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On introducing an image-based 3D reconstruction method in archaeological excavation practice

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ABSTRACT

Image-based 3D modeling has already proven its value for the recording of excavations, however until now its application has remained rather small-scale. We have examined the possibilities and limitations of image-based 3D modeling in the recording of an entire excavation, and its impact on the workflow of the excavation process and the post-excavation processing. Our results suggest that image-based 3D modeling can be an excellent and suitable method for the recording, documentation and visualization of the excavated archaeological heritage. It offers great possibilities for increasing the quality of the archived archaeological excavation record. The high-resolution geometric information allows a straightforward quantification of the data. However it also brings along new challenges, including a change in the workflow of the excavation and the post-excavation process. Although there are limitations, these are greatly surpassed by the possibilities of the method. We believe that image-based 3D modeling can cause a(n) (r)evolution in archaeological excavation practice.

1. Introduction

An archaeological excavation usually leads to the discovery and understanding of the archaeological remains. In most cases it paradoxically also leads to the very destruction of the context and the integrity of those remains (Lucas, 2001). Because of its destructive character, an excavation therefore requires accurate, high-resolution recording techniques that maximize the *ex-situ* 'preservation' of the cultural heritage. New technologies, along with the flexibility and non-dichotomous thinking they allow, offer new opportunities and challenges for archaeologists and excavation recording practice (Hodder, 1999: 209). Among these technological innovations, the development of three-dimensional (3D) recording techniques is particularly relevant (Remondino and El-Hakim, 2006). This technology can allow proceeding from a two-dimensional (2D) record (e.g. plans, drawings, sections, profiles and photographs) to a 3D record of the archaeological heritage, a 3D structural dataset, enhancing current and future understandings of the site.

During the last decade, the application of 3D recording techniques in archaeology and heritage studies has increased exponentially (Pavlidis et al., 2007). The recent developments in image-based 3D modeling, and the implementation of structure from motion and dense stereo-reconstruction algorithms in low-cost software packages are particularly interesting, offering an accurate, straightforward and affordable alternative to range-based 3D modeling techniques (e.g. De Reu et al., 2013; Koutsoudis et al., 2013; Verhoeven, 2011). Recent research towards the application of image-based 3D modeling for the recording of archaeological landscapes (e.g. Verhoeven, 2011; Verhoeven et al., 2012), excavations (e.g. Barsanti et al., 2012; De Reu et al., 2013; Dellepiane et al., 2013; Doneus et al., 2011; Forte et al., 2012; Hashash et al., 2006; Opitz et al., 2012; Pollefeys et al., 2000, 2003), rock art (e.g. Plets et al., 2012a, 2012b) and monuments (e.g. Koutsoudis et al., 2013) all have illustrated both the value and the potential of this technology for heritage studies and management.

Although image-based 3D modeling has already proven its value for the recording of excavations (e.g. De Reu et al., 2013; Dellepiane et al., 2013; Forte et al., 2012), until now its application has remained rather small-scale. The main reason is the absence of a straightforward methodology that allows a swift use and a full integration in the excavation's workflow. Image-based 3D modeling has been used extensively to record single features or objects, but

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seldom to register the complete excavation process. We have examined the possibilities and limitations of image-based 3D modeling over the complete recording process of an entire excavation (excavation surfaces, stratigraphy, sections, profiles and samples), and its impact on the workflow of the excavation process and the post-excavation processing. The Boudelo-2 excavation, which explored part of a reclaimed medieval wetland (De Smedt et al., 2013), was used as a case study. Due to the variability in archaeological features -both brick and earth structures were present- and the soil characteristics -the site was located within a stratified wetland context-, the Boudelo-2 excavation offered ideal opportunities to test the 3D-workflow.

2. Materials and methods

2.1. Case study: the Boudelo-2 excavation

The study site is located within the boundaries of a Late Glacial palaeolake in the north of Belgium (Fig. 1). The reclaimed wetland was part of the monastic outer court of the former Cistercian abbey of Boudelo, of which the main buildings were located on an adjacent coversand ridge. The abbey was founded in 1197 and expanded during the 12th and 13th centuries when it played a prominent role in the strategies of the Counts of Flanders to reclaim the wastelands for economic purposes. After the abbey's dismantling in 1578, the area was abandoned. The abbey's remains stayed hidden until remnants of the abbey church and the cloister range were discovered during excavations in the 1970's and 1980's (De Belie, 1997).

In 2011, an electromagnetic induction (EMI) survey revealed the previously unknown reclaimed wetland bordering the sandridge which harbored at least two compounds, consisting each of a large brick building situated on raised platforms surrounded by a complex of ditches (De Smedt et al., 2013). Two excavation trenches (Boudelo-1, 2011 and Boudelo-2, 2012) were laid out across the most apparent features detected by the EMI survey, revealing four brick structures and cutting through the detected ditches (Fig. 1).

During the 2011 campaign, a 40 m long soil profile as well as all unearthed brick structures were recorded by means of image-based 3D modeling. The site was part of a series of test cases examining the recording of archaeological features by means of image-based 3D modeling conducted on multiple archaeological excavations in northwestern Belgium (see De Reu et al., 2013). At all sites, the 3D recorded structures were also recorded by means of traditional manual recording techniques (hand drawing of structures on plan and oblique photographing of features with digital camera). At this stage of research, a complete 3D recording of all discovered features had not yet been applied.

Following the promising results of the test case sites, including the Boudelo-1 site, we decided to proceed to a complete 3D recording of the Boudelo-2 excavation. The excavation was done in a rectangular trench of ca. 5 × 60 m large, specifically laid out to make a cross-section of the ditches, platform and buildings discovered by EMI-measurements (Fig. 1). The 3D recordings included all three stratigraphic levels of excavation, all unearthed brick and earth structures in plan as well as in sections, all samples and sampling locations and, finally, two 60 m long soil profiles. This means that everything that would traditionally have been recorded manually was recorded through image-based 3D modeling. Therefore, the workflow of the Boudelo-2 excavation had to be adapted to this alternative recording strategy; only very limited manual recording was undertaken and conducted only as a backup for the image-based 3D modeling recordings.

2.2. 3D recording

To generate a metric 3D model, only a set of high quality photographs documenting the scene and at least three ground control points (GCPs) with known *x*-, *y*- and *z*-coordinates are needed (AgiSoft LLC, 2012a; De Reu et al., 2013). The GCPs are necessary to achieve an absolute 3D georeferencing of the scene. A georeferenced 3D model allows the extraction of accurate metric information, and the computation of orthophotos and digital surface models (DSMs).

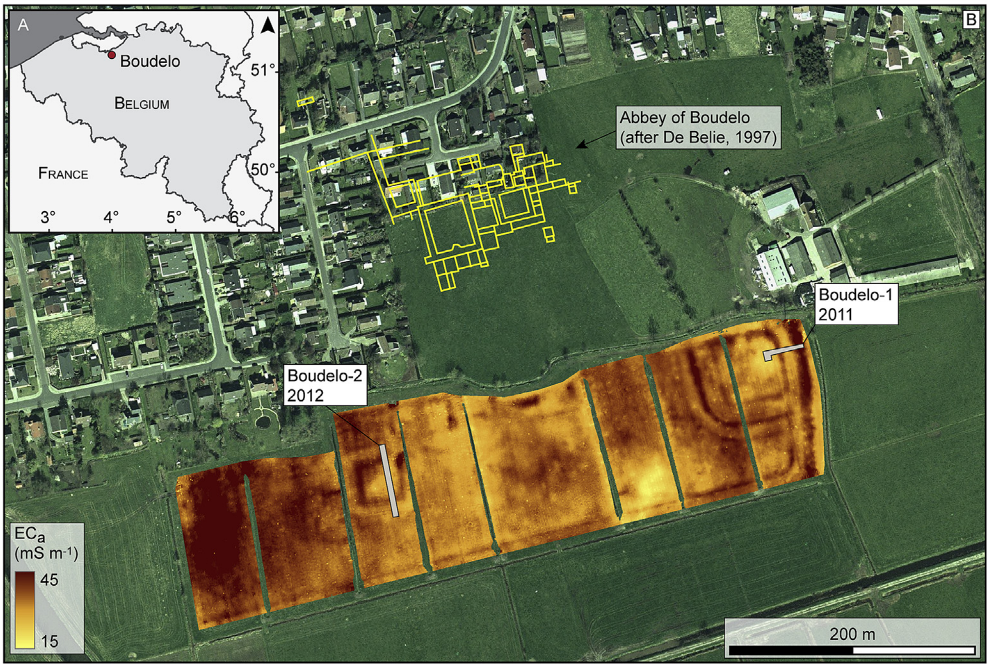

Fig. 1. Location of the study site in Belgium (A). Orthophoto (AGIV, 2003) of the study area with plotted apparent electrical conductivity (ECa) data of the wetland site, gathered through EMI survey, with in the north the layout of the Boudelo Abbey shown (B).

Table 1
Characteristics of the image-based 3D modeling process of the four parts of excavation surface 2 (PC: point cloud; PM: polygonal mesh).

Part	Area (m^2)	*n* photo	Photo/m^2	*n* GCP	Error (m)	RMSE (*x*)	RMSE (*y*)	RMSE (*z*)	PC (points)	PM (faces)
1	86.99	71	0.82	40	0.015	0.007	0.011	0.008	405k	19M
2	36.89	46	1.25	20	0.008	0.004	0.006	0.004	375k	15M
3	78.37	145	1.85	45	0.015	0.006	0.010	0.010	960k	17M
4	88.25	60	0.68	49	0.011	0.005	0.006	0.007	365k	19M
Total	**290.50**	**322**	**1.11**	**154**						

All photographs were taken with a 12.1 megapixel Nikon D700 FX reflex camera equipped with a 24–70 mm f/2.8G ED AF-S NIKKOR objective. The photographs were taken from unique viewpoints with sufficient overlap (i.e. the same point should be visible from at least three different images). To document larger areas, the camera was mounted on a pole, however in most cases the camera was handheld. The ground control points were recorded using a Leica GS14 RTK-GPS with differential corrective.

2.3. 3D model generation

The software PhotoScan (professional edition, version 0.9.0), developed by AgiSoft LCC, was used to generate the 3D models (AgiSoft LLC, 2012b). This software allows the generation of a 3D model in a largely automated three-step process, i.e. (1) image alignment and sparse point cloud generation, (2) dense 3D surface generation and (3) texture mapping, with the possibility to intervene at any stage (De Reu et al., 2013; Verhoeven, 2011). Several

Fig. 2. Excavation surface 2: orthophoto before preprocessing the photographs (A); orthophoto after prepossessing the photographs (B); orthophoto with the (archaeological) features delineated as polygons (C); DSM (D).

researches have described the high accuracy of the 3D models obtained with this software (e.g. De Reu et al., 2013; Doneus et al., 2011; Koutsoudis et al., 2013; Verhoeven et al., 2012), demonstrating its usefulness in the documentation of the destructive process of an archaeological excavation. The success and accuracy of the image-based 3D reconstruction is affected by the feature richness of the recorded surface or object, and thus high accuracy results are not always guaranteed. An excavation, however, is a good example of a feature-rich surface.

All data were processed using a Dell™ Precision™ T7500 with One Intel® Xeon® X5680 (3.33 GHz, 6.4 GT/s, 12 MB, 6C) processor, 24 GB DDR3 1333 MHz ECC-RDIMM (6 × 4 GB) memory, a 64-bit operating system (Windows 7) and a 2 GB GDDR5 ATI FirePro V7800 graphic card.

2.4. GIS integration

To integrate the 3D models of the archaeological excavation with the other excavation data (e.g. context labels, descriptions, interpretations and artifacts) both a 2D (ESRI's ArcMap) and a 3D GIS (ESRI's ArcScene) environment were used. Four different file types were derived from the 3D models and used in post-excavation management and analysis.

The first file type was the traditional 'aerial' or horizontal orthophoto. An orthophoto is a geometrically correct 2D image that has all the geometric characteristics of a map (Petrie, 1977). The orthophotos were derived from the georeferenced 3D model. Orthophotos of the excavation surface were used in the field as excavation plans the day after they were recorded. Orthophotos were also generated for all sections, brick structures and palaeoecological sample locations to link their exact geographic location with the excavation surface.

Secondly, DSMs were extracted from the georeferenced 3D model to study height variations at the site. The 2.5D DSM represents the topography of the uppermost surface of the orthophoto (Newby, 2012). These were used in addition to the orthophotos, providing additional height information during and after the fieldwork for the study of the excavation surfaces and brick structures.

Thirdly, vertical ortho-images were used to study the stratigraphy of profiles, sections and samples. These were created by reprojecting the GCPs along a predefined x-axis. Detailed information on the depth of the features and layers could be extracted from the geometrically correct vertical ortho-image. These 2D ortho-images were derived from the 3D models after reprojection of the GCPs.

The previous files were all produced to be used in a 2D GIS environment. The 3D GIS was used to work with the actual 3D data. Therefore, the 3D models were exported as VRML files and imported as multipatch files in the 3D GIS environment.

3. Results

3.1. The Boudelo-2 excavation in 3D

The recordings made by means of image-based 3D modeling documented the same archaeology (i.e. archaeological levels, sections, samples, profiles etc.) as if it was recorded by means of traditional methods; only the way of recording differed.

Image-based 3D modeling was applied to record all of the three excavation levels. Two surfaces covered the entire 300 m^2 of the trench, while the third level covered only localized deepened parts of the trench associated with the bases of the brick structures. Surface 1 and 2 were both recorded with approximately 300 photographs each and 150 GCPs. Due to weather conditions and the time needed to clean the entire surfaces, both excavation surfaces were recorded in four different phases (Suppl. video 1). Table 1 gives an overview of the recording of surface 2 (Fig. 2).

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jas.2013.08.020.

3D models were processed immediately after the recording. The aim was to use the orthophotos and the DSMs derived from these 3D models as an excavation plan in the field. The automated process allowed overnight data processing, which meant that the orthophoto and DSM were available the next day, ready to be used in the field. Due to long computation times and the large amounts of data, it was only possible to generate low resolution models for next-day use. A rather fast processing of the 3D models was needed to keep up with the pace of the excavation process, and to check the output of the recordings. Also, it was not possible to perform a preprocessing of the photographs, which for excavation surface 2, recorded in four different phases, resulted in the clearly changing weather/light conditions being visible in the textured 3D model (Fig. 2A). After preprocessing the images for the high-resolution models, the color difference and appearance of the different parts of excavation surface were largely removed (Fig. 2B in the Web version). Field recordings, context numbers, descriptions and interpretations were linked as shapefiles to the textured orthophotos (Fig. 2C). The DSM provided detailed height information on the excavation surfaces (Fig. 2D).

During the excavation, three brick structures were revealed and extensively recorded in 3D. Fig. 3 illustrates brick structure 1 as part of excavation surface 3. This feature was recorded with 78 photographs. The point cloud (generated using a high accuracy alignment) contained 400,000 points and the polygonal mesh (with high quality and smooth geometry) contained 5 million faces. The georeferencing of the relative 3D model was performed with 25 GCPs and achieved a total root mean squared error (RMSE) of 0.011 m and 0.006 m, 0.007 m and 0.006 m for the RMSE on the x-, y- and z-coordinates respectively.

Not only was the brick structure extensively recorded, but so was the process of the discovery: i.e. the brick structure in surface, in section, completely unearthed and cleaned (Fig. 4). Brick

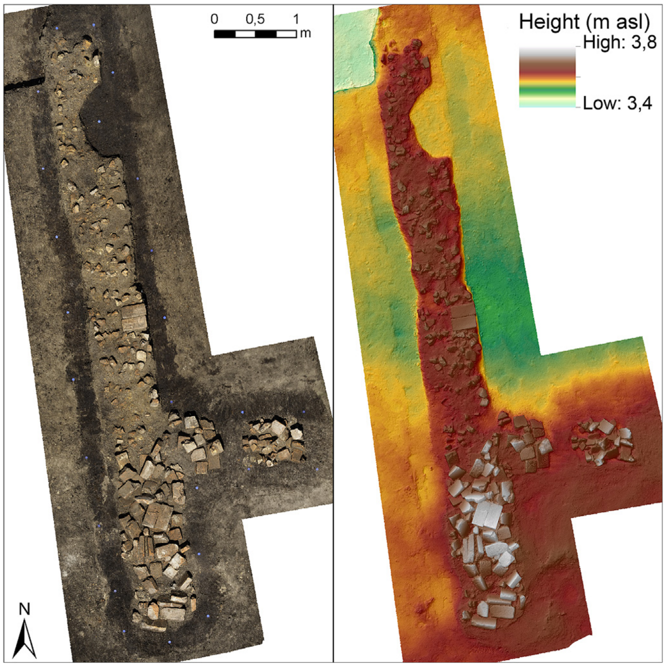

Fig. 3. Orthophoto (left) and DSM (right) of brick structure 1 as a part of excavation surface 3.

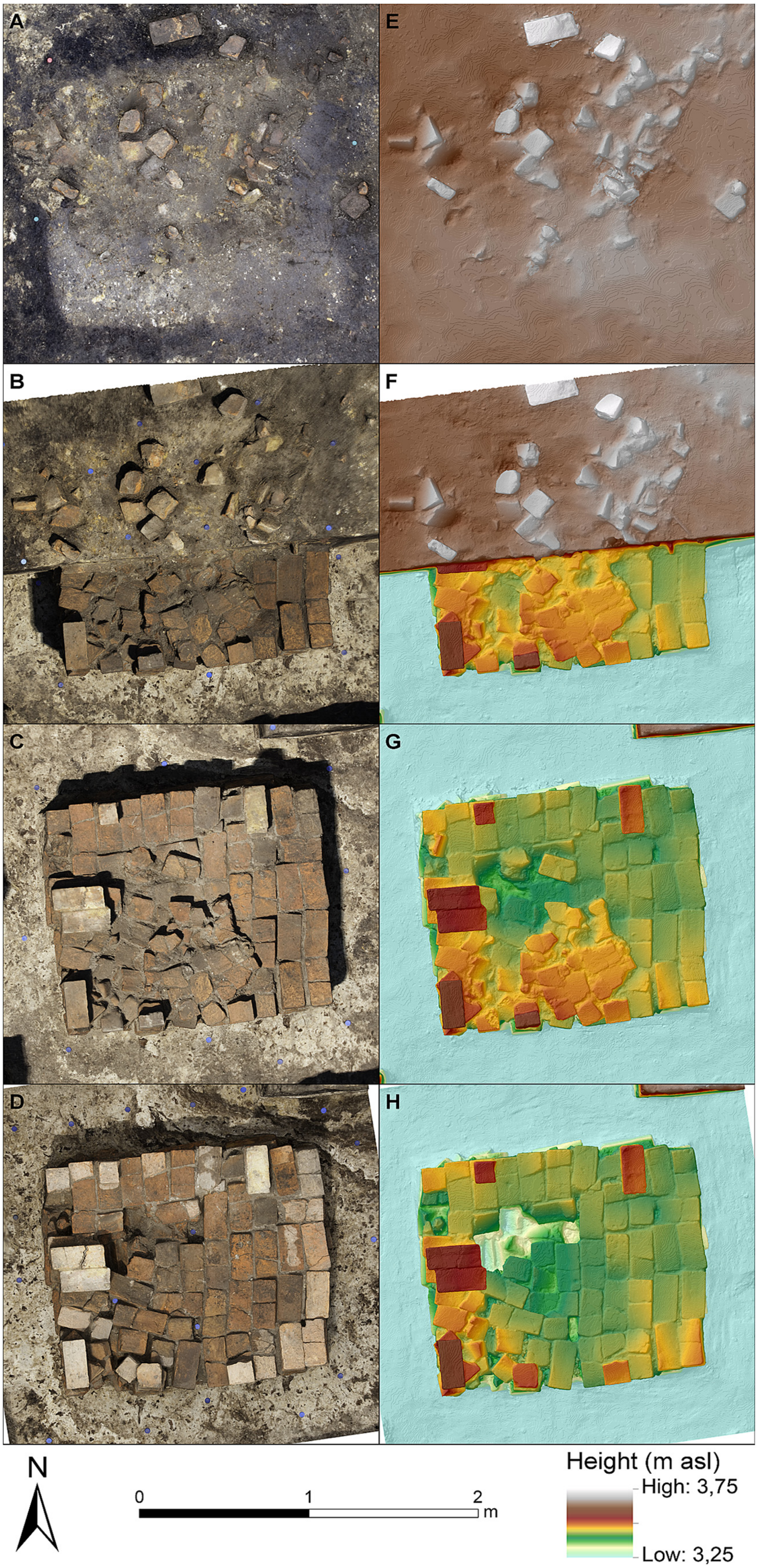

Fig. 4. Four different times of recording of brick structure 2. The excavation process is visualized in the sequence of orthophotos (A–D) and DSMs (E–H). The brick structure is shown in surface (A; E), in section (B; F), unearthed (C, G) and cleaned (D; H).

Table 2
Characteristics of the image-based 3D modeling process of the four recording phases of brick structure 2 (PC: point cloud; PM: polygonal mesh).

Phase	*n* photo	*n* GCP	Error (m)	RMSE (*x*)	RMSE (*y*)	RMSE (*z*)	PC (points)	PM (faces)
Surface	Part of excavation surface 2, part 3 (Table 1)							
Section	57	21	0.012	0.006	0.008	0.006	300k	10M
Unearthed	92	25	0.012	0.005	0.006	0.009	450k	10M
Cleaned	66	24	0.012	0.007	0.006	0.008	385k	10M

structure 2 was recorded at four different times during the excavation process, given in Table 2. The process of unearthing and cleaning the brick structure can be seen in the sequence of orthophotos and DSMs, illustrating the sequence of the excavation process (Fig. 4; Suppl. video 2). A comparison between the DSMs of the different recording phases confirmed the accuracy of the recordings (Fig. 5). Differences of more than 0.01 m between two consecutive models occur almost exclusively in excavated and/or cleaned parts of the structure, while the untouched part was attributed the same height values. To visualize and study the construction of the brick structure four vertical ortho-images were extracted from the 3D model that show the four sides of the brick structure in front-view (Fig. 6). These allow determining the

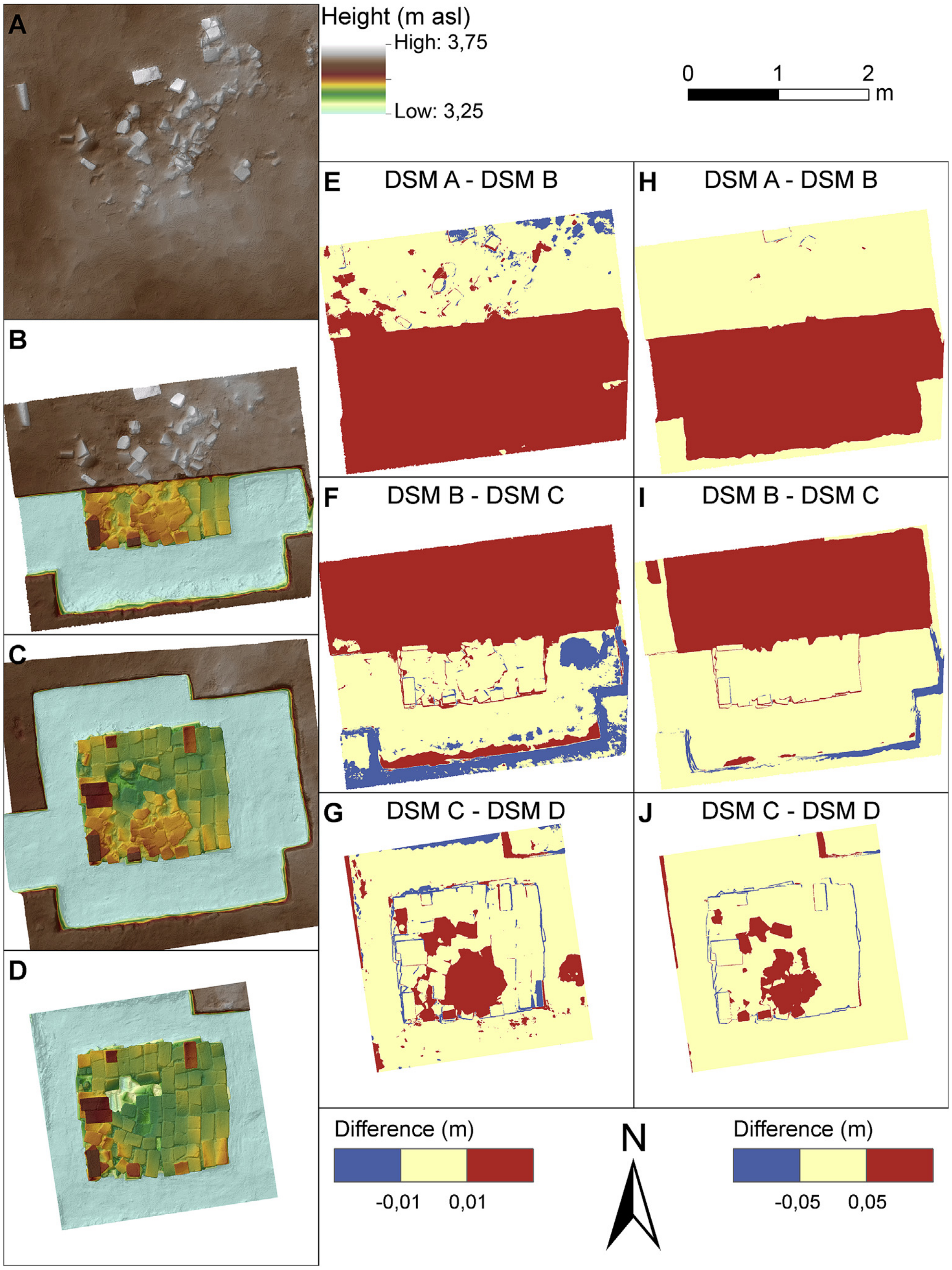

Fig. 5. Analysis of the height differences in the DSMs derived from the 3D models of the recording sequence of brick structure 2. DSM A is compared with B (E; H), B with C (F; I) and C with D (G; J). E–G highlight height differences of ±1 cm; H–J highlight differences of ±5 cm.

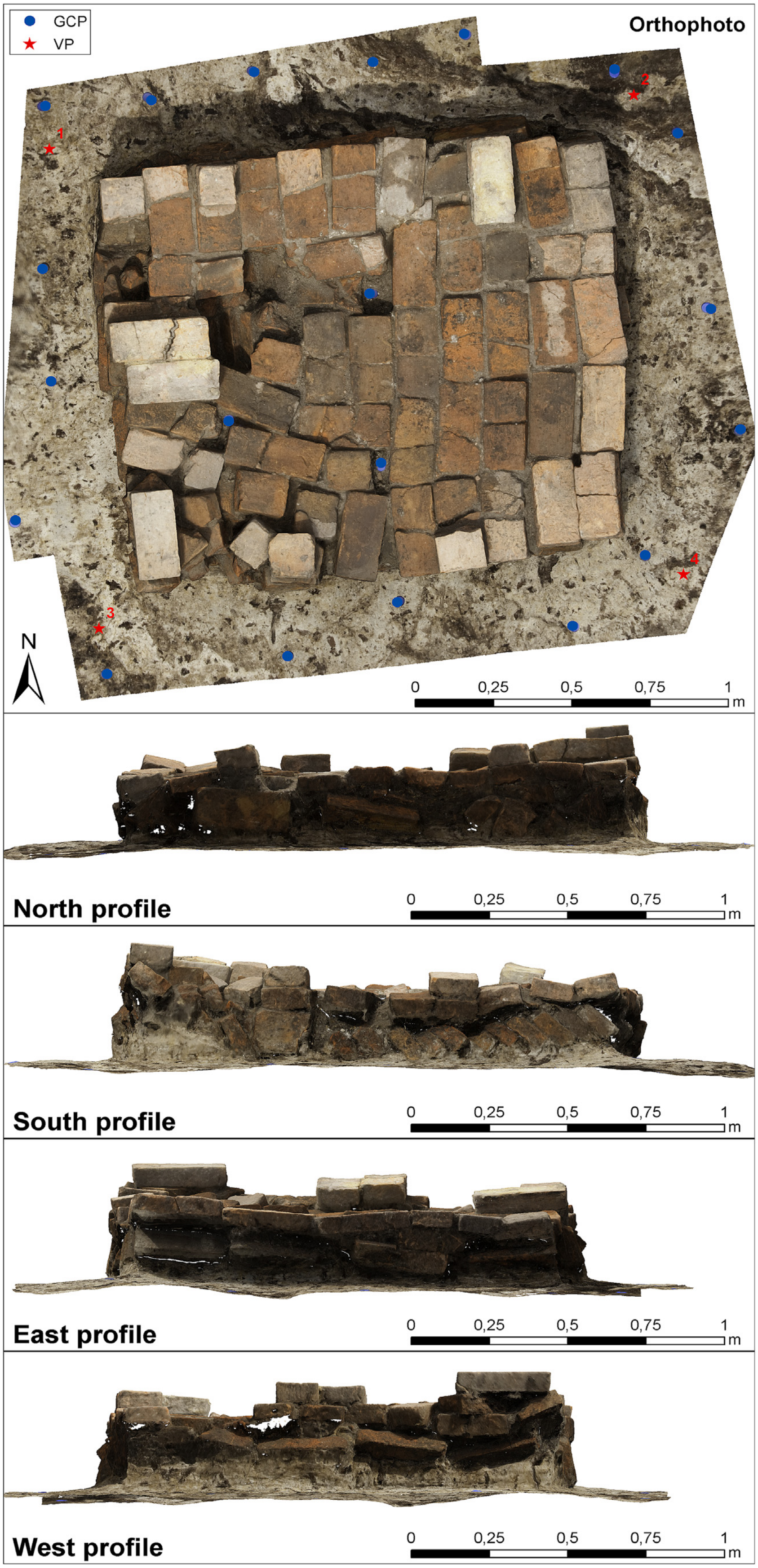

Fig. 6. One horizontal orthophoto and four vertical ortho-images derived from the fourth 3D model of brick structure 2. The vertical ortho-images were calculated along the axes formed between the points 2 and 1 (north), 4 and 2 (east), 3 and 4 (south) and 1 and 3 (west).

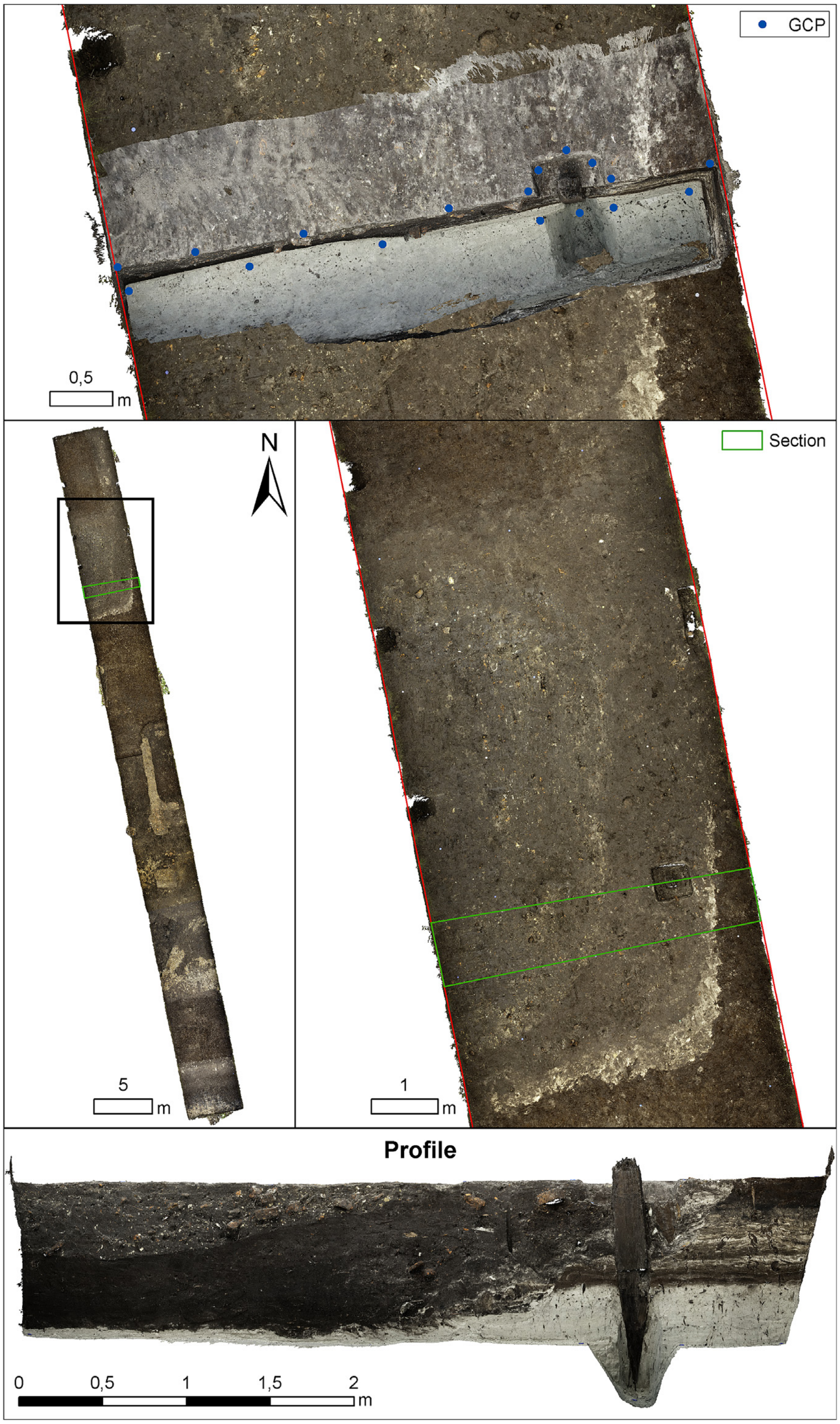

Fig. 7. Orthophoto of Section 1 on top of an orthophoto of excavation surface 2 (top); location of Section 1, visualized as a simple polygon in relation to excavation surface 2 (middle); vertical ortho-image of Section 1 (bottom).

positions of each individual brick and hence the ways in which the buildings were constructed in this wet environment. The 3D excavation data of the brick structures also allowed comparison with the EMI data, where the detailed information about size and depth of the structures could be correlated with the EMI signal (De Smedt et al., 2013).

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Apart from the sections through brick structures, seven sections were made through earthen features, i.e. ditches and pits. Fig. 7 illustrates one of the sections, recorded with 49 photographs, made at the end of one of the ditches near the entrance of the compound (Suppl. video 3). The point cloud (generated using a high accuracy alignment) of this feature contained 345,000 points, and the polygonal mesh (with high quality and sharp geometry) consisted of 6.5 million faces. The georeferencing of the relative model was performed with 17 GCPs and achieved a total RMSE of 0.014 m and RMSE of 0.008 m, 0.008 m and 0.009 m for the *x*-, *y*- and *z*-coordinates respectively. Horizontal orthophotos of sections were produced to link the location of the sections immediately with the excavation surface (Fig. 7). Vertical ortho-images were generated to visualize the section as a geometrically correct profile (Fig. 7). The combination of an orthophoto and a vertical ortho-image provided all the necessary horizontal and vertical geometric information needed for the study and understanding of the sections. Based on the vertical ortho-images, digital drawings of the sections and profiles were made at the office, when the excavations were over, hence saving time and avoiding errors in section drawings derived from manual measurements in the field (Fig. 8). Vertical ortho-images and digital drawings were linked with other field recordings, such as field notes, descriptions of the profile, artifacts and soil characteristics (Suppl. video 4). The combination of detailed and photorealistic textures and appearances with the high accuracy of the recording enabled us to review the profile, to further detail its description of color and texture, and in fact to revisit the site with colleagues in the office.

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The two 60 m long east and west-profiles of the trench (Suppl. video 5) were also recorded with image-based 3D modeling. Both profiles containing natural and anthropogenic layers were documented with 250 photographs and 80 GCPs. Just like the excavation surfaces, the profiles had to be recorded in different phases due to the workflow of the excavation (3 phases for the west profile, 2 phases for the east profile) which was influenced by the weather and the amount of work needed to complete the cleaning of one profile. Vertical ortho-images of the profiles were extracted from the 3D model (Fig. 9). These provide a detailed image of the lithology and sedimentological context of the site, and the anthropogenic features that were found in this environment. Field notes, layer descriptions and interpretation were added to the profiles as shapefiles. Just as for the sections, the detailed texture combined with the high accuracy allows the revisiting of these profiles (e.g. Suppl. video 5). The geometric stratigraphic data that could be derived from the 3D recordings of the profiles were used to calibrate and validate EMI derived landscape models (Fig. 9) (De Smedt et al., 2013).

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Finally, 10 palaeo-ecological samples were taken in sections or profiles and their location was recorded with image-based 3D modeling. Horizontal orthophotos were produced to map their exact geographic location, while vertical ortho-images were generated to document their exact stratigraphic position in the section or profile. The palynologist and macrobotanist used the vertical ortho-image to derive metric information from the profile, and to get an idea of the wider stratigraphical context of the sample. Access to this information can increase the understanding of taphonomy and stratigraphical context of complex samples (Fig. 10).

3.2. *The workflow of the excavation*

The use of image-based 3D modeling as the recording method of the excavation had a certain impact on the workflow of the excavation. The most important consequence was that the excavation plan was not immediately available after the recording. The processing of the photographs to 3D models and the extraction of orthophotos from these models requires a fair amount of time, from a few hours up to a day, depending on the number of images, the scale and the complexity of the scene, the desired accuracy of the alignment and the desired quality of the mesh. In the best case, a (low resolution) excavation plan was available a few hours after recording. However, in most cases the generation of an orthophoto calculated during the evening and night to be available the following day as field-plan, was a more realistic goal. The same was experienced with the profiles and the brick structures. The 3D models of most of the sections and the samples, like all the high resolution models of the excavation surfaces, brick structures and profiles could only be processed after the fieldwork. Due to the limited control on the success of the recording, and the impossibility of repeating any individual recording, significant attention was paid to developing a thought-out photographing strategy during the fieldwork. Labels, notes, descriptions and interpretations had to be stored elsewhere. After encountering this problem during the fieldwork we decided to produce sketches, documenting the archaeological feature, which stored this important information. As soon as the digital data were available, these

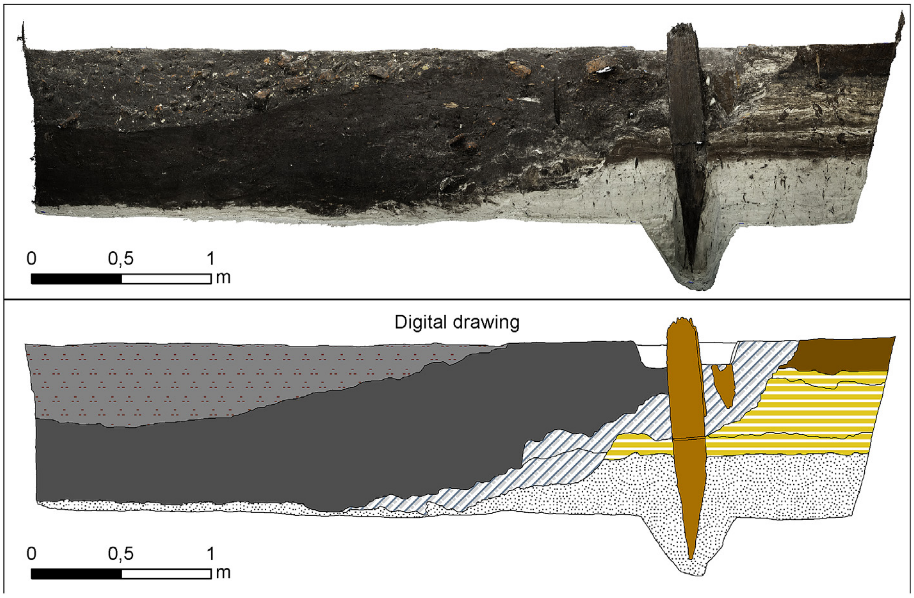

Fig. 8. Textured vertical ortho-image (top) and digital drawing derived from the ortho-image (bottom) of Section 1.

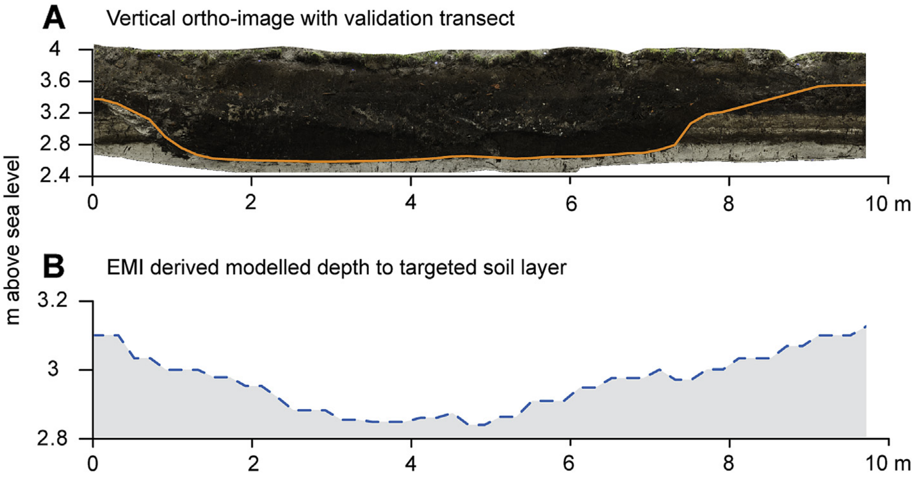

Fig. 9. Vertical ortho-image of a part of the western profile used to validate the EMI derived depth models (A) and the EMI modeled depths along the same transect (B) showing the correlation between both datasets and the accuracy of the EMI depth model (De Smedt et al., 2013).

were linked with the related feature again. Off course, this process can also be fully digitalized in the future, e.g. by using database-forms on Tablet PCs.

3.3. *Data format*

Horizontal orthophotos, vertical ortho-images and DSMs were very suitable to be used in the 2D GIS environment as these contain high resolution excavation data. Textures and appearances of anthropogenic and natural features could be visualized and explored with photorealistic detail. Metric information could be extracted both along the *x*-, *y*- (horizontal orthophoto and DSM) and *z*-axes (vertical ortho-image and DSM). These files were easy to produce, handle and link up with other kinds of excavation data (e.g. context numbers and descriptions) (e.g. Fig. 8). However, a part of the recorded 3D data were not fully exploited as the 3D data are rescaled to 2(.5)D data formats.

Integrating the 3D models in a 3D GIS was expected to be a possible solution for this. It turned out to be impossible to import high resolution models into the GIS-environment, only low resolution models could be handled, which resulted in a serious decimation of the high resolution information that was present in the orthophotos and DSMs. More positively, it provided more spatial information about the site. For example, it provided a more direct link between the excavation surfaces (horizontal data) and the profiles and sections (vertical data). However, these data were not very user-friendly and consequently not used by the excavators in the post-excavation processing of the excavation.

4. Discussion

Our goal was to determine the possibilities and limitations of image-based 3D modeling for the complete recording of archaeological excavations. The results suggest that image-based 3D modeling can be an excellent and suitable method for the recording, documentation and visualization of the excavated archaeological heritage. It offers great possibilities for increasing the quality of the archived archaeological excavation data. However, it also brings along new challenges, including a change in the workflow of the excavation and post-excavation processes.

The most important benefit of adopting image-based 3D modeling is the significant increase in quality of the recording when compared to traditional recording methods. The recording of 3D shape and texture is of great importance for archaeology (see De Reu et al., 2013). Firstly, unlike traditional recording techniques, the 3D shape of archaeological features is fully recorded and appreciated with image-based 3D modeling. Secondly, the accuracy that can be achieved is high and avoids manual drawing errors; it is even higher than essentially needed on archaeological excavations (Doneus et al., 2011). Thirdly, the combination of accuracy, 3D shape and detailed texture, brought together in a far more objective recording of the excavation, makes it possible to virtually revisit the excavation and to walk over the excavation surface or along profiles again. Although the potential of the 3D shape will not be fully exploited, the detailed texture, the accurate metric information and the objectivity of the recording is completely available in the 2D environment. And even when the 3D data are rescaled to 2D orthophotos or 2.5D DSMs, to be used in a 2D GIS environment, the

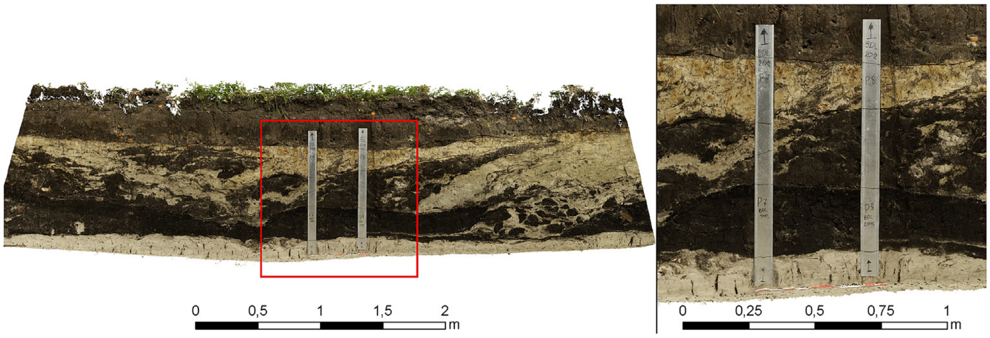

Fig. 10. Vertical ortho-image of a palaeo-ecological sample in one of the profiles (left); detail (right).

scientific value of the data are still significantly higher than achievable through traditional manual recording methods. Other advantages can be found in the time-efficiency of recording during fieldwork and the fact that the excavation is immediately recorded in a digital format (without the need of paperwork). Additionally, the appealing visual and 3D-character of the method provides important educational and visualization possibilities, which can be used to great benefit in raising public awareness of archaeological heritage.

3D excavation data offers without doubt research options that are harder or even impossible to investigate through traditional recording techniques. One of these possibilities is the opportunity to compare and fuse the 3D excavation data with results of the geophysical survey undertaken prior to the excavation. Such comparisons and data integrations are particularly valuable for interpreting, validating and inverting geophysical data. In our case study, data fusion allowed us to accurately reconstruct the entire reclaimed wetland area in 3D (see De Smedt et al., 2013).

Although image-based 3D modeling, just like other applications in digital archaeology, has its problems and limitations (e.g. Zubrow, 2006), these problems and limitations are greatly surpassed by its possibilities and can be overcome by the archaeologist. In the first place, a change in the workflow of the archaeological excavation is required when image-based 3D modeling is applied as the primary recording technique in the field. Unlike traditional manual (drawing and tape measurements) and digital (e.g. total station) recording techniques, the output is not immediately available in the field. In the best case, an orthophoto and DSM, derived from a low-resolution 3D model, is available a few hours after recording. Although in our experience, the orthophoto and DSMs were mostly only available the next day, hence bearing important consequences for the further documentation and the workflow of the excavation. Labels, descriptions and interpretations cannot be added immediately to the recording, but need to be stored elsewhere and linked up with the excavation records later. This is not an ideal situation, but inherent to the recording technique with its indispensable processing times. It is absolutely necessary that a solid solution for this problem is defined before the start of fieldwork. Another consequence of not having the output immediately available is that there is no possibility of instantly checking the recording, but only after a few hours when the excavation has already proceeded further. Therefore, a lot of attention has to be paid to the recording strategy, because it can only be done once, without any direct control of the output. To produce results fast with PhotoScan, the CPU/GPU power and available memory are important, however current average-priced computer systems are unable to deliver the highest possible data quality at the times required in the excavation workflow.

Our case study illustrates that image-based 3D modeling can be used to record all aspects of an excavation, from excavation surfaces over sections to profiles: everything that would be documented with traditional recording techniques can be recorded with image-based 3D modeling. As such, it provides a far more objective documentation of an excavation than an interpretative hand-drawing or some selected oblique photographs. However, a fully objective documentation can never be achieved as decisions and interpretations are still made by the archaeologist. The way of recording is different and provides a more objective recording of the archaeologist's subjective decisions. Furthermore, it is important to record the archaeological feature after it was interpreted. When reviewing (e.g. by scratching it with a trowel) and interpreting an archaeological feature, the recording strategy can be improved.

The amount of digital data collected and generated is enormous, resulting in questions of data storage, accessibility and preservation (e.g. Chen, 2001). Although beyond the scope of this paper, these questions need to be thought of and answered if we want to proceed from a 2D towards a systematic 3D documentation of the archaeological heritage.

Without doubt we believe that the possibilities of image-based 3D modeling for the recording of archaeological excavations far exceed its current limitations. Furthermore, computer technology is advancing *so rapidly that the limitations are becoming mute* (e.g. Zubrow, 2006). With new software developments and increasing computer power, the quality of the output, along with the usability and accessibility of the data will only improve (e.g. 3D GIS). Today the full potential of 3D models is not fully realized, yet when using image-based 3D modeling, the quality of the recorded data already offers possibilities far beyond those of traditional recording techniques.

5. Conclusion

We believe that image-based 3D modeling can cause a(n) (r) evolution in archaeological excavation practice. The scientific value of the generated data qualitatively surpasses that achieved through traditional recording techniques. Furthermore, the high-resolution geometric information allows straightforward quantification of the data. The recording of the excavation can also proceed faster and more efficiently. Currently there is no possibility of immediately checking the output of the recording, and at least a few hours of processing time are required before the data can be evaluated. Consequentially, major attention has to be paid to the quality of the recording strategy, as it can only be done once and without direct feedback. The processing time also prevents storing (context) labels, descriptions and interpretations immediately on the visual excavation records, therefore creating a need for them to be stored elsewhere and linked up afterward. Nevertheless, the possibilities of the method greatly surpass its limitations. Proceeding from a 2D to a 3D recording method of archaeological excavations is of paramount importance for increasing the value of the excavated and digitally preserved heritage. Furthermore, these datasets can act as a robust basis for further integration with other survey and excavation datasets. Finally, we believe that the high quality images and the possibilities for easy manipulation have a large potential for raising public awareness of archaeological heritage.

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