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Digitising stećci – 3D documentation and relief visualisation of medieval tombstones

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ABSTRACT

This study explores the medieval funerary phenomenon of stećci through advanced digital techniques. Employing photogrammetry and structured light scanning, we digitised a number of stećci to compare the effectiveness of these methods for accurate surface reconstruction. The comparisons have shown that both methods are capable of producing comparable models under optimal capturing conditions. A number of different smoothing and mesh refinement techniques were employed to remove surface deformations and make the carvings more visible. The use of surface-enhancing visualisations proved to be a prerequisite for accurate and reliable interpretation of the iconographic and epigraphic features on stećci. Among the tested visualisations, those based on Digital Elevation Models (DEM) were the most effective, with the Simple Local Relief Model (SLRM) combined with hillshading from three directions (HSMD) proving particularly reliable.

1. Introduction

The medieval tombstones, known as stećci (singular stećak), can be found scattered across the landscapes of Croatia, Serbia, Montenegro and especially in Bosnia and Herzegovina (BiH). They represent a unique funerary phenomenon that developed between the 12th and 16th century and are a testament to the rich cultural and historical heritage of the region. Stećci are a blend of local traditions, various religious beliefs, multiple artistic expressions displaying a rich iconography and writings. They were made from the local limestone and appear in six main forms (Fig. 1.), with a multitude of variations. Current records indicate more than 3300 sites with over 72,000 stećci throughout the Western Balkans, including more than 60,000 in BiH alone. This phenomenon has also been recognised by UNESCO and was inscribed to the World Heritage list in 2016 (Bešlagić, 1982; Lovrenović, 2009).

Around 8 % of stećci feature inscriptions and decorations, engraved in low relief, displaying iconography that links medieval Europe and local Balkan traditions. Less than 400 monuments are currently known, bearing inscriptions in the Bosnian Cyrillic script. The language and script are purely local; they both developed in the 9th century and are extinct today (Lovrenović, 2009; Vego, 1962). The extensive quantity and widespread distribution of stećci tombstones have posed challenges for an in-depth scholarly examination of this phenomenon. Although studied extensively by historians, these monuments remain vastly understudied by archaeologists. Inscriptions, however, have triggered the interest of various scholars early on, with the first studies published in the closing decades of the 19th century (Asbóth, 1888; Truhlenka, 1895). The wealth of iconographic and epigraphic knowledge present on these monuments offers a distinctive perspective into the ideologies and lifeways of the medieval population that erected stećci.

The systematic research on stećci has been impeded by their number and wide geographical distribution. Although the monuments themselves had been studied by historians and art historians, the archaeological research is more limited, be it on a micro level, i.e. a necropolis or a grave, or on a larger, landscape scale. The issues that prevent scholars from studying stećci are many (see Čaval et al., 2021).

This paper focuses on the digitisation and visualisation processes of the tombstones themselves. Previous digitisation efforts focused primary on the use of photogrammetry with some limited use of laser scanning (Radosević and Rizvić, 2012; Čaval et al., 2021; López-Menchero et al., 2022). Detailed comparisons between the two methods concerning the stećci monuments are notably lacking. We tested and compared the two 3D data capture methods to obtain an accurate surface geometry. Precise

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and high-resolution 3D models are required for millimetre-level measurements of surface grooves that may contain traces of chisel marks. We hope these will shed more light on the techniques used by the master carvers and possibly to help identify individual craftsman (Imer et al., 2023). A topic that has not been deeply explored when it comes to stećci research is also the use of surface enhancement and visualisation techniques that have become quite prevalent in the study of rock art research and epigraphy in the last decades.

1.1. Earlier research on the digitisation and visualisation of stećci tombstones

Digitisation refers to the process of creating digital representations of physical objects, artefacts, or sites with the use of three-dimensional (3D) scanning technologies. This approach involves capturing the geometric and sometimes textural details of objects in a digital format, allowing for precise and immersive documentation, preservation, and analysis. Several methods are employed in 3D digitisation, including laser scanning, structured light scanning and photogrammetry. These techniques generate high-resolution, spatially accurate 3D models that can be explored and studied virtually. Various rendering methods can then be applied to enhance and visualise surface features, such as inscriptions and carved motives (Guidi and Frischer, 2020).

In recent years, the stećci digitisation efforts have seen a sizable growth. One of the first efforts of 3D capturing was attempted by the Faculty of Electrical Engineering in Sarajevo at the beginning of the 2010s. Researches applied laser scanning (Minolta Vivid 910 with <1 mm level accuracy) and photogrammetry to digitise the famous stećak from Donja Zgosca that allegedly belonged to the Bosnian king Stjepan II, who died in 1353 (Radosević and Rizvić, 2012). In the following years, another campaign digitised all stećci kept at the National Museum of Bosnia and Herzegovina, resulting in a "Digital Catalogue of Stećaks" (http://h.etf.unsa.ba/dig-katalog-stecaka/) (Rizvić and Sadžak, 2010; López-Menchero and Rizvić, 2014; Ramic-Brkic et al., 2019).

One of the largest stećci digitisation efforts was undertaken by the Global Digital Heritage (GDH) in 2019 and 2021. They digitised a total of 46 stećci located in the National Museum of Bosnia and Herzegovina and at other locations near Sarajevo and in eastern BiH. Their choice of photogrammetry as the main digitisation method for stećci is based on its speed, cost-effectiveness and ability to achieve excellent results in both the quality of the geometry and the final textures of 3D models. They used software package Reality Capture for model reconstructions. The downloadable models are published on the Sketchfab repository under a Creative Commons Attribution licence. For most, the original surface geometry was decimated to reduce polygon count for optimal web-display. The surface detail was preserved in the form of normal maps, which means that none of the mesh-based visualisation methods can be applied to them (López-Menchero et al., 2022).

Great efforts have been put into documenting and digitising the srećci cemeteries located around Dubrovnik and at other places on the coast of Dalmatia (Croatia). These models were also produced photogrammetrically and use basic material capture (MetCap) and radiance scaling shaders for virtual surface enhancement (Perkić, 2019; Perkić and Vuković, 2023).

1.2. Goals of the study

As indicated, the previous digitisation efforts of stećci focused primarily on the use of photogrammetry with some limited use of laser scanning. Detailed comparisons between the two methods are lacking. The study by Radosević and Rizvić (2012) has become dated, as new and more capable structure-from-light (SfL) scanners have become readily available in recent years. We tested the two capturing methods to see if we can capture an accurate surface geometry. A topic that has not been

Fig. 1. 3D reconstructions of stećci tombstones belonging to the five typical forms (after Bešlagić, 1971, 1982; Wenzel, 1965): (a, b) plate, (c) pillar (d) chest, (e) pseudo-sarcophagus, (f) cross (models not to scale).

deeply explored in stećci research is the use of surface enhancement and visualisation techniques, which have become quite prevalent in the study of rock art and epigraphy over the last decade (see Carrero-Pazos et al., 2016; Carrero-Pazos et al., 2018; Cassen et al., 2014; Rolland et al., 2021).

The principal objective of the presented research is to investigate the adequacy of digitisation through photogrammetry in generating high-resolution 3D models suitable for visualisations and millimetre-scale measurements. It is established that Structure-from-Motion (SfM)-based close-range photogrammetry yields highly reliable results when applied appropriately (Luhmann et al., 2023, 14–18). Nonetheless, laser scanners are generally regarded as offering the highest level of accuracy and surface quality, and are often used as ground truth for measuring the quality of photogrammetric SfM data (Nocerino et al., 2020). Numerous studies have undertaken comparative analyses of 3D scanning, characterized by Structure-from-Light (SfL) modelling with structured light scanners and image-based SfM modelling techniques (Remondino et al., 2014; Bianconi et al., 2017). Additionally, some studies concurrently employ both techniques (Alshawabkeh et al., 2020). The effectiveness of each approach is contingent upon the specific requirements of the task at hand, with neither method universally prevailing. Single-method applications may prove insufficient for particular applications, as both techniques exhibit inherent strengths and limitations depending on the contextual nuances (Polo et al., 2022). With this in mind, we set out to test both methods using a real-life example. Tombstone No. 4 at Milavići (Fig. 2) was chosen as the test case due to its rich decorations with bas-relief motifs.

Various methods such as tracing, oblique light photography and rubbing or frottage have traditionally been used to document rock art, (Nordbladh, 1981). Although these methods capture the rock art aesthetically, they have inherent shortcomings as they introduce varying degrees of human bias directly into the documentation process, which is often imperceptible to subsequent users. Furthermore, these methods do not reliably capture the depth information of the carvings themselves. The importance of capturing the depth of these features goes beyond preservation, as it also provides opportunities for visualisation, post-processing and research.

Fig. 2. Photogrammetry derived 3D composite render of the Milavići Tombstone No. 4 and the excavated grave below it. The deceased was placed in a grave structure made of stone slabs (the sides of the stone slabs were digitally removed to expose the skeletal remains).

For a better understanding and interpretation of the inscriptions and motives carved in the stećci surfaces, different visualisation methods have to be applied. Researchers of petroglyphs have been trying to find the best way to record and visualise their subjects since the very inception of the discipline. Recently, modern techniques of 3D surface capture have seen a sharper rise as photogrammetry and laser scanning have become more accessible to researchers (Magnani et al., 2020; Matsumoto, 2022).

Several techniques exist for visualising stone carvings using 3D models and we can categorise them in two groups:

- methods that are applied to 3D mesh geometry, generating a 3D visualisation based on various shading techniques designed to enhance surface concavity (Cassen et al., 2014; Pires et al., 2015; Pena-Villasenin et al., 2019; Mark and Billo, 2021; Potter et al., 2023);
- methods in which height information is extracted from the surface of the 3D geometry in the form of a raster digital elevation model (DEM) and is used to apply GIS visualisation techniques (Lymer, 2015; Carrero-Pazos et al., 2016; Torregrosa-Fuentes et al., 2018; Horn et al., 2019).

Below, we present some popular DEM and mesh based visualisation methods that have been used by scholars. We have tested them to see which give the best results for our research on stećci. It should be noted at the outset that this paper does not dismiss other existing methods. We strongly support findings that the combination of results from a number of appropriate methods is necessary for a comprehensive evaluation of a surface (see e.g. Kokalj and Somrak, 2019).

Our criteria for selecting visualisations are based on our research topics:

- visual annotation and interpretation of iconography and inscriptions;
- raster-based machine learning applications, such as automatic segmentation and classification of iconography and automatic recognition and transcription of inscriptions;
- education and popularisation of the stećci cultural heritage.

1.3. *The environmental imprint on stećci*

The environmental factors impacted stećci heavily through time and are in particular notable today. In the 21st century, acid rain and temperature fluctuations have displayed a profound effect on the preservation of these tombstones. The rock from which stećci are made is usually local limestone as there are no other more suitable rock formations (like granit or marble) available in the region. This limestone is very prone to weathering and erosion (Fig. 3); the quality of the iconography and inscriptions on the monuments has significantly degraded. This is exacerbated by the pervasive presence of lichens, moss, and dense vegetation, which, together with forest expansion, have resulted in the complete overgrowth of numerous cemeteries, and subsequent fragmentation of the tombstones. The seeds that start growing from small fissures add to the destruction of a tombstone by growth, which expands the fissures and eventually cracks the tombstone. We often find “an explosion” of small rock fragments where a complete stećak once stood with a large shrub or a tree growing from the middle of it.

A comprehensive and systematic study of the weathering impact on stećci does not exist, thus we cannot estimate the limestone surface degradation rate. The variability in environmental conditions across different geographic locations of gravesites complicates the assessment and emphasises the need for detailed research in this domain. Our preliminary examination shows that tombstones situated in mountainous regions, characterized by pronounced weather fluctuations, exhibit more severe levels of surface degradation compared to those in

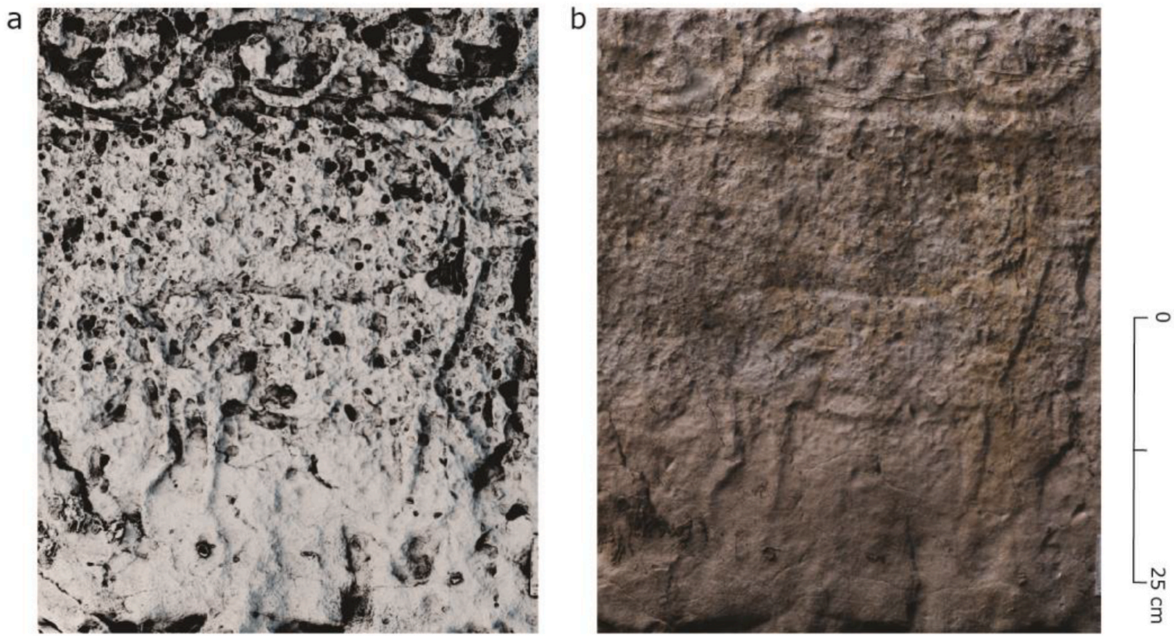

Fig. 3. A segment of the decorated surface of stećak 4 from Milavići. Prior to excavation, the bottom part of the tombstone was submerged underground and smoothed by subsurface chemical weathering while the upper part was exposed to the elements and shows visible pitting. The surface details on the 3D reconstructed model (a) were visualised using ambient occlusion in Blender. The shape and depth of concavities in the stone are less pronounced on a photograph (b).

lowland areas. The lowland stećci also display signs of weathering, possibly because the local limestone is of inferior quality. Addressing this specific concern necessitates a dedicated study, which exceeds the scope of the present paper. The observed variations highlight the complexities inherent in the weathering patterns affecting stećci tombstones and emphasise the importance of site-specific investigations.

Đelmo (2010) estimations of surface degradation are based on contemporary visual inspection of the monuments and the comparison of the visibility of the iconography with that on archival photographs or drawings from older publications. Even with this method he came to the conclusion that all the observed stećci show signs of weathering. The estimates are influenced by the many factors that affect the quality of historical photographs and the inherent subjectivity of illustrations. Old photographs are often of low resolution and not always shot in the best lighting conditions. Similarly, drawings in publications are an interpretation of what the author saw and can be unreliable for accurate comparisons (Fig. 4). However, such a comparison is a promising technique when objectivity is ensured. We believe accurate 3D reconstructions with detailed metadata and paradata, estimated biases, and archived source data will enable such comparisons.

2. Materials and methods

Our study area is eastern Herzegovina, in the modern municipalities of Bileća, Berkovići and Nevesinje. The stećci sites presented in this paper are located in geographically and environmentally diverse places

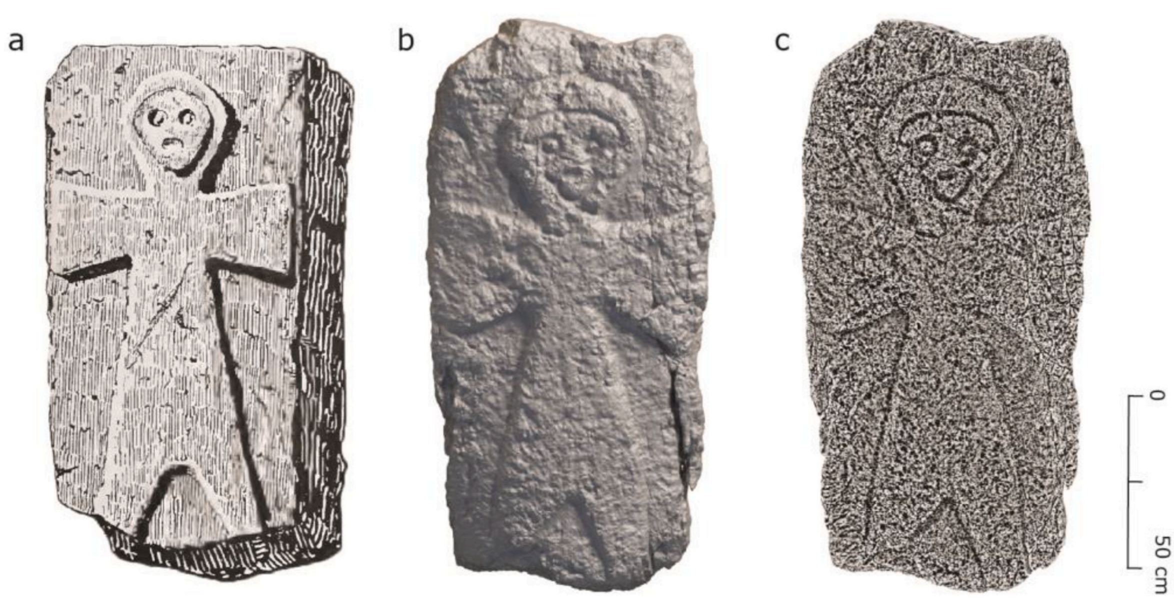

Fig. 4. Stećak 423 from Milavići. Example of a hand drawing (a) from the end of the 19th century (Truhlenka, 1895, 421, Fig. 41), compared to two visualisations derived from a photogrammetric model. (b) Render with side illumination, (c) visualisation based on the Blender Geometry node pointiness value.

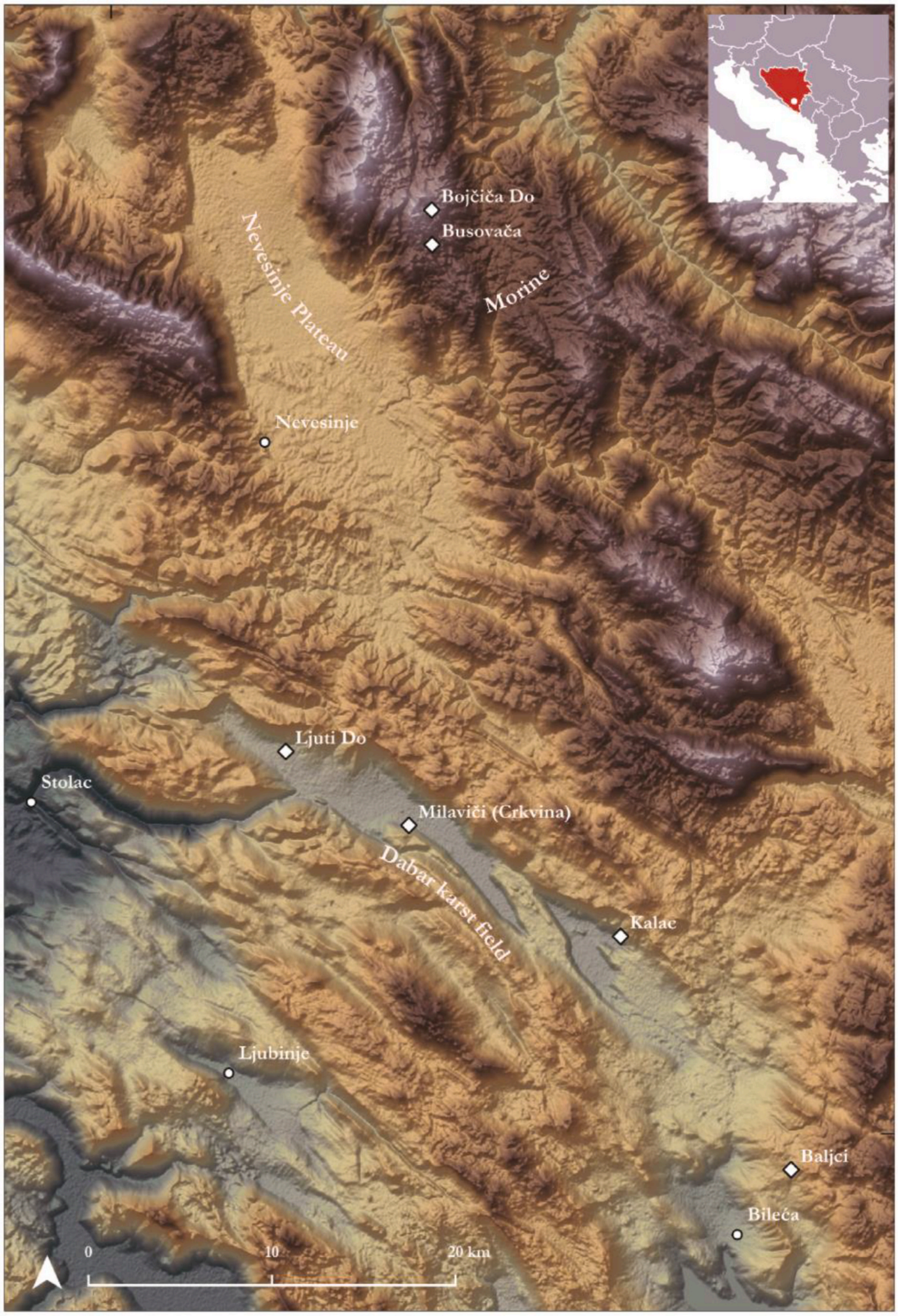

Fig. 5. Map of the sites in southern Bosnia and Herzegovina.

(Fig. 5). Several sites show a pattern of use during the prehistoric eras and subsequently in the Middle Ages, with a notable absence of activity during the intermediate Roman period (Miletić, 1959; Jašarević and Antić, 2017), although this might be due to the level of research.

Our goal was to digitise stećci of diverse sizes and forms and from various types of necropolises. We are primarily interested in the preservation of details in the models and in trying out different visualisation techniques and therefore digitised a selection of stećci that are decorated with typical iconography or bearing inscriptions. Ten are presented in this paper. Due to their sheer number at some sites, we did not attempt to digitise entire cemeteries at this stage as this would require a different workflow and additional resources. The research sites are located in the lowlands of the Dabar basin (Milavići, Ljuti Do) and the highlands of the Morine plateau (Busovača, Bojčiča Do), in the medieval *župas* Dabar, Rudine, and Nevesinje (The term “župa” is of Slavic origin and is in this context understood as an administrative unit of a self-sufficient community). Other sites (Kalac, Baljci) mentioned in the text have not been fully explored and the stećci there were digitised during topographic archaeological surveys. The site maps and descriptions are available as supplementary material.

Milavići is a contemporary communal cemetery in the municipality of Bileća. It was a burial site for a larger community during the medieval period, as evidenced by the preservation of 352 stećci tombstones (Bešlagić, 1971). Tombstone No. 4 (Fig. 6) is located in the southwestern part of the cemetery, its form is that of a chest sitting on a rectangular base (200×120×50 cm). The stećak is decorated on four sides with bas-relief motifs. The southern side is decorated with the “kolo” dance, represented by a row of female figures and one male holding hands. The northern side is decorated with motifs of deer in motion. The eastern side is decorated with a figure riding a horse and carrying a lance or

Fig. 6. Milavići: Stećak No. 4 in-situ.A view of the southern side.

spear. The western side is decorated with a single roe deer.

2.1. *Structured light scanning (SfL) data acquisition and processing*

The structure-from-light data was acquired with the EinScan Pro 2x Plus handheld scanner by Shining3D, which can capture data at various levels of detail. This ranges from a point distance of 3 to 0.25 mm. The Rapid Handheld Scanning option was used, which advertises a speed of 30 frames per second, up to 1,5M points per second, and accuracy of up to 0.05 mm. A consumer gaming laptop with a CUDA-supported graphics card was used to process the data during the scanning phase (12 GB of VRAM).

To see the different levels of surface detail, we scanned the stećak three times at different resolution settings (3 mm, 1 mm and 0.25 mm). The acquisition process requires the use of the proprietary EXScan Pro software package, which enables the acquisition of dense point clouds, the alignment of point clouds, and the reconstruction of the surface mesh. The low-resolution scans (3 and 1 mm) were performed in one session and produced good-quality models. Because the number of points captured per session is limited, the high-resolution scan had to be performed in three batches. This limit is based on the available video memory of the graphics card. The resulting point clouds had to be aligned and merged to obtain a complete reconstruction of the tombstone. We then exported the resulting point clouds and scaled mesh models to original resolution and without post-processing for use in other software packages (.e57 for pointcloud data and.obj for mesh data). The properties of the captured point clouds and reconstructed mesh models are listed below (Table 1).

The captured data shows that by using low and medium scan settings we lose a large amount of surface detail. We also encountered a number of practical problems during the scanning process. The scanner is extremely sensitive to daylight – the manual recommends using it at night for outdoor data acquisition. Even on a cloudy day, we had to set up a temporary tarp cover over the tombstone to scan the entire object. The scanning process itself proved to be laborious, as at least three people – one scan technician and two assistants – were needed to scan the entire tombstone.

Table 1
Properties of the structure-from-light derived models for stećak Milavići No. 4. (in millions).

scanning settings	dense point cloud (M)	mesh face count (M)	mesh vertex count (M)
high quality (0.25 mm)	83	112,5	56,4
medium quality (1 mm)	3	6,6	3,3
low quality (3 mm)	2	3,6	1,8

2.2. *Photogrammetric acquisition (SfM) and processing*

Photogrammetry is a technique that generates precise 3D models from two-dimensional images. The process involves the identification and matching of corresponding points on multiple photographs, from which camera parameters and scene geometry are deduced. This geometric reconstruction is facilitated by algorithms that calculate the spatial relationships between the identified points, generating accurate and detailed three-dimensional models (Luhmann et al., 2023, 10). Key elements include feature extraction, camera calibration, bundle adjustment (BA), and triangulation. Feature extraction identifies distinctive points in images, while camera calibration ensures accurate determination of camera positions and orientations. Bundle adjustment refines the camera parameters to enhance accuracy, and triangulation computes the spatial coordinates of points in the scene. The integration of these techniques enables photogrammetry to produce high-fidelity 3D representations, making it a robust methodology for applications in the cultural heritage sector (Luhmann et al., 2023, 693).

We used an off-the-shelf, mirrorless Fujifilm X-S10 camera with a cropped APS-C CMOS 26 MP sensor with the Fuji XF 18–55 mm f2.8–4.0 R LM OIS and the Viltrox 13 mm f1.4 lenses. All photos were taken in RAW format, with aperture settings between 5.6 and 11, low ISO setting range from 160 to 640 and automatic focus. The shutter speed was kept faster than 1/100s when possible. Because the sides of the monument bearing the inscriptions and iconography are relatively flat, the shallow depth of field was not of great concern. Photographs were taken handheld, or with help of a monopod (see Tables 1 and 2a-b). The camera's in-body image stabilisation (IBIS) was switched off, as previous studies have shown that its use can have a negative impact on image alignment and the accuracy of the reconstruction (Nocerino et al., 2022). The optical image stabilisation (OIS) of the lens was also switched off as the camera setting automatically turn on IBIS if OIS is enabled. Optimal photographic coverage was obtained by systematically photographing

Table 2a
Camera specifications.

Fujifilm X-S10	
Sensor name	Fujifilm X-Trans
Sensor type	APS-C BSI-CMOS
Sensor size	23.5 mm × 15.6 mm
Image resolution	6240x4160
Pixel count	26 MP
Pixel size	3.76 μm
Full frame crop factor	1.5 (18 mm, equivalent to 27 mm on full frame cameras)
Still image file format	14bit RAW

Table 2b
Camera settings for Milavići stećak No. 4 photography.

Number of photos: 504					
Capture date: March 20, 2023					
Focal length	Aperture (f-stop)	ISO	Shutter speed	IBIS	RAW
18 mm	8	200	1/200-320	Off	Yes

the tombstones from multiple angles at distances of approximately 1–2 m. Next, detailed nadir and oblique images of the entire surface were captured. This ensured a good overlap of images for feature registration and alignment. We placed several scale bars coded with markers on the tombstone. Besides the reference stećak, other tombstones were also digitised in this manner (see Table 4).

The original RAW files were exposure corrected in Adobe Lightroom and exported as full-sized JPEG files (at compression level 10). Research has shown that using JPEG images, instead of the RAW or TIFF files, has a negligible impact on reconstruction results (Martínez-Fernández et al., 2022, 22). Lens distortion correction profiles were switched off before export. According to previous research (Apollonio et al., 2021, 30) it is best to let the photogrammetry software apply those corrections in the bundle adjustment phase. We did not perform the camera calibration procedures, rather we used the self-calibration option that Metashape uses to determine both the interior and exterior orientation parameters. Previous research has shown the efficiency of the SfM self-calibration reconstruction process, achieving the same results as those obtained using the geometric camera calibration process (Apollonio et al., 2021, 31).

Photogrammetric image-based reconstruction was performed using the commercial software package Agisoft Metashape (software version 1.7.4) because it offers all the tools needed for an effective digitisation workflow. Images were then loaded into Metashape and processed using the previously well-established workflow procedures and settings seen in Fig. 7. Images were aligned with the highest quality alignment settings to produce a sparse point cloud. Generic preselection setting was turned off, as it allows for more precise image alignment. The sparse point clouds were optimised using the Gradual selection tool. Workflow consists of selecting and removing points based on error thresholds, and optimising the calibration coefficients. The main optimised parameters are Reprojection uncertainty (values below 35), Projection accuracy (values below 2.7) and most importantly Reprojection error (values below 1 but ideally in the 0.5–0.3 range). The optimised sparse point cloud was used for calculation of depth maps and these to generate the 3D models. In accordance with a standard workflow, we opted not to generate a mesh model from a dense point cloud because the used version of Metashape can produce high-fidelity meshed models straight from the depth maps, skipping the dense point cloud generation altogether. This saves a lot of processing time and manual point cloud filtering, as the dense cloud is usually noisy. The models were generated using the High setting and the Face count option set to off, which produce the model at the highest possible resolution. In case this option is switched on the program automatically decimates the model to the set face count limit. Models were scaled using the scale bars placed in the photographs. The same three-point scale bars were used to place the 3D model in a local coordinate system, defining the origin point and the x- and y-axis. Three models were created for every stećak. A high-resolution model for measurements and DEM extraction, a medium-resolution model for use with other software packages and a low-resolution model for web presentation. This was achieved by manually decimating the high-resolution models. Surface textures were generated for all models (Albedo/Diffuse and Normal map). The colour accuracy of the albedo textures was not given great consideration as the tombstones are not painted and are often covered with lichen. Surface height information in the form of a digital elevation model (DEM) as well as an orthomosaic was generated for every plane of interest. This was accomplished using the Planar projection with manually placed markers on the planes of interest. The majority of the visualisations were computed on original high-resolution data, be it in the form of mesh geometry or height data. The basic properties of the generated models can be seen in Table 3.

2.3. Mesh smoothing and surface refinement

Due to weathering, almost all of the digitised tombstones show considerable surface degradation. This often appears as “noise” on the surface of the 3D models and makes the inscriptions and iconography less visible, if not illegible. To enhance the surface geometry of the model, we used noise reduction filters available in MeshLab (TwoStep Smooth, Laplacian Smooth, Taubin Smooth) and Metashape (Refine Model tool). In MeshLab, we gained good results with the sequential use of the TwoStep Smooth and Laplacian Smooth filters, as well as the Taubin Smooth filter. The best parameters for the filters are noted in Table 5.

However, the Refine Model tool in Metashape gave better mesh smoothing and surface enhancement results (Fig. 8). The workflow for this refinement can be seen in Fig. 7. It is based the generated high-resolution model, which is then decimated to a low face count and smoothed with the preserve edge setting checked. We use this model as the basis for the Refine Model tool. The number of refinement iterations can be set depending on the condition of the surface. The range of 10–20 iterations produced the best results for our models. Additional smoothing using the Smooth Model tool can be applied after this step to even further reduce the roughness of the surface geometry. This method proved to be the most reliable in removing surface imperfections caused by weathering and preserving and enhancing other surface features such as inscriptions and iconography. The refined models were only used for visualisation purposes as the act of refinement alters the surface topography, thus making them unreliable for measurements.

3. Comparison of SfM and SfL mesh models

When comparing the two original models of No. 4 stećak from Milavići, we used the structured light scan as ground truth and compared with the photogrammetric model. The first visual inspection of the generated models revealed that only the high-resolution (0.25 mm) SfL scan with over 110 million faces, was comparable to the reconstructed SfM model. The 1 mm scan appears much less sharp and the surface details surface details such as concavities smaller than about 2 mm are lost and edges are visibly smoothed. These problems are exacerbated on the 3 mm scan. Similar workflows have already been applied in various comparable studies. (Polo et al., 2022; Apollonio et al., 2021, 29; Teppati-Losè et al., 2022; Nocerino et al., 2020).

Because both SfM and SfL high-resolution models have a comparable number of polygons, it was impractical to work with the complete models. We aligned the two models, i.e. co-registered them to the same reference system with artificial points that we placed on the stećci before data acquisition. After the initial alignment, we extracted three smaller segments from each of the motif-decorated models. Each segment was then finely registered using the iterative closest point (ICP) algorithm

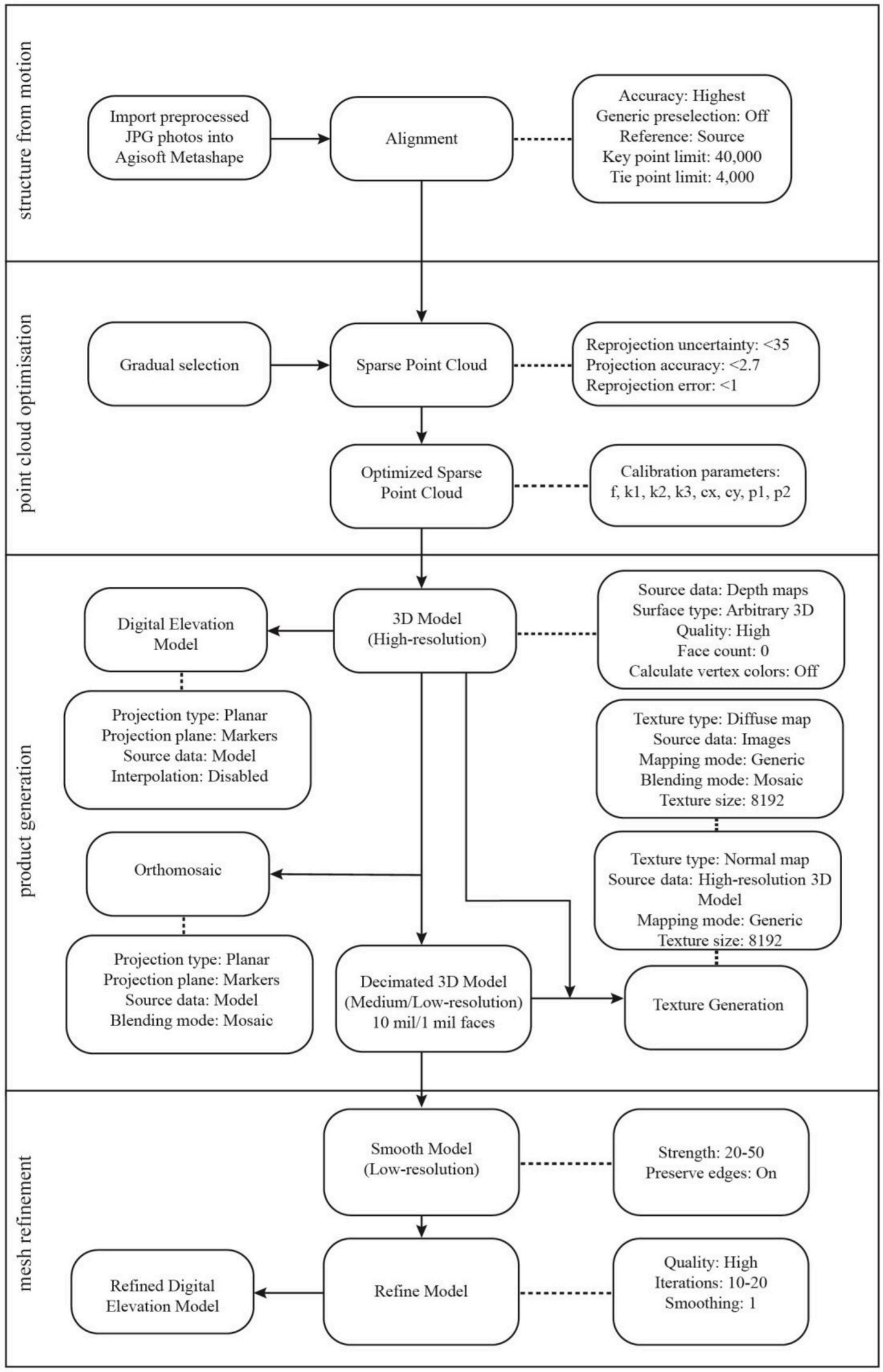

Fig. 7. Agisoft Metashape workflow and settings used.

implemented in CloudCompare. The RMS errors for the alignment of the segmented models are shown in Table 6. All reported errors are minor, well below 0.2 mm in each case.

The precision of the SfM was assessed by measuring distances between sampled points on the vertices, faces, and edges of the SfM and SfL mesh models. We used the Hausdorff distance calculation method implemented in Meshlab. Additionally, we calculated the signed Euclidean distance between the two meshes. The results are similar and we thus only present the results and profiles derived from the Hausdorff distance calculation (Table 6, Figs. 9–12). 99 % of measured distances between the meshes fell well below 0.5 mm, therefore the maximum distance for the calculation was constrained to 1 mm. After considering the constraint, 80 % of the measured distances fall within the range of 0.2 mm. This means we are approaching the limits of accuracy expectations for this method of model comparison, as discrepancies of this scale are likely attributable to alignment and/or scaling errors between the compared meshes.

To gain further insights into surface deviations among the models, we compared surface profiles of a 0.134 mm DEM in QGIS (Figs. 9–11). The focus was primarily on areas featuring motifs, particularly the side adorned with the 'Dancers'. The results indicate that the photogrammetric surface reconstructions closely resemble those obtained from the structured light scan. While minor height deviations are observed, primarily attributed to alignment errors, the photogrammetric mesh

Table 3
Properties of the generated photogrammetric 3D models. The reference stećak in No. 4 from Milavići.

site	stećak No.	stećak code	aligned images	tie points (k)	mesh face count (M)	mesh vertex count (M)	DEM resolution (mm)	Bundle adjustment reprojection error (pix)	residual RMSE (pix)
Milavići	4	MIL_4	504/504	333	148	74	0.13	0.486	0.067
Milavići	56	MIL_56	682/682	99	210	105	0.30	0.602	0.213
Milavići	423	MIL_423	102/102	43	23	11	0.33	0.510	0.181
Milavići	468	MIL_468	345/349	72	52	26	0.47	0.584	0.235
Busovaća	2	BUS_2	192/192	54	41	20	0.36	0.456	0.147
Bojčiča Do	2	BOJ_2	177/177	71	40	20	0.15	0.527	0.230
Kalac	1	KAL_1	105/105	34	40	20	0.16	0.974	0.306
Kalac	2	KAL_2	203/203	36	85	43	0.57	0.486	0.067
Ljuti Do	56	LJD_56	218/218	64	19	9	0.24	0.602	0.213
Baljci	1	BAL_1	153/153	16	43	21	0.16	0.510	0.181

Table 4
Camera exposure settings for all digitised stećci mentioned in this paper.

site	stećak number	photos	focal length (mm)	focal lenght (full frame eqivalent)	aperture	ISO	shutter speed	date (d.m.y)
Milavići	4	504	18	27	8	200	1/200-320	March 20, 2023
Milavići	56	682	18	27	8	200	1/120-180	March 20, 2023
Milavići	423	102	13	20	11	160	1/100	June 20, 2023
Milavići	468	349	13	20	11	160	1/125	June 21, 2023
Busovača	2	192	13	20	11	160	1/180	September 7, 2023
Bojčiča Do	2	177	13	20	8	160	1/400	September 6, 2023
Kalac	1	105	18	27	5.6	400	1/125	March 21, 2023
Kalac	2	203	18	27	5.6	640	1/100	March 21, 2023
Ljuti Do	56	218	13	20	8	160	1/40-320	July 14, 2023
Baljci	1	153	18	27	8	160	1/80	June 24, 2023

Table 5
Parameters of MeshLab smoothing filters.

TwoStep Smooth	Laplacian Smooth	Taubin Smooth
Smoothing steps: 5 Feature Angle Thresholds: 5 Normal Smoothing steps: 7 Vertex Smoothing steps: 10	Smoothing steps: 5-10	Lambda: 1 Mu: 0.6 Smoothing steps: 10

exhibits slightly more noise and faces challenges in accurately reconstructing small concave features. Nevertheless, these discrepancies remain well below the 1 mm threshold, that was chosen on the basis of being able to identify differences in stonecutting techniques and recovering details such as iconography and inscriptions.

4. Results of the visualisations

In this chapter, we present two complementary approaches for surface enhancement of 3D stećci models: mesh-based shading and DEM-based visualisation. The mesh methods, Radiance Scaling in MeshLab, Blenders Ambient Occlusion and Cavity shaders, and the Cycles "Pointiness" geometry node, operate directly on model meshes to remap light intensities, simulate occluded lighting, and exploit vertex curvature for emphasising concavities, convexities, and fine grooves. In contrast, the DEM workflow treats each 3D model as a microscale elevation raster, applying hillshading (single and multidirectional), Simple Local Relief Models (SLRM), and other relief-visualisation filters via our Relief Visualisation Toolbox to isolate micro-relief and accentuate edge detail. Together, these pipelines reveal weathered inscriptions and bas-reliefs: the mesh shaders provide immediate, mesh-native previews, while DEM techniques yield highly automatable, annotation-friendly imagery with robust trend-removal and surface-enhancement capabilities.

4.1. Mesh-based shading visualisations

4.1.1. Radiance Scaling

Implemented in the MeshLab software package, this rendering technique focuses on shape visualisation through shading adjustments, manipulating light intensities around specific features. It stablishes a correlation between shading and surface variations, thus increasing the plasticity of the shape by visually emphasising concavities and convexities (Fig. 13b). This shader has been implemented in particular for enhancing details in carved stones (Vergne et al., 2010) and has been extensively applied in the field of rock art research. This technique has for example been used to interpret Roman inscriptions (Carrero-Pazos and Espinosa-Espinosa, 2018), enhance visibility of bas-relief carvings (Mark and Billo, 2021), and to visualise Pleistocene fossilised tracks (Carvalho et al., 2022).

4.1.2. ambient occlusion

Ambient Occlusion (AO) is a computer graphics technique included in many software packages. It calculates the surface illumination of an object, considering the reduced light brightness caused by the surface occlusion. It has been used by Rolland et al. (2021) to document carved stones. We used the Blender implementation that computes how much of the hemisphere above the shading point is occluded. The effect can be further adjusted using a colour ramp (Fig. 13d). This effect is best used in combination with other visualisation techniques that further enhance the surface concavity.

4.1.3. Blender and Gigamesh visualisations

The open-source 3D modelling software Blender offers also several other visualisation methods (Blender, 2025). Besides the basic MetCap shaders it has many edge- and surface-enhancing features available. One of the simplest and fastest is the Cavity enhancing shader (Fig. 13b), available in the viewport settings. Other techniques require the use of shading nodes, but allow for a myriad of different visualisation options and combinations. The most useful for us was the Geometry Node Pointiness value (Fig. 13e). This visualisation is available with the Cycles rendering engine and returns an approximation of the curvature of

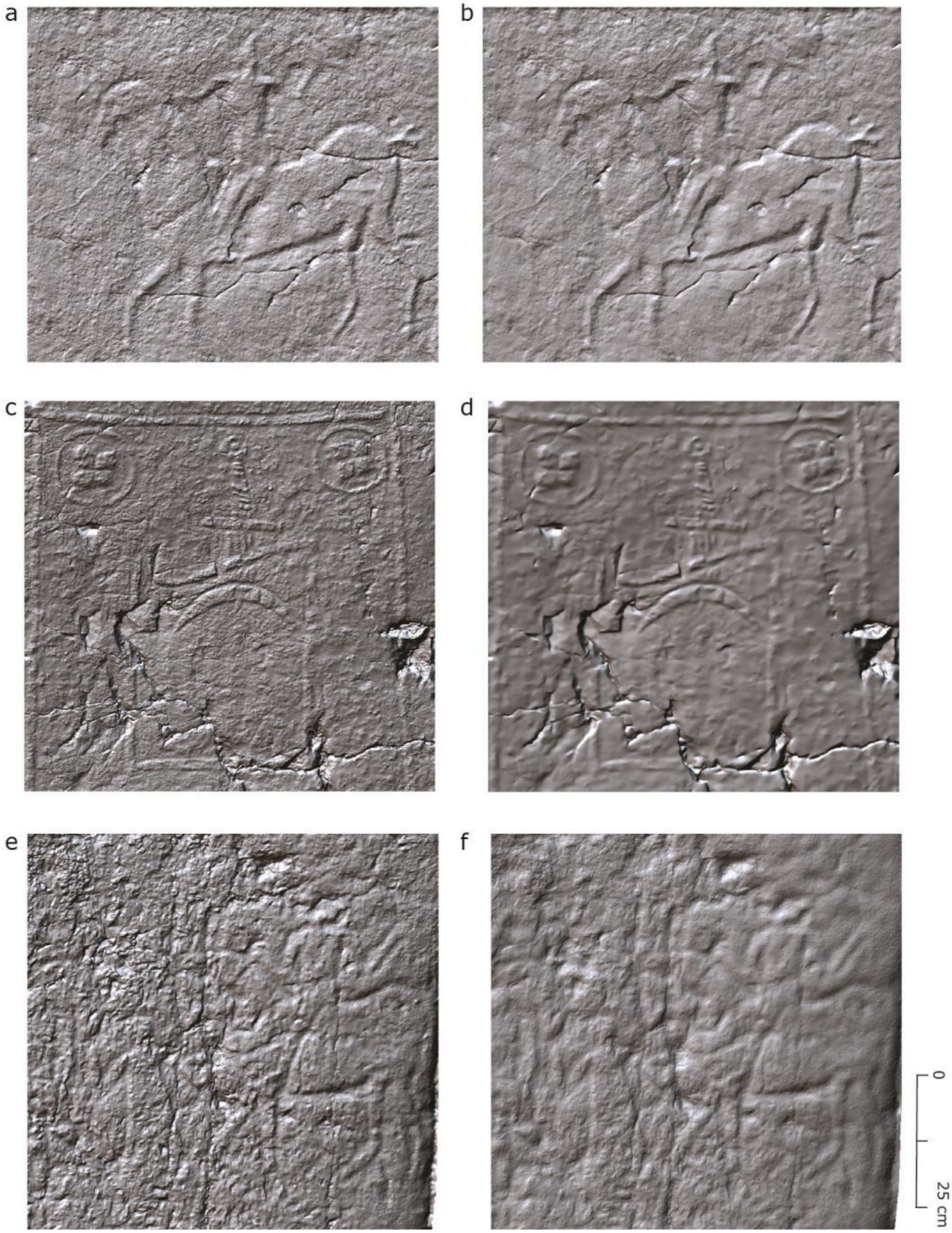

Fig. 8. Comparison between the original (left) and refined models (right). Example of the well preserved stećak No. 56 from Ljuti Do (a, b). Example of a somewhat eroded stećak No. 2 from Busovača (c, d). Example of a heavily eroded stećak No. 1 from Baljci (e, f). MetCap visualisation.

the mesh. Manipulation of this value using the colour ramp function can greatly enhance the surface details. The major downside of this method is that when it comes to larger meshes the calculations are computationally more expensive. The result is also similar to the MSII (Multiscale Integral Invariant) visualisation (Fig. 13f). This method is especially beneficial for the detection of attributes and various visual patterns on flat geometry, where shapes and patterns are carved into the surface (e.g. ancient tombstones, votive stones with inscriptions etc.) (see Mara and Kromker, 2017). The software package GigaMesh (version 5.12.2) was specifically designed for applying MSII visualisations to cultural heritage objects. But is also computationally more demanding than the rest of the mentioned methods.

Table 6
Error values reported during the ICP registration. Hausdorff distance (HD) calculation parameters and absolute reported distances.

Milavići No. 4	ICP RMSE (mm)	HD number of samples (M)	HD Max. distance (mm)	HD Mean distance (mm)	HD RMSE (mm)
n4_Dancers	0.15	6	1	0.11	0.15
n4_Deer	0.11	4	1	0.08	0.11
n4_Rider	0.12	6	1	0.11	0.16

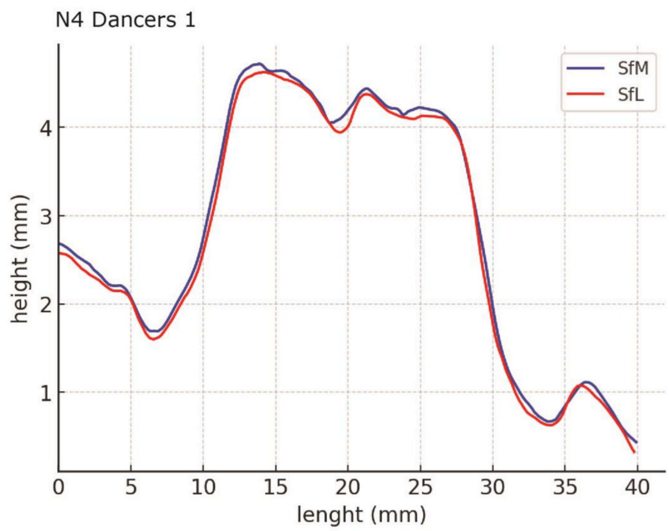

Fig. 9. DEM based cross section of the surface features of the Dancers 1 motif.

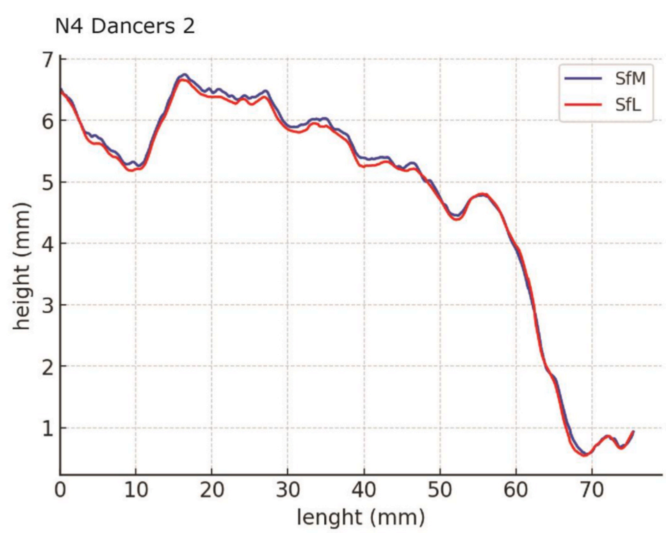

Fig. 10. DEM based cross section of the surface features of the Dancers 2 motif.

4.1.4. Mesh based visualisations results

The methods mentioned above were tested on the photogrammetric and structured light derived models of the stećci. For this purpose, the model geometry had to be considerably reduced in order to be successfully processed by the software packages. This was achieved by decimating the surface of the models as much as possible without losing finer details. This was achieved by careful visual inspection of the original and decimated meshes. This resulted in model with face counts in the range from 1 to 5 million. The visualisation methods applied this way offered good results and were found to offer excellent surface enhancement. The main downside of this approach is the complex workflow that requires the use of multiple software packages and the added processing time that comes with decimating and exporting the 3D models. Generating surface textures of multiple visualisations in different software environments and then combining them all on a single model proved to be challenging. For this reason, we focused on the DEM based workflow as it allows for quicker annotation of the data with comparable visualisation results that can be largely automated and allow us to work with full resolution data.

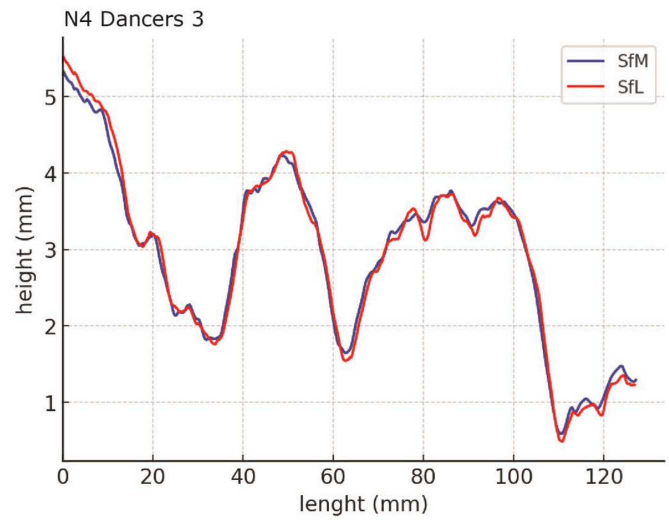

Fig. 11. DEM based cross section of the surface features of the Dancers 3 motif.

4.2. DEM based visualisations

A digital elevation model (DEM) is usually a raster representation of a topographic surface, where values in the raster represent above sea level elevations of bare ground or tops of object on the ground. DEMs are today usually created using data from various remote sensing sources, e. g. satellite imagery and airborne laser scanning. One of the key applications of DEMs is terrain visualisation, where the data is used to generate compelling visual representations of the surface topography. These visualisations include hillshades, slope maps, and contour lines, which help convey the topography, ruggedness, and spatial relationships of the terrain. They are also used in the fields of rock art study and epigraphy. In this case, the surface of an object is treated as a microscale DEM, with visualisations generally used to highlight topographic features in a landscape. By incorporating elevation data into detailed analyses of artefacts and monuments, a better understanding of the relationship between the carvings and the surrounding surface can be achieved. Overall, the use of DEMs in the visualisation of cultural heritage allows us to take advantage of the myriad of advanced GIS analysis tools and applications that are already extensively used at the landscape level.

For the visualisation of the generated stećci DEMs we used our open-source Relief Visualisation Toolbox (RVT), developed to help visualise raster elevation model datasets (Kokalj and Somrak, 2019; Zakšek et al., 2011). The tool was primarily designed for airborne laser scanning datasets but was found to be similarly effective at visualising microscale elevation data. The visualisation methods currently implemented are:

- hillshading,
- hillshading from multiple directions (HSMD),
- PCA of hillshading,
- slope gradient,
- simple local relief model (SLRM),
- sky-view factor,

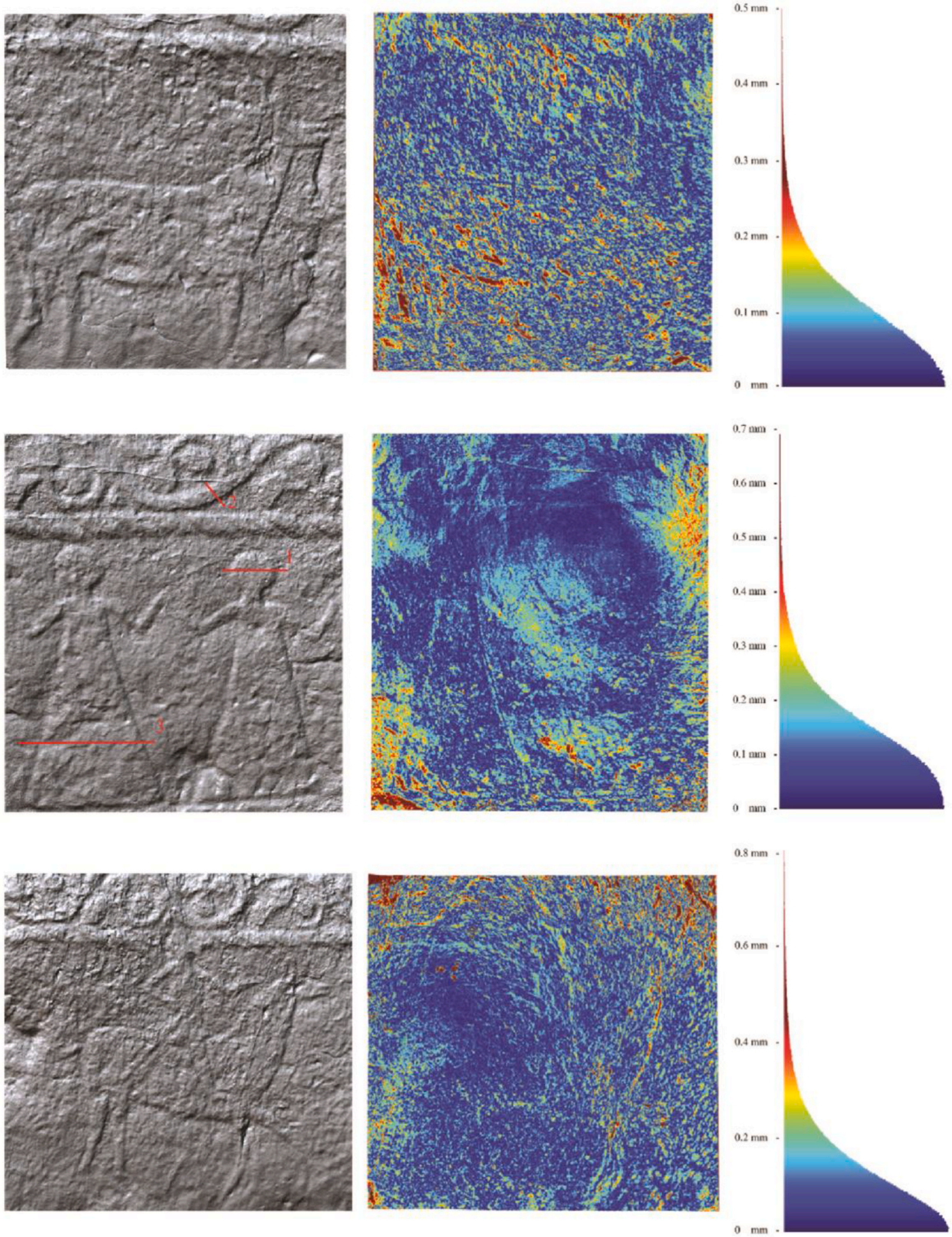

Fig. 12. Histograms of the Hausdorff distance for the three segments (right). MetCap visualisation of the surface mesh (left). N4_Deer (top), N4_Dancers (middle), N4_Rider (bottom).

- anisotropic sky-view factor,
- positive and negative openness,
- sky illumination, and
- local dominance (LD).

Experimenting with all proved that the visualisations that gave the best results in landscapes with flat terrain also performed best when visualising flat carvings and bas-reliefs on the stećci tombstones. However, the two visualisations, HSMD (Fig. 14b) and SLRM (Fig. 14c–d), provided the best results overall. While the local dominance visualisation produces a similar result to SLRM, it requires about 10 times more computational resources. The sky view factor and openness methods did not give satisfactory results.

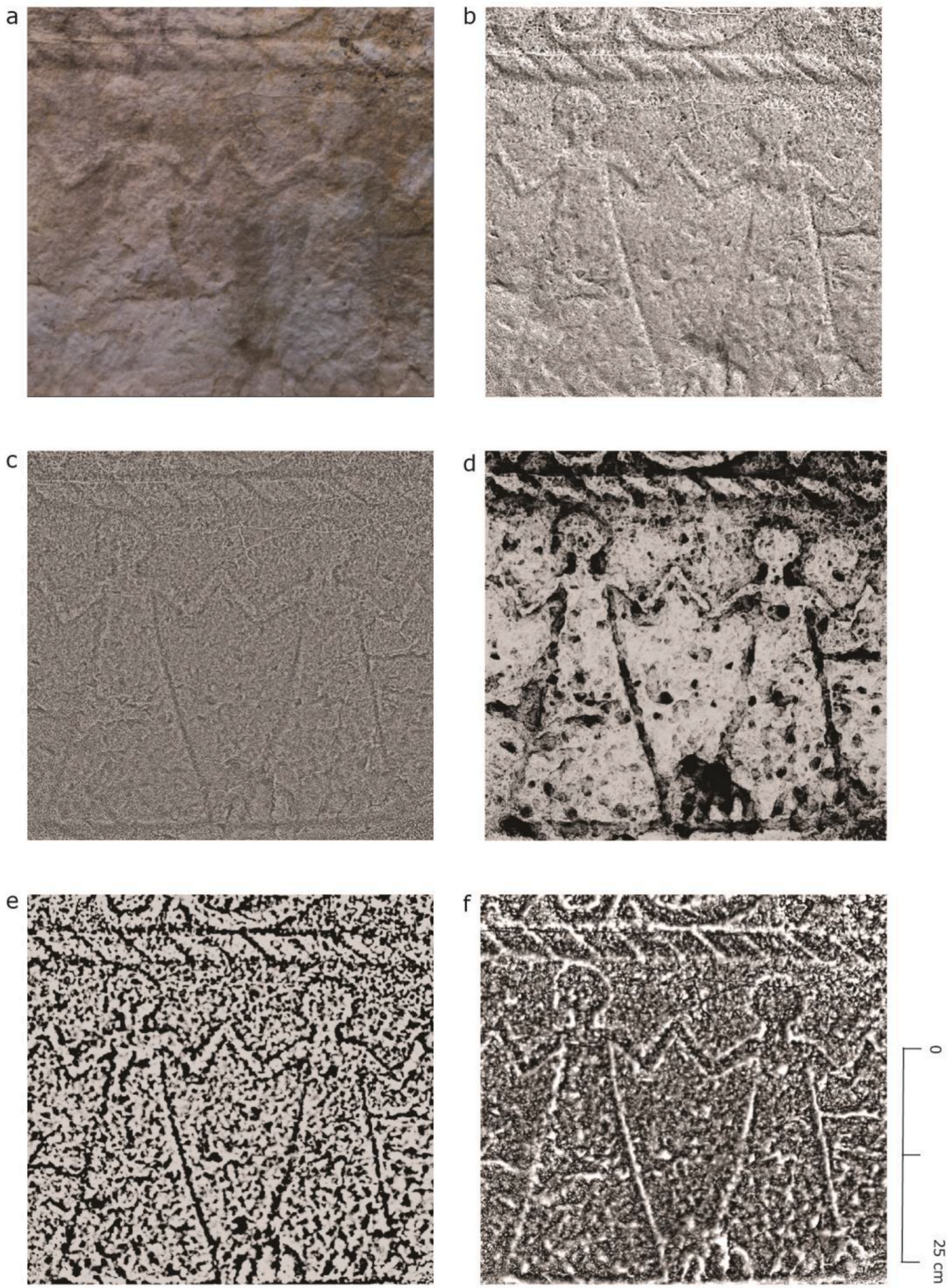

Fig. 13. Mesh-based shading visualisations on a section of the stećak No. 4 from Milavići. a) textured mesh, b) Blender cavity shader, c) Radiance Scaling, d) Ambient Occlusion Node 128 samples, e) Blender pointiness node, f) Gigamesh MSII.

4.2.1. Simple local relief model

The SLRM method (also LRM) was chosen primary because it allows the separation of localised small-scale features from large-scale surface features. This is known also as trend removal. When working with a DEM, the trend (i.e. the larger surface shapes) is represented by a smoothed (generalized) version of that DEM. Smoothing can be achieved by applying a low-pass convolution filter. Trend removal is then performed by subtracting the smoothed DEM from the original DEM.

Fig. 14. An orthophoto (a) and DEM-based visualisations on a section of the stećak No. 4 from Milavići. b) Hillshading from three directions (315°, 22.5°, 90°, H35), c) simple local relief model (R10), d) simple local relief model (R50), e) a combination of simple local relief model (R)10 and hillshading from three directions. f) Manual annotation of a group of dancers.

The resulting difference map contains only the local deviations from the general surface shapes (Kokalj and Hesse, 2017, 20–21).

This method has been already proven to be effective in the visualisation of rock carvings and was successfully used to visualise the surface details of the Fontcalent stone slab from Alicante (Torregrosa-Fuentes et al., 2018), Roman period epigraphic monuments and Iberian rock art carvings (Carrero-Pazos et al., 2016), among others.

4.2.2. *Multidirectional hillshading*

Relief shading, also known as hillshading or shaded relief (MDHS), provides the most “natural”, intuitively readable visual impression and is a standard feature in most GIS software (Kokalj and Hesse, 2017, 16). Unlike traditional hillshading, which considers illumination from a single light source, multidirectional hillshading takes into account illumination from multiple directions. This approach offers a more comprehensive and nuanced representation of terrain features, emphasising subtle details and providing a better understanding of the three-dimensional characteristics of the modelled surface. This representation is similar to the basic shaders we find in most 3D modelling software packages.

4.3. *Combined visualisation workflow*

It has been shown that a combination of several visualisations is required to minimise the loss of information (see e.g. Kokalj and Somrak, 2019). We used SLRM in combination with hillshading from three directions (MDHS – elevation of the light source 35°, azimuths: 315° in the red band, 22.5° in the green band, 90° in the blue band) to create an effect that preserves the volume and detail of the surface, while at the same time emphasises and enhances the edge details of the inscriptions and iconography. This was accomplished by blending the SLRM image with the MDHS image using the multiply function and applying brightness and contrast corrections to the final image. By assigning different colours to different height ranges of the SLRM, the three-dimensional nature of the surface becomes more apparent. This colorization not only helps to create aesthetically pleasing visualisations, but also makes it easier to identify negative and positive features on the surface of the monument.

We computed the visualisations on the original DEMs, the refined DEMs, and the smoothed DEMs. We found that for well-preserved surfaces, the original models were more than sufficient to provide reliable results. For the stećci with eroded surfaces, the high-resolution refined models were the most useable. Multiple SLRM visualisations were generated with a radius of 10–50. The images were rendered with QGIS in either singleband-gray or singleband-pseudocolor with a user-defined colour ramp. The values for contrast enhancement and colour ramp depend on the resolution of the input DEM and must be set manually. These combined visualisations (SLRM + MDHS) were then used to manually annotate the visible inscriptions and motifs (Fig. 14e and 15; more examples are available in the supplementary material section).

5. Conclusion

Stećci represent a unique medieval funerary phenomenon and are a testament to the rich cultural and historical heritage of the Western Balkans. The vast majority of stećci are exposed to weathering and erosion, therefore their digitisation and surface visualisation techniques are necessary for their documentation and preservation. Our research has focused on the use of photogrammetry and structured light scanning techniques. In this study, we have demonstrated that high-resolution

Fig. 15. A section of Stećak No. 1 from Kalac. a) A motif of a male and female figure and an inscription or graffiti in poor condition. A combination of simple local relief model (R10) and hillshading from three directions. b) Manually annotated figures and inscription on an orthophoto background.

structure-from-motion (SfM) photogrammetry can serve as a standalone method for the millimetre-scale digitisation of medieval stećci, yielding mesh discrepancies of less than 0.5 mm when compared to structured-light (SfL) scans. While SfL scanning remains invaluable in lowlight environments or where rapid, single-capture acquisitions are required our results show that SfM produces models of comparable geometric fidelity using only standard photographic equipment and simple scale-bar integration. All quantitative comparisons between SfM and SfL were based on tombstone No. 4 from Milavići, which served as our reference example; the remaining nine digitised tombstones were employed solely for the generation of visualizations.

Post-processing of derived models proved helpful in revealing the surface details of heavily degraded tombstones. This involved a variety of different methods to smooth and refine the mesh to remove surface deformations and make the iconography and inscriptions more visible. The use of surface-enhancing visualisations has proven to be a prerequisite for accurate and reliable interpretation of the iconographic and epigraphic features on heavily weathered stećci. The use of DEM-based visualisations has proven to be the most practical approach. In particular, the use of the Simple Local Relief Model (SLRM) in combination with multidirectional hillshading (HSMD) seems to provide the best results. This method offers all the advantages of the traditional GIS workflow and the resulting raster images (especially the SLRM visualisation) are also ideal for machine learning applications. These visualisations also provide good results with basic automatic mask-based feature vectorisation. Mesh-based visualisations give excellent results, but their creation and management are more complex and computationally demanding than working with DEM raster data.

On the basis of these findings, we recommend that large-scale stećci documentation initiatives prioritize SfM photogrammetry for its operational efficiency, ease of deployment, and scalability across dispersed sites, reserving SfL scanning for specialized cases where its rapid capture or insensitivity to ambient light is indispensable. Future work should focus on expanding our 3D archive of representative tombstones, refining automated iconographic classification algorithms on combined SLRM + HSMD outputs, and adhering to open-data best practices, publishing raw imagery, DEMs, and processing scripts in DOI-linked repositories to foster reproducibility and enable cross-site comparative studies.

CRediT authorship contribution statement

Luka Škerjanec: Writing – original draft, Visualization, Data curation. **Saša Čaval:** Writing – review & editing, Supervision, Project administration. **Žiga Kokalj:** Writing – review & editing, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2026.e00497.

Data availability

The data that support the findings of this study is openly available on the Zenodo repository at https://doi.org/10.5281/zenodo.15872963. Any additional data is available from the corresponding author upon reasonable request.

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