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**DIGITAL PHOTOGRAMMETRY FOR THE DOCUMENTATION OF STRUCTURAL DAMAGE IN
EARTHEN ARCHAEOLOGICAL SITES: THE CASE OF AJINA TEPA, TAJIKISTAN**

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Abstract

Ajina Tapa is one of the most important archeological sites in central Asia and it was fully excavated in the 1960s with modern documentation techniques. The UNESCO/Japan Trust Fund project 'Preservation of the Buddhist Monastery of Ajina Tapa, Tajikistan' started in 2005 and will be completed in 2008. Being scientific documentation one of the project aims, three-dimensional mapping of the walls and geomorphological mapping of the whole site were carried out. Digital stereo-photogrammetric techniques were applied to record the surface morphology of the earthen walls. Presently the walls are heavily eroded, especially if compared to their outline as recorded in the 1960s. In addition, the top part of the damaged wall is rounded, and the basal part shows the typical erosional pattern known as coving. Wind and rain are responsible for the decay of top parts and hence their rounded shape. At the bottom, salt attack causes erosion in combination with abrasion caused by wind and windblown silt. When the wall loses its strength against its own load, the upper and middle part of the wall collapses suddenly. Digital photogrammetric techniques are extremely useful for documenting such phenomenon and the shape of the wall before collapsing. It is ascertained here that such monitoring system supplies basic data to take measures for preventing collapse.

Keywords: Close-range Photogrammetry; Weathering; Erosion; Salt; Loess

1. Introduction

The project 'Preservation of the Buddhist Monastery of Ajina Tapa, Tajikistan (Heritage of the Ancient Silk Roads)' is one of the operational schemes that were recently launched by UNESCO/Japan Trust Fund in central Asia. Other conservation projects include the Silk Road sites of the Chuy Valley in Kyrgyzstan (Krasnaya Rechka, Ak Beshim, Burana), Otrar Tobe (Kazakhstan), and Fayaz Tapa (Uzbekistan). The main objectives of the project are: scientific documentation of the site, setting up of a master plan for the site, application of appropriate conservation and maintenance schemes, promotional activities at both national and international level, training in the maintenance, conservation, and monitoring of the earthen archaeological sites.

The monastery of Ajina Tapa was dated between 7th and 8th centuries AD and it was excavated in the 1960s by Soviet archaeologists led by Boris Anatolevich Litvinskij (Litvinskij and Zejmal, 2004). The site is entirely built of earth, partly of mud brick and partly of *pakhsa* (pisé or rammed earth construction), which is the compaction of earth between restraining surfaces. After the excavation no appropriate preservation work was carried out. As a consequence, the site has been much destroyed by weathering. One of the possible causes of deterioration of the monument is salt crystallization (Kuchitsu et al., 1999, Topal and Sozmen, 2003) that affect the building material (Goudie and Viles, 1997). One of the outcomes of salts attack is coving and this generally occurs at the bottom of walls (Fodde, 2007a). It is inferred here that the upper part of Ajina Tapa's walls tend to fall when support is lost due to coving. However, no previous documentation of such phenomenon was carried out correctly with recent technology.

In this study, documentation with digital photogrammetry (one of the scientific aims of the project) was applied to the decayed earthen monument. Such technique was successfully employed in the field of engineering geology in connection to aerial photographs for example for studying landslides (Mora et al., 2003, Casson et al., 2003, Brückl et al., 2006), failed slopes (Oka, 1998), and ground deformation due to earthquake (Kanibir et al., 2006). Recently, close-range photogrammetry is applied not only to cultural heritage for documentation purposes (Koutsoudis et al., 2007, Yastikli, 2007, Yilmaz et al., 2007, Fujii et al., 2007a), but also to the geological and geotechnical field as a measurement tool (Fujii et al., 2007b, Fujii et al., 2007c). In this study, the process of structural damage of earthen materials will be put in relation to the change of monument shape as recorded by close-range photogrammetry during nine month. This analysis will provide useful information for the conservation and preservation

of the site.

2. Study area

2.1 Geology and geography around the site

Ajina Tapa, located west of the Pamirs at about 100 km south from the capital city Dushanbe (Fig. 1), is positioned at the average elevation of 500 m above sea level. The climate of this area can be considered as continental steppe. Rainfall is concentrated in the winter period and is rare in the summer when solar radiation is intense. The average annual precipitation is about 260 mm/y during 1961-1990 as documented by the world weather information service in the town of Kurgan-Tube (located about 15 km west from Ajina Tapa).

The geology around the site is composed of Cretaceous sedimentary rocks which are covered with Tertiary sediments (Commission for the geological map of the world, 1981). Loess is widely distributed in this area, its origin being the weathering of rocks and sediments. These aeolian (windborne) deposits of loess soil are: predominant in the central asian steppes, typical of areas with little or no vegetation, the particle size is towards the fine end of the soil index, no presence of gravel, and carbonates and salts can be high if compared to other types of soils.

The site is currently surrounded by a wide system of cotton fields. The topographic height of the field is about one metre higher than the floor of the site of Ajina Tapa. There are irrigation canals in the field, and they reach depth of about two metres lower from the cotton field.

2.2 The site of Ajina Tapa

The systematic excavations were undertaken in Ajina Tapa from 1961 to 1975 under the supervision of main experts from the Moscow's Institute of Oriental Studies of the Russian Academy. Much information was produced and stored in the archives and a report was published in Russian and English (Litvinskij and Zejmal, 2004). According to such report, the monastery of AjinaTapa was made of two parts: the monastery area, which is characterized by an open courtyard measuring 19 x 19 m, and the temple area with massive terraced stupa which is a dome-shaped Buddhist shrine in the courtyard. Both mud brick and *pakhsa* (rammed earth) were employed for the construction of the monastery walls. Those materials are made of loess or local earthen materials. In addition, *pakhsa* was found at the lower level, generally 15-20 cm height from the floor (Litvinskij and Zejmal, 2004). At the time of excavation, a 13

metre-long sleeping Buddha was discovered in one of the corridors. The Buddha, made of soil and mud plaster, was cut into pieces and transported to the National Museum of Antiquities of Tajikistan (Dushanbe) where it was conserved and displayed. It is actually considered to be the largest Buddha in central Asia after the destruction of the Bamyian statues in Afghanistan in 2001 (Fodde et al. 2008b).

After the excavation, no protection or preservation work has been carried out for the buildings of the monastery. At present the site is much decayed and the reconstruction of original shape of the walls is rendered difficult.

2.3 Characteristics of mud brick and pakhsa

Both mud brick and *pakhsa* are mainly composed of yellowish silt. The average particle size distribution for mud brick is: clay (14.7 %), silt (64.9 %), sand (19.9 %), and gravel (0.5 %), in contrast for *pakhsa* is: clay (14.2 %), silt (57.3 %), sand (26.1 %), and gravel (2.4 %). Both historical mud brick and *pakhsa* show similar particle size distributions. However, the ratios of silt and sand are a little different. The difference is proportional to physical shrinkage test, which provides clear difference between mud brick (3.1 %) and *pakhsa* (2.4 %) (Fodde et al. 2008a, in print). Other two physical tests were carried out (Fodde et al. 2008a, in print). The erosion test shows slow for mud brick and medium for *pakhsa* compare to other earthen materials in central Asia. The wetting and drying test shows very slight failure for both mud brick and *pakhsa* compare to other central Asian materials. Both mud brick and *pakhsa* contain soluble salts. Average soluble salt contents are 3.7 % for mud brick and 6.6 % for *pakhsa* (Fodde et al. 2008a, in print). Those might be potential origin for salt attack deterioration.

3. Method

3.1 Digital photogrammetry

Three-dimensional mapping of the monastery walls was carried out by means of digital photogrammetry, scientific documentation being one of the project aims. Photogrammetry is the science that measures the objects on photographs (Linder, 2003). Obviously, we can only get two-dimensional co-ordinate from a single photo (two-dimensional plane). If two photos of the same object are taken from different directions, three-dimensional co-ordinates of the object can be calculated. Historically, photogrammetry has been employed to construct topographic maps from stereo-photographic pairs of aerial photographs. This technique can be

applied to close-range mapping with a hand-held camera and lens (Atkinson, 2003). Recently, the power of computers has dramatically risen, and it became possible to directly use digital photos for the work of photogrammetry in aid of computer. Such technique is called digital photogrammetry.

3.2 Digital Terrain Models of the damaged walls

Using a pair of overlapping digital images (Fig. 2), the three-dimensional (3-D) morphology of a wall can be reconstructed. The information of camera positions and directions, in which the pair of stereo-photographs were taken, are needed to get the three-dimensional co-ordinates. However, it is very difficult to get the accurate positions and directions at the same time when taking the photographs. Coordinates of control points which must be included into photogrammetric evaluation were determined by the use of a geodetic Total Station (TS). The camera positions and directions can be inversely calculated from the control points by means of least-square adjustments (Schenk, 1999, Linder, 2003). A 3-D digital photogrammetric software was employed to calculate the camera positions, and to get 3-D information on the surface topography. After the calculation of camera positions and directions, the software can give matching of the same positions on a pair of digital images due to the difference of color and contrast, and generates 3-D coordinates of the points. Those points are connected with lines, and the surface morphology of the wall is constructed as Triangle Irregular Network (TIN; Fig. 3). It is called Digital Terrain Model (DTM; Fig. 4a). The great advantage of digital photogrammetry is to connect the photo images to a DTM. The result is a texture mapping model, which can be viewed from arbitrary directions (Fig. 4b).

3.3 Mapping the site of Ajina Tepa

Close-range photogrammetry has been applied to not only the walls but also the topography of the whole site. Generally, aerial photographs are suitable to make the topographic map of a wide area. However, we had no chance to take high resolution aerial photographs of the site for use of stereo-photogrammetry.

Fig. 5 shows a low resolution map of the site. This is made from three-dimensional records which have been gained from a mobile Global Positioning System. In the temple area, northwestern part of the site, eleven DTMs were constructed from eleven pairs of

stereo-photographs taken on the ground. The highest position of the site is at the top of the stupa, which is positioned in the center of the temple area. Seven DTMs around the stupa (broken lines in Fig. 5) are made from seven pairs of stereo-photographs which have been taken from the top of the stupa. Other four DTMs (solid lines in Fig. 5) including the stupa are made from photographs, taken from the positions around the stupa. Eleven DTMs cover total part of the temple area. In the monastery area, the southeastern part of the site, three DTMs were constructed. Two pairs of stereo-photographs were taken from the top of the stupa, and another pair of photographs from the southeast rim of the site. The top of the stupa was far from the monastery area. In addition, some areas were hidden by walls when the photographs were taken from the stupa. For example, grey areas in Fig. 5 could not be photographed from the top of the stupa. To obtain a total mapping, direct measurements of the hidden areas were carried out with TS. Figure 6 is the final result of the mapping of the whole site. The maximum height difference of the site is about 7 metres between the top of the stupa and the floor of the monastery area.

3.4 Accuracy for the measuring (photogrammetry and Total Station)

In the site of Ajina Tapa, two benchmarks were settled as reference system on both margins of the boundary between stupa and monastery area (Figure 6). Relative positions of those two benchmarks were measured by TS in the accuracy of less than 15 mm. Coordinates of control points, which were included into stereo-photographs, were determined by TS. At the same time of measuring the control points, the benchmarks were also measured by TS. Therefore, the 3-D coordinate of the position of TS could be calculated by triangulation. Two distances from the benchmarks, one horizontal angle between the benchmarks, and two vertical angles to the benchmarks are measured by TS. Therefore, the position of TS can be calculated by means of LSM. The residual from the calculation of LSA by means of TS, which is called as R_{ts} for convenience, was 92 mm for the southwestern side of Wall-A (Figure 2).

The accuracy of photogrammetry must be also considered. Firstly, the resolution of photogrammetry can be calculated as follows,

$$\sigma_{xy}=(H/C)\delta_{CCD} \quad (3.1)$$

$$\sigma_z=(H/B)\delta_{xy} \quad (3.2)$$

σ_{xy} : the resolution parallel to the photo-plane, x is horizontal and y is vertical on the photograph. σ_z : the resolution vertical to the photo-plane. δ_{CCD} : the resolution of CCD. H: the

distance from the cameras to the object. B: the distance between two cameras. C: focal length of the camera (lens). In the case of the southwestern side of Wall-A (Figure 2), H is about 14 m, B is about 4.4 m, C is about 18 mm, and δ_{CCD} is 0.0079 mm. So σ_{xy} is about 6.2 mm, and σ_z is 20 mm. The residual from the calculation of LSA for camera positions and directions, which is called as R_{ph} , was 98 mm, and it is much larger than σ_z . The R_{ph} is almost as same as the R_{ts} .

In the case of the northeastern side of Wall-A, R_{ts} is 38 mm. While, σ_z is 55 mm and it's close to the R_{ph} (70 mm). Therefore, the accuracy for the measuring of historical walls and topographic surface is affected by the largest number among the resolution of photogrammetry, the accuracy of measuring by TS or photogrammetry. As a result of measuring all walls and topographic surface, the accuracy is less than 100 mm for in the site.

3.5 Photogrammetry and other techniques

Laser scanning and TS can be also employed for general topographical surveys. In this study, TS was used for measuring the reference benchmarks and the control points. However, it is difficult to measure thousands of 3-D coordinates for topographic survey by operating total station manually. Laser scanning can automatically correct the 3-D morphology of the surface. Compare to photogrammetry, in which five or more control points are needed for the calculation of camera positions and directions in the site, the positions and directions of laser equipment might be needed for absolute coordinate in the site. In photogrammetry, photo-images can be gained simultaneously. Photo-images can also produce color information of the objects. In addition, stereo-photogrammetry enables us to observe details on stereo-pairs of photographs (Fujii et al., 2007c). This advantage is very useful for engineering geologists to read the deterioration of the objects.

4. Results

4.1 Morphology of damaged walls

Four damaged walls (refer to the frames in Fig. 7) were mapped in 3D with digital photogrammetry. Two pairs of photographs of each wall were taken to make DTMs of both the sides, except for the Wall-A. As to the Wall-A (Fig. 7), which is in reversed L-shape in ground plan, pairs of photographs of the northeast and southeast sides were taken from the northeast and southeast directions respectively, and another pair of photographs of the L-shaped wall

was taken from the southwest direction (Fig. 2). The control points for each pair of stereo-photographs have 3-D coordinate, which were defined by the bench marks . Therefore we could establish the original mutual position of each DTM, and complete sections of each wall could be obtained. Fig. 8 shows a north-south section of the Wall-A (Fig. 7). The massive wall had been constructed with *pakhsa* blocks or mud bricks on *pakhsa* base, and the original shape of the section might be rectangular. The original thickness of the wall was 2.4 metres, which is recorded in Litvinskij and Zejmal' (2004). The original height of the wall is not clear for Wall-A, but the walls of the monastery area had average height of 2.5 metres with maximum of 5 metres (Litvinskij and Zejmal, 2004). Maximum width of the remained wall is about 2 metres (Fig. 9). In fact, the wall is largely eroded as seen in the sections. The current shape of the wall is much different from the original rectangular one due to erosion. First, upper part of the wall was strongly eroded and looks rounded. Both sides (north and south) are eroded deeply. The erosion of the north side is a little bit harder than the south side. Second, basal part was undermined to make shallow coves, and was eroded asymmetrically. Its south side was more deeply eroded than north side of the wall.

Some measured sections of damaged walls are shown in Fig. 9a-d. Fig. 9b shows an east-west section of the Wall-B, which is situated at the southern monastery area and oriented in north-south direction (Fig. 7). Upper part of the wall is eroded, and the top is rounded. Both the sides (east and west) are equally eroded. Maximum width is about 1.5 metres, and it's thinner than the original thickness of 2.4 metres. The basal part is more deeply eroded than the middle part of the wall. Other damaged walls show more or less similar features, indifferent to their positions and orientations. Common characteristics of the erosion are as follows:

1. The walls are largely eroded compare to the original outlines.
2. Top of the walls is eroded and rounded.
3. Basal part is more or less undermined and thinner than middle part of the walls.

4.2 Process of erosion seen in the Wall-A

Rapid erosion can be seen at the south-eastern end of the Wall-A (in circle of Fig. 7). The basal part was severely eroded in August, 2006 (broken lines in Fig. 10). The height of the wall was then about 4 m, but the basal part of 0.5 - 0.8 m from the ground surface was deeply undermined. The maximum depth of the erosion is about 0.6 m. It looks like a notch. About

nine months after, top and middle part of the wall had been collapsed, and the surface of the wall became simple plane in May, 2007 (solid lines in Fig. 10). The volume of the collapsed part is about 1.6 m³, which is calculated from a series of eroded thickness measured at 0.1 m intervals of the height. Reference horizontal sections are shown in Fig. 11b, though the intervals of the height are 0.3 m. The sections of both 2006 and 2007 are made from DTMs which are calculated from the same 10 control points (Fig. 10a left). Therefore, both the sections are almost duplicated except for the collapsed or eroded parts (Fig. 10b). These data obtained by digital photogrammetry provide the quantitative basis to evaluate the advancing erosion process of the wall. We could successfully disclose the damage of the wall in the site of Ajina Tepa.

5. Discussion

5.1 Erosion by rain and wind

Before the former excavations, the site was totally covered with sediments and formed as topographic mound (Litvinskij and Zejmal, 2004). After the excavations, appropriate preservation or protection work has not been done for the buildings in the site of Ajina Tepa. Therefore, the building walls have been exposed since 1975. The erosion test shows slow for mud brick and medium for *pakhsa* compare to the other earthen materials in central Asia. In contrast, the wetting and drying test shows very slight failure for both historical materials. Therefore, rain and wind might have been main erosive causes to the top of the walls for about 30 years. Winter is the rainy season in the area of Ajina Tepa, so the walls are progressively eroded by rain water in such season. The building wall was lost by the erosion, resulting to rounding of the top of the buildings (Fig. 11-1a).

5.2 Decay mechanism at the basal part of the wall (salt attack)

In central Asia and thereabout, salt crystallization or salt attack is an important erosion agent that causes the decay of the basal part of walls in earthen archeological sites. Average soluble salt content of historic earthen material was calculated in three central Asian sites: 4.7% in Ajina Tepa, Tajikstan (Fodde, 2008), 3.8% in Krasnaya Rechka, Kyrgyzstan (Fodde, 2007c), 5.6% in Otrar Tobe, Kazakhstan (Fodde, 2007b and 2008). In the site of Ajina Tepa, salt is actually crystallized on the excavated surfaces of the walls (Fig. 12). It was analyzed by XRD, and

halite, calcite and gypsum are the major salt minerals crystallized on the walls. Mud brick and *pakhsa* contain soluble salt, so these salts might be transformed by groundwater. Vertical profiles of evaporation rate were measured on the surface of the walls (Watanabe et al., 2008), demonstrating that the rate is maximum at the ground, and gradually decreases with the height. It indicates that the moisture is essentially supplied from the groundwater. On the height of 1 metre from the ground, the evaporation rate is small enough compared to the ground. The erosion of the basal part for each wall has less than 1 metre height. Therefore, it is clear that soluble salts were transported to the surface with capillary groundwater, and crystallized on the basal part of the walls accompanying by evaporation of groundwater as moisture. The current floor of the site is lower than the around topographic field and close to the groundwater table. Therefore it's easy for groundwater to evaporate on the floor in the site. The salts cause damage on the wall (Goudie and Viles, 1977), and combination of the wind and windblown silt strengthen the power of erosion. With the repetitions of the above process, the basal part became thinner and thinner than the middle part of the walls (Fig. 11-1b).

It should be also noticed that the upper parts of walls, having lower salt content, are characterised by the phenomenon known as 'petrification', consisting in the natural creation of a protective hard crust of clay. This can be directly inspected in several earthen structures in Central Asia, but a scientific study of the phenomenon is still at an early stage. In addition, long term monitoring is needed for the evaluation of accurate rate of decay by salt attack.

5.3 Collapse of the wall

Due to the thinning of the basal part by salt attack, the upper wall lost support from the lower basal part. Eventually, protruded part of the wall was collapsed (Fig. 11-2). The collapse can be caused by structural weakness especially in rainy winter season, because earthen materials contain more moisture and have less strength. However earthquake or other exterior efficiency might affect the sudden failure of the wall. The thickness of the wall becomes thinner and the surface is planar after the collapse, but the erosion by soluble salt attack, rain, and wind continues to decay the wall (Fig. 11).

5.4 Conservation works

Conservation works have been done by this project (Fodde et al. 2008a, in print). Some unstable walls had been already supported by buttresses made of new mud brick and plaster (Fig. 13). The design of the wall is not vertical and the bottom is thicker than the top. This is to

prevent not only the failure or collapse of the walls, but also the decay by salt weathering. The conservation work will continue and drainage system be constructed until the end of 2008. It will be essential for the flow of surface rain. Topographic map (Figure 7) is applied to design and construction for their conservation works.

6. Summary and Conclusion

A scientific documentation of the archeological site of Ajina Tapa constitutes one of the central elements of the UNESCO/JAPAN Trust Fund preservation project. Three dimensional mapping of the Buddhist Monastery of Ajina Tapa was done as part of the project. Four unstable walls were also mapped by digital stereo-photogrammetry. They were already more or less damaged by erosion and collapse. Salt attack caused the erosion of the basal part of the walls, resulting in thinning of the walls. The upper and middle parts collapsed in losing the support from the underlying basal part. It would be interesting to clarify the speed of erosion in the site. However, more consideration or future monitoring will be needed. It's difficult to identify when the collapse rose for each wall during last 30 years. For example, the Wall-D is much thinner than original one, which had 2.4 metres thick refer to Litvinskij and Zejmal (2004). Both sides might be collapsed before 2005. Consequently, there are sediments from the collapse on both sides of the Wall-D (Fig. 9d). It implies that the speed of erosion is not equal in the site. It is suggested that erosion be studied intentionally to find an effective method to preserve the site.

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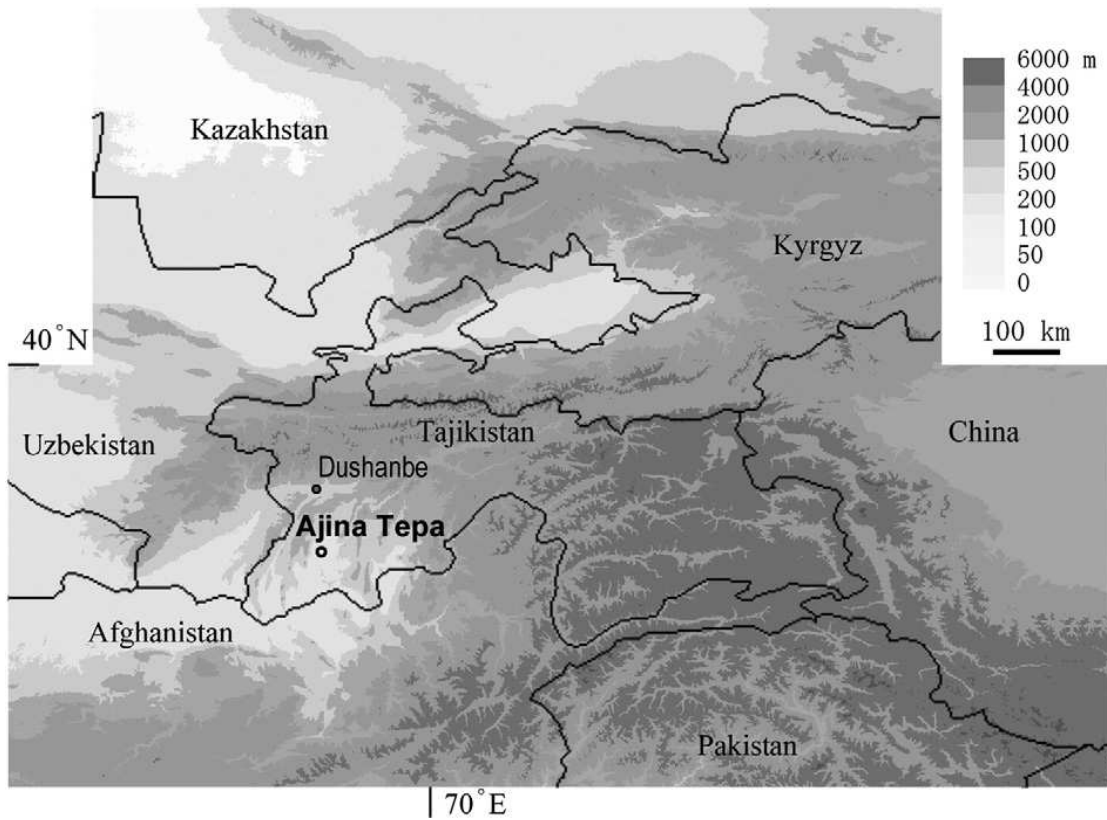


Fig. 1. Index map of Ajina Tepa (basal map is from Global Map, <http://www.iscgm.org/>).



Fig. 2. A pair of stereo-photographs of a damaged wall (Wall A in Fig. 8). White circles on the left photograph show control points.

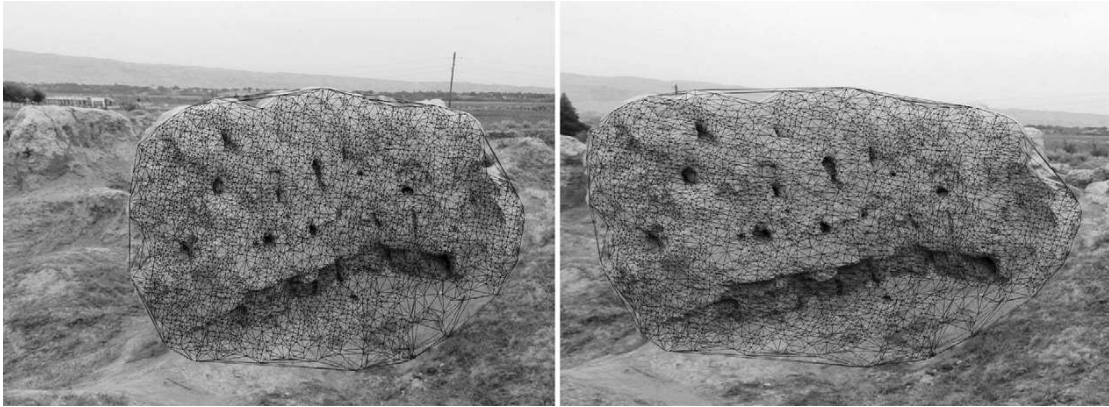


Fig. 3. Triangle Irregular Network (TIN) on a stereo-pair of photographs (Fig. 2).

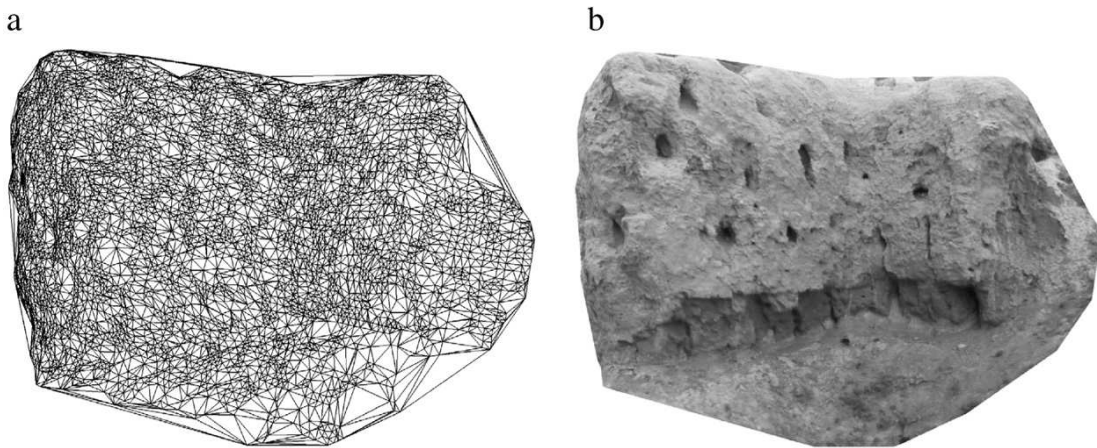


Fig. 4. Digital Terrain Model (DTM) of the damaged wall (Figs. 2 and 3). a: DTM constructed by means of TIN. b: Texture mapping model. Photo images are put on the DTM.

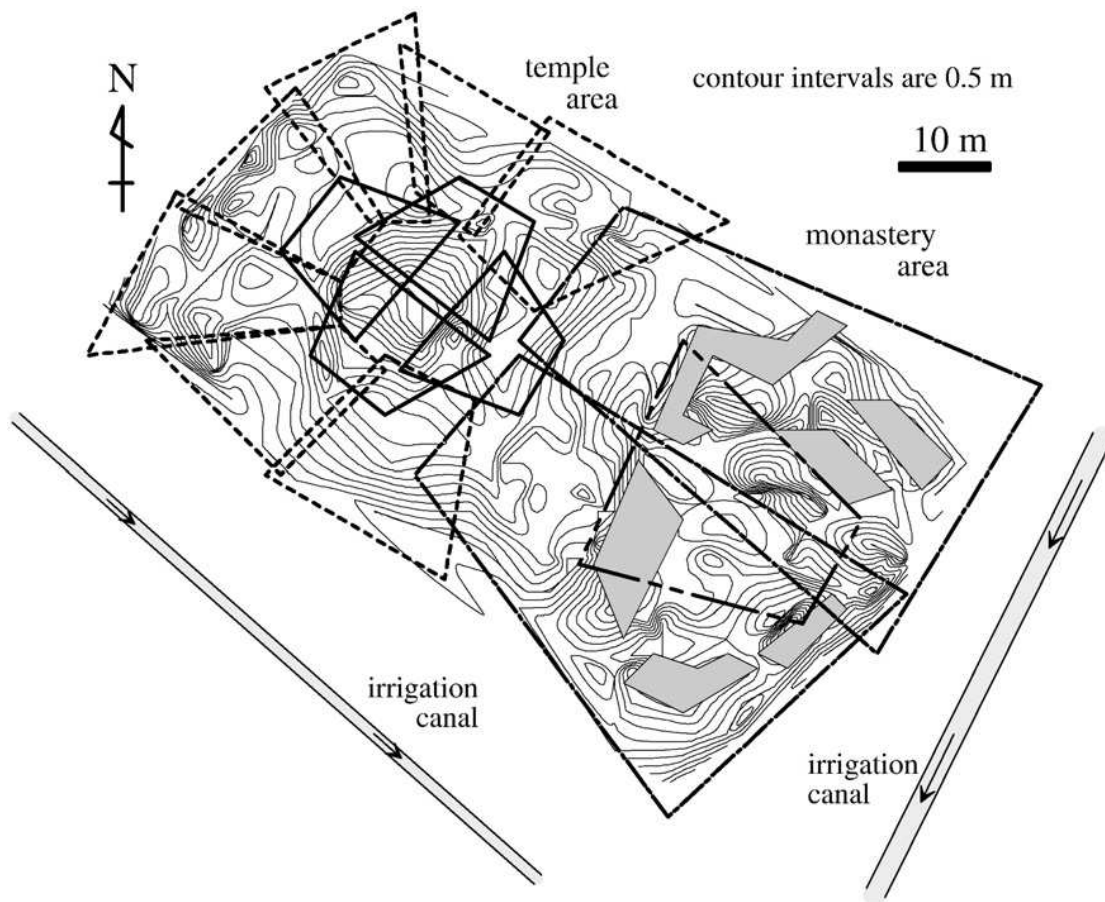


Fig. 5. Parts for taking pairs of photographs for high resolution mapping on low resolution map of the site. Solid and broken polygons (trapezoid) show the positions of 13 pairs of stereo-photographs. Each pair of photographs was taken from the shortest side of each trapezoid. Two pairs of stereo-photographs in the monastery area were taken from the top of the stupa, and some grey areas were hidden by walls.

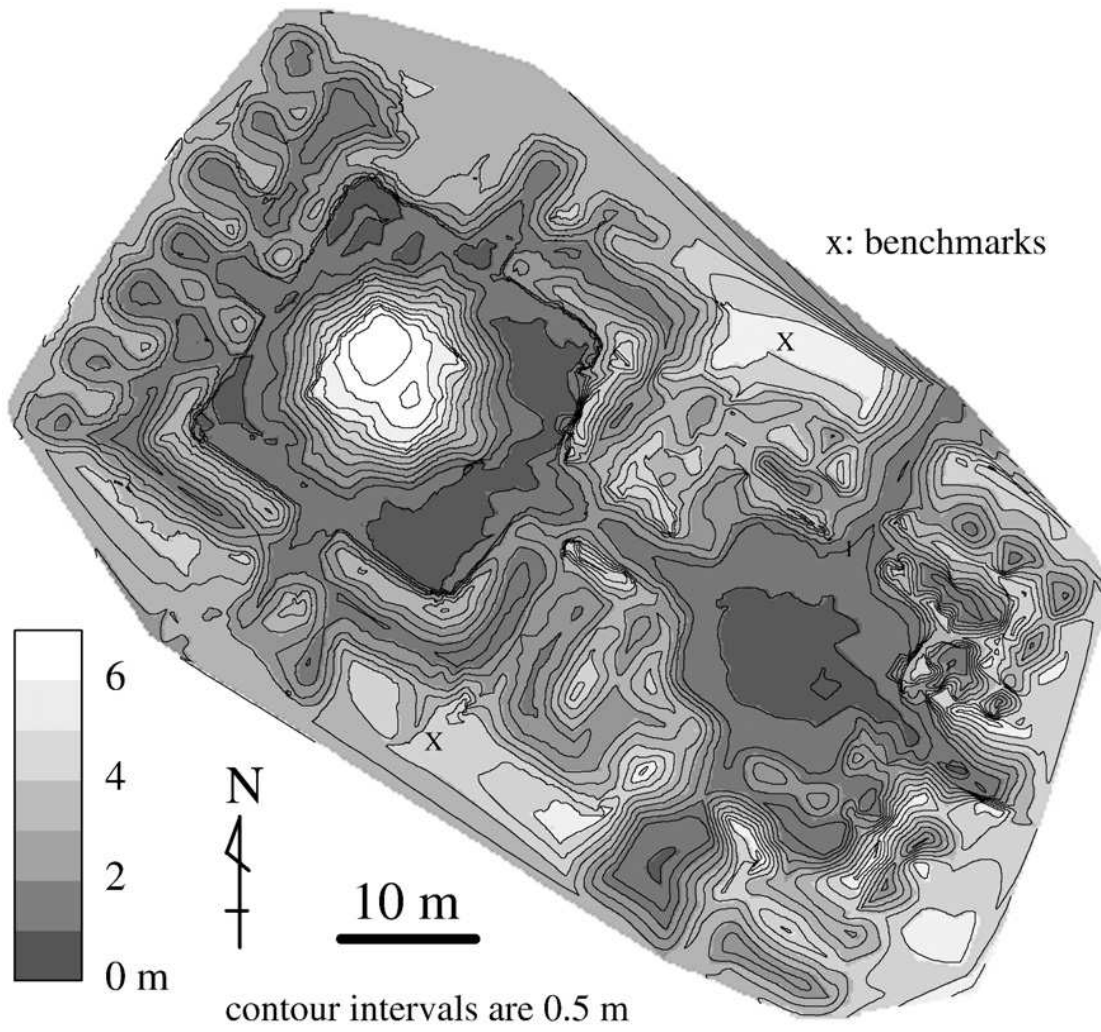


Fig. 6. High resolution map of Ajina Tepa. Topographic coordinates were gained from each pair of photographs

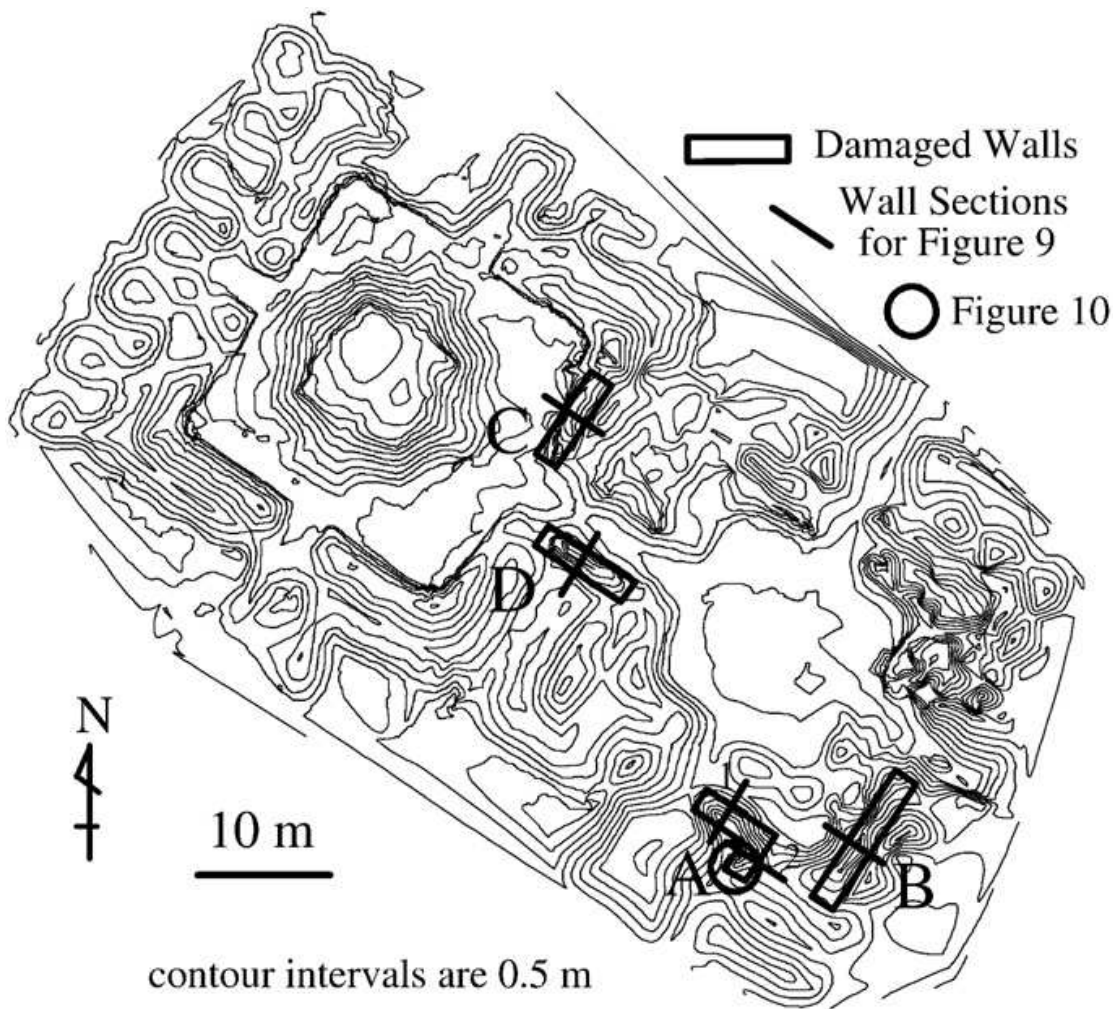


Fig. 7. Location of the damaged walls

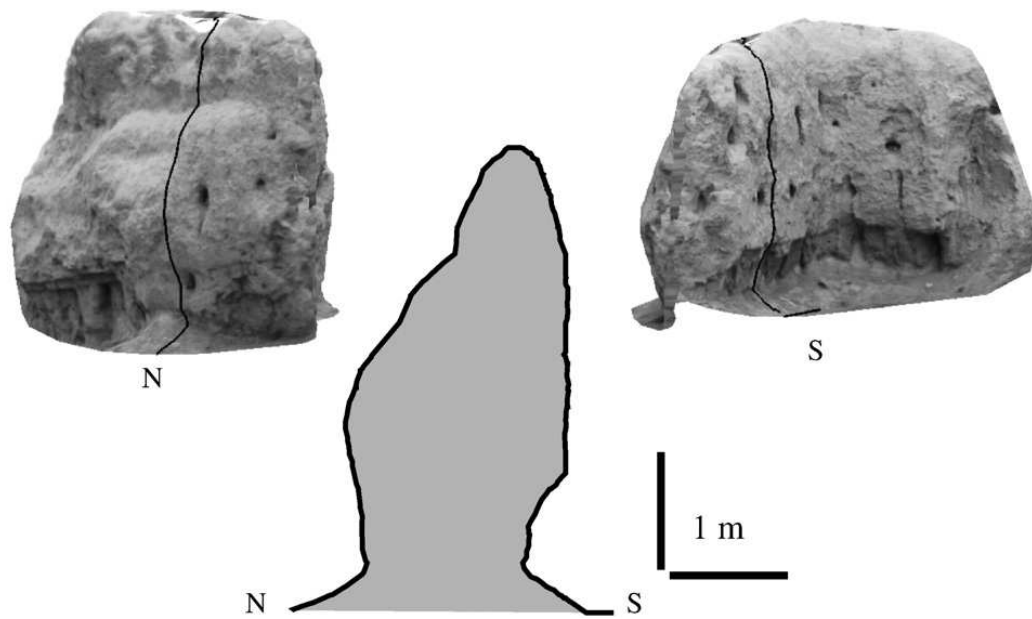


Fig. 8. A section of Wall A in north–south direction. Upper two photos show the positions of the section on texture mapping models.

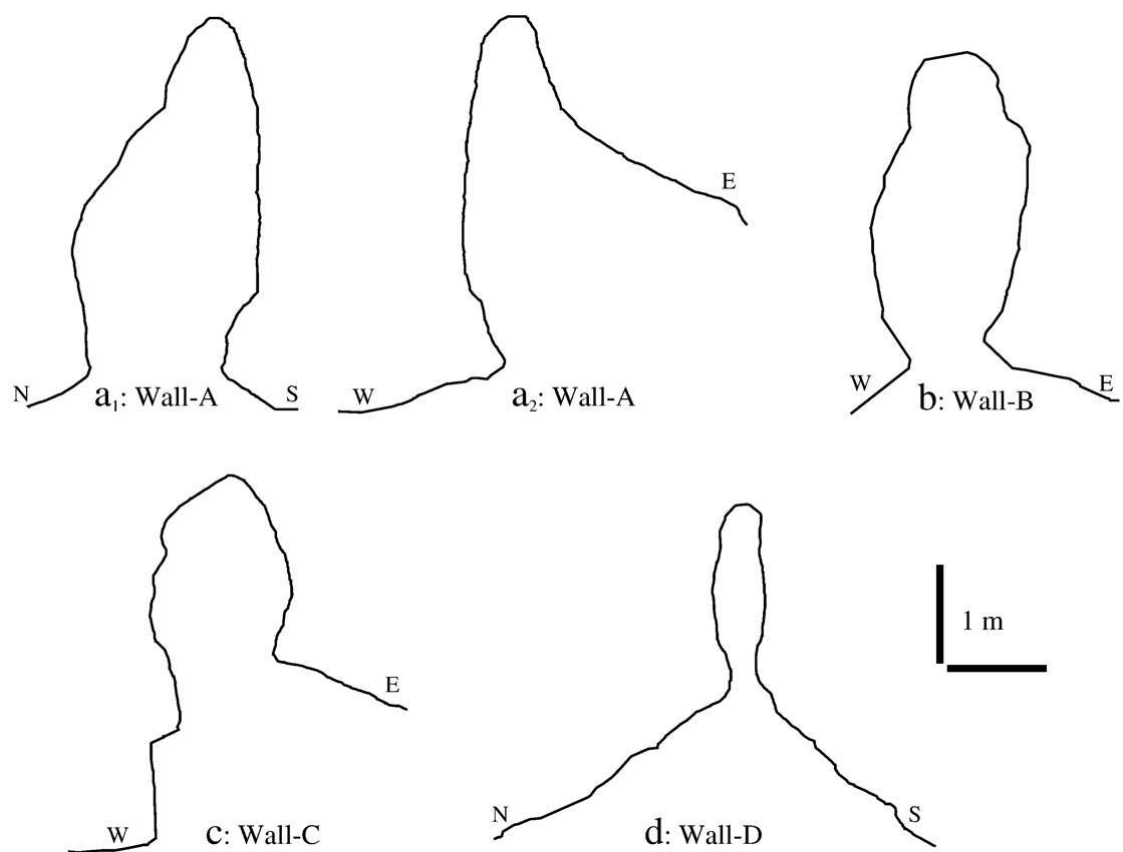


Fig. 9. Sections of the damaged walls. See Fig. 7 for locations of the walls.

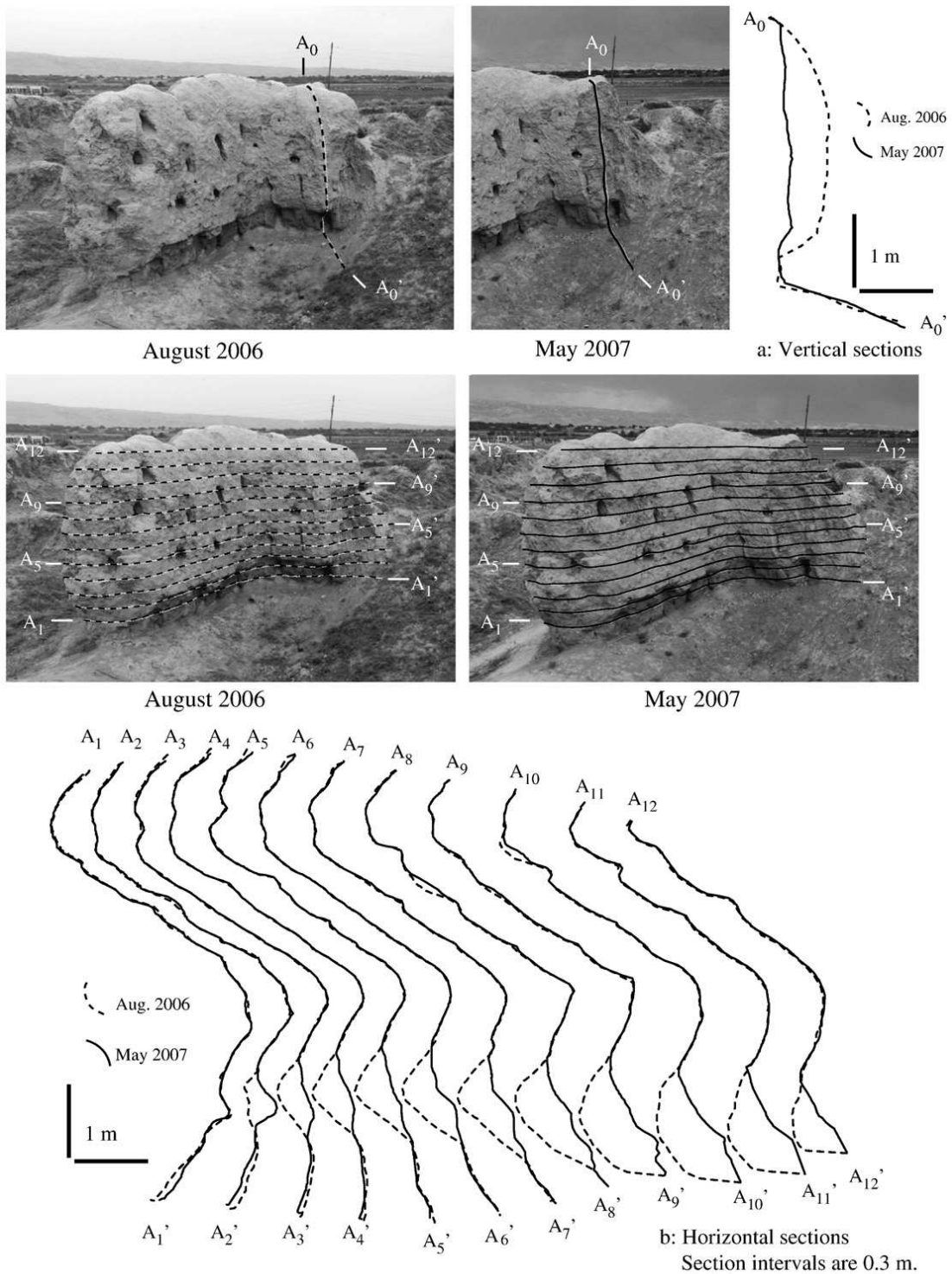


Fig. 10. Change of Wall A (L-shaped segment). Upper row: views from southwest, left in 2006, right in 2007. a: Vertical profiles. Middle row: photos showing reference horizontal sections, left in 2006, right in 2007. Lower row: ground plans of the reference horizontal sections. Southern rim collapsed between August 2006 and May 2007.

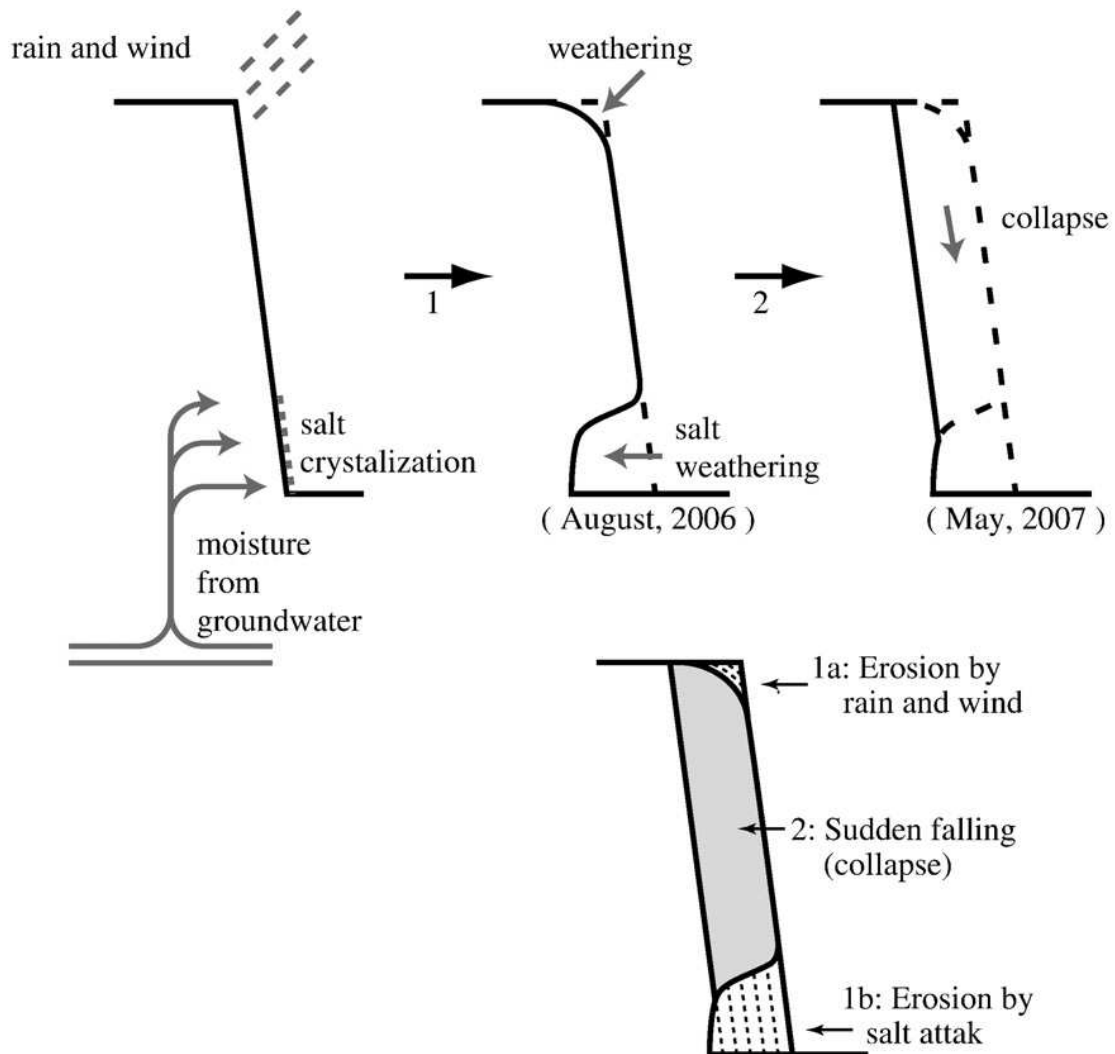


Fig. 11. Schematic erosional process of the wall. 1: Soluble salt is transported with capillary groundwater, and crystallized on the surface of the wall. Salt crystallization attacks and erodes the basal part of the wall. The top part of the wall is also eroded by rain and wind. 2: The upper wall, which lost support due to the thinning of the basal part, collapses suddenly. The wall surface becomes planar, and the erosion will continue to decay the wall.



Fig. 12. Salt precipitation on an excavated surface of the building wall. The excavated height is about 1 m.



Fig. 13. An example of conservation work. Wall-B is supported by buttresses made of new mud bricks.