanical simulations, and historically derived parameters within a single digital environment, the project establishes a transparent chain of inference in which each interpretive step can be traced back to measurable evidence. The digital twin implemented for the investigated wall sector functions as an evolving analytical framework, allowing controlled comparison between alternative projectile mor-

phologies, firing conditions, and spatial configurations while preserving explicit links to the documented surface evidence.

More broadly, the project challenges the predominance of purely narrative reconstructions in digital heritage. Rather than presenting a fixed account of past events, the proposed Information System invites users to engage with evidence, models, and alternative interpretations. In this sense, the work aligns more closely with an evaluative and participatory paradigm, in which historical understanding is constructed through critical interaction with data instead of passive consumption of reconstructed stories. This approach reinforces scientific accountability and long-term preservation, since the same digital assets that support analytical reasoning also serve as durable documentation of fragile material evidence.

Although the Pompeian context represents a particularly favorable preservation scenario, the methodological sequence developed here—non-invasive acquisition, morphometric analysis, RM processes, mechanical evaluation, and structured data integration—remains transferable to other fortified contexts in which measurable impact traces survive.

5. Conclusions

The research presented in this article underscores the methodological importance of metrically reliable digital surveying in the scientific investigation of ancient siege warfare. The systematic documentation of ballistic traces, acquired through non-invasive techniques and processed within a calibrated analytical workflow, establishes a robust empirical basis upon which mechanical evaluation and historically informed interpretation can be developed. In the absence of such structured documentation, subsequent simulations and reconstructions would remain largely speculative.

The results indicate that ancient artillery systems can be investigated starting from their measurable physical effects instead of relying exclusively on typological comparison or textual description. This shift strengthens the analytical rigor of experimental archaeology by grounding interpretive reasoning in quantifiable geometric and mechanical parameters. In the Pompeian case, this approach enables a more differentiated understanding of the interaction between weapon categories, firing dynamics, and defensive architecture, without presupposing predetermined narrative scenarios.

Within cyclical and interactive processes that are inherently interdisciplinary, the outcomes achieved and organized within a federated model allow the results to be further developed through different visualization approaches. Different levels of visualization of the 3D models, together with graphic processing, information modeling, infographic representation, and haptic experience, make it possible to extract and abstract analytical information in order to render them visible within a deliberately interactive environment. A plurality of languages and techniques thus contributes to the construction of cognitive spaces through which historical memory can be explored and reconstructed. In the present case, this process is grounded in the objectivity of reality-based 3D models, in the calculations derived from RE procedures, and in the exegetical sources and studies related to the corpus of reconstructions.

From this perspective, the role of reality-based and metrically reliable digital survey becomes particularly evident. The overall results nevertheless show that the role of specialists in this field does not end with ensuring traceability, portability, interoperability, and multidisciplinary accessibility. Rather, the system aspires to evolve over time into an ecosystem composed of elements organized into categories of information and models that can be cross-referenced and progressively updated.

In fact, a central outcome of the project lies in the implementation of an integrated Information System and digital twin environment. By maintaining explicit connections between raw survey data, processed models, mechanical outputs, and certified reconstructions, the system supports transparent inference and interdisciplinary collaboration. The same

infrastructure that enables analytical testing also guarantees long-term data preservation and controlled generation of derivative outputs, including simulation-ready geometries and fabrication models. Over time, such digital infrastructures may evolve into structured digital environments in which datasets, models, and interpretive hypotheses can be progressively expanded, cross-referenced, and updated.

The framework developed within the SCORPiò-NIDI project therefore extends beyond the specific historical episode examined here. It provides a transferable methodological sequence—from acquisition to structured data integration—that may be applied to other fortified contexts where impact evidence survives. Certain cases are already known: for example, the walls of Jerusalem, which were also subjected to siege activities involving Roman artillery. However, unlike the Pompeian case examined here, further strategies would be required in order to distinguish ancient impact traces from those produced by later medieval assaults. In this respect, comparison with the Pompeian evidence could prove extremely useful, provided that ongoing conflicts do not threaten the preservation of these sites. Similar difficulties arise in other well-known archaeological contexts, such as Hatra, where the chronological attribution of impact marks remains a complex issue.

The study of ancient weapons and siege evidence does not conflict with the widely shared rejection of war; rather, it aims to encourage intellectual progress by documenting and interpreting the technological knowledge embedded within archaeological evidence from an interdisciplinary research perspective.

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Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-Dimensional
CH	Cultural Heritage
FEM	Finite-Element Modeling
IS	Information System
RE	Reverse-Engineering
RM	Reverse-Modeling

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