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Damage quantification of built stone on Dark Gate (Belgrade, Serbia): sample of damage index application for decay rate evaluation

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Abstract The Dark Gate is the monument of culture, part of the cultural and historical complex of the Belgrade Fortress. It is constructed of limestone blocks that after 270 years of exposure to environmental conditions and different anthropogenic influences show wide ranges of decay forms. During 2007, detail registration of all built limestone microfacies and weathering forms was done using tools of monument mapping. A correlation scheme “intensity– damage category” was made according to the type, intensity, and distribution of damage forms. For quantification of decay rate of the Dark Gate, damage indices were calculated on the bases of mapping results. Calculated values of damage indices (>3) reflected differences between separate zones of the gate (south–north façades, east–west oriented parts of the gate). This approach allowed assessment and comparison of weathering rates according to the gate’s position and the exposure of the stone to environmental influences. The linear damage index showed that the moderate damage is the dominant category on the entire monument, while the progressive damage index implies to the need of urgent

intervention. After 7 years, re-evaluation of these parameters was done. New data of weathering mapping and recalculated values of damage indices reflected significant acceleration in decay rate. By comparing weathering maps and values of damage indices from 2007 and 2014, the eastern part of the gate was separated as the zone of the monument that had suffered the heaviest damage. Differences among the values of damage indices showed that the position of the gate is one of the main causes of the present state of stone blocks built in the Dark Gate. They also showed that a carefully made damage category scheme is a key diagnostic tool in each restoration project.

Keywords Limestone · Mapping · Damage index · Decay rate · Progression

Introduction

In many regions of the world, stone was historically the predominant material used for building and artistic purposes. Although stone is generally considered an epitome of durability, factors such as climate change, pollution, use demands, lack of maintenance, and inappropriate past treatments present challenges for the conservation of stone buildings, structures and objects. Effects and rate of stone decay depend on these factors acting independently or more frequently together in different combinations, as well as of the properties of the stone itself, creating stresses that accumulate within stonework over time. Therefore, the rate of decay and weathering effects can vary considerably, and direct causal connection is not easy to define. Precise problem diagnosis is a first and crucial step in order to adequately respond to the conservation issues. It is essential that the complex case history be established through the

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holistic approach that provides assessment of the building as a whole and treats it as a product rather than the sum of its individual parts (Smith and Prikryl 2007; McCabe et al. 2007).

In the field of stone conservation, monument mapping method is generally accepted as an essential part of condition survey, being cost-effective and non-destructive procedure that provides comprehensive information on the type and distribution of changes on the stone surface produced by the weathering processes (Fitzner et al. 1992; Siegesmund et al. 2002; Svahn 2006; Doehne and Price 2010). In order to map those changes, characterization of stone deterioration has to be done by classification of weathering forms. Weathering forms are described with the aid of specific terminology utilizing morphological and geometrical criteria (Siedal et al. 2011). In the attempt to harmonize classification approaches and overcome terminology problems, various systems have been established (Normal 1/88 1990, VDI 3798 1998, ICOMOS-ISCS 2008). Glossaries on stone deterioration patterns allow qualitative assessment of weathering forms, therefore they are a commonly used tool for mapping of weathering forms for conservation purposes, as well as for assessing past treatments (Massa et al. 1991; Vergès-Belmin 1992; Martin et al. 2002). However, glossaries alone do not provide methodology for damage quantification. In order to assess state of conservation of stone monuments, many authors combine stone mapping with other non-destructive or micro-destructive investigation techniques (Laurenzi Tabasso 2004; Delgado Rodrigues et al. 2004; Odgers et al. 2008). Although effective, this approach is rarely affordable in less developed countries and hardly cost-effective for more “commonplace” built heritage.

A comprehensive monument mapping method developed by the working group ‘Natural stones and weathering’/Aachen University of Technology (Fitzner et al. 1995, 1997a, b) is cost-effective and non-destructive procedure that allows a quantitative registration, according to lithotypes and to type, intensity and distribution of weathering forms. The mapping method ensures an important contribution to comprehensive and reliable damage diagnosis. It was applied to a vast number of monuments worldwide (Fitzner and Heinrichs 1994; Fitzner et al. 1997a, b, Heinrichs and Fitzner 2000, 2007; Fitzner and Heinrichs 2002; Rothert et al. 2007). Also, it was used as reference for a number of researches on techniques for assessment of stone decay (Ball and Young M 2000; Turkington and Smith 2004; Kukela and Seglins 2011).

Based on quantitative evaluation of damage categories, monument mapping method was further developed to calculate damage indices (Fitzner and Heinrichs 2002). Proposed linear and progressive damage indices and mapping results enable:

- Quantification of damage intensities and damage categories that allow conclusive quantification and rating of stone damage for entire stone monuments and judgment of need and urgency of intervention (Fitzner and Heinrichs 2002).
- Evaluation of average and higher damage categories proportion; the linear damage index corresponds to the average damage category, whereas the progressive damage index emphasizes the proportion of higher damage categories (Fitzner and Heinrichs 2002).
- Patterns of damage indices help evaluate damage processes and can lead to better understanding underlying causes.
- Zonation of weathering forms is indicative for certain intensity and type of weathering processes and environmental impacts (Heinrichs and Fitzner 2000).
- Maps of damage categories locate those parts of a monument which interventions have to focus on.
- The consequent use of weathering forms, damage categories and damage indices can be a very suitable strategy for controlling conservation measures and for regular re-evaluation of monuments in the framework of long-term survey and maintenance of monuments (Fitzner and Heinrichs 2002).
- By assessing level of damage of each stone block on the monument, quantity of conservation material needed to carry out necessary conservation-restoration treatment, as well as the costs of intervention could be more precisely assessed.

Among 409 immovable cultural monuments established in Belgrade, Belgrade fortress is one of 15 rated with the outstanding cultural significance for the Republic of Serbia. The present day appearance of the Belgrade Fortress as a fortified whole was shaped during a period of almost two millennia. It is the oldest urban settlement in Belgrade, dating back to prehistoric times. During the long period of their building and rebuilding, the fortifications evolved from an ancient fortified military camp, i.e., castrum, over a medieval fortified town to a modern bastion of artillery fortress. At present, 19 gates are preserved to testify of the fortress’s long history. These gates were built of almost pure limestone stone blocks. They have been exposed to various environmental and anthropogenic impacts for hundreds of years. Consequently, some of them were very damaged and they required conservation–restoration treatment in order to preserve structural integrity of a monument.

Methodology of Fitzner et al. (1995) has been adopted for mapping of several gates at the Belgrade fortress during extensive restoration works undertaken from 2006 to 2008. It contributed to efficient planning of conservation and restoration interventions. Mapping of the Dark Gate at Belgrade fortress was first done in 2007 in the scope of

above-mentioned restoration campaign. However, conservation–restoration treatment of the stone façades was not implemented. This provided the opportunity to revisit the monument in 2014 to repeat the mapping and compare it with results from 2007. Research objective was to rate damage to the monument and assess weathering progression over the period of 7 years. With the aim to examine relation of damage indices and zones of the highest decay, linear and progressive damage index were calculated for stone façades of the Dark Gate according to their orientation, as well as for the entire monument. The results obtained on this way could enable a better understanding of mechanism of decay in specific microenvironmental conditions, as well as to evaluate applicability of adopted Fitzner’s methodology to monitoring monument’s state of conservation.

Historical background

The Dark Gate is situated on the Belgrade fortress, as a part of the same-named bastion, which was partially destroyed when the nearby boulevard was built (Fig. 1).

The exact period or the start of construction is unconfirmed, but it is documented that it was built during the

Turkish occupation and after 1739 based on the data from the Turkish archives and plans of the War Archives in Vienna (Popović 2006).

The gate consists of a front façade, central aisle and three side rooms with fireplaces for guards in two of them. The south façade of the gate consists of recessed arch and simple pilasters and may have been constructed in two phases. The inner part was built in the first phase and consists of an arch with a decorative rosette in the apex. A rectangular niche is placed above the arch with slots mechanisms for moving part of the bridge at the same height. External baroque treatment in the form of profiled portals and final cornice was probably constructed in the second phase (Fig. 1b).

The northern façade consists of a central part, the portal, and side curtain walls without decorations (Fig. 1c). Restored cannon openings are placed above the central aisle, toward the south façade. On the eastern side, the gate is leaning on the slope which descends from the Upper Town of the fortress, while on the western side River Sava is 50 meters away.

According to the type of building material, the gate is a heterogeneous structure. South façade is built entirely of limestone blocks, while the inner part of the gate and the northern façade are built by combining stone blocks and



Fig. 1 a Location of the Dark Gate in Belgrade, Serbia; b South façade of the gate; c North façade of the gate

Table 1 Classification scheme of weathering forms and intensities for the built stone blocks in the Dark Gate in correlation to damage category

Group	Main weathering forms	Damage category					
		1	2	3	4	5	
Loss of stone material	Surface recession	Intensity of decay					
		Depth (cm)					
		<0.2	0.2–0.5	0.5–1	1–5	>5	
	Relief	Depth (cm)					
		<0.2	0.2–0.5	0.5–1	1–5	>5	
	Outburst	Volume (cm ³)					
		<10	10–125	125–500	500–1,000	>1,000	
	Discoloration/deposits	Crust	Mass of detaching stone material				
			Low	Medium	High		
		Discoloration	Level of color change				
Low			High				
Soiling	Degree-covering of surface (%)						
	<20	20–50	>50	–	–		
	Biological colonization	Degree-covering of surface					
		Low	High	–	–	–	
Detachment	Granular disintegration	Mass of detaching stone material					
		Low	Medium	High	–	–	
	Flaking	Mass of detaching stone material					
		Low	High		–	–	
	Contour scaling	Thickness of the scales (mm)					
<1–2		2–5	5–10	>10	–		
Detachment of crusts	Mass of detaching stone material						
	Low	Medium	High	–	–		
Fissures/deformation	Fissures	Number and dimensions of fissures					
		–	Small	Large	–	–	

brick, connected with lime mortar. 283 processed, rectangular, less often trapezoid stone blocks are embedded in the façade of the gate. An average size of blocks is 50/25 cm. The surface area of south façade is 32 m² and the surface area of the stone built part of the north façade is 11.4 m². The surfaces of some stone blocks are encribed with graffiti markings from the Janissary corps from the period when Belgrade was under Turkish rule (Fotić 2008, 2009). Small interventions done in the past are notable on the façades. Traces of cement mortar are visible.

The research was carried out for the first time in 1965 with the aim of obtaining information on the gate's state of conservation (Vujičić-Vulović 1970). New investigation was carried through in 2006, during which the presence of moisture on the inside surface of the vaults of the side rooms on the east side was noted, which indicated damage to the waterproofing layers above.

Restoration works in the center aisle and side rooms were carried out in 2008. Brick walls were cleaned, missing and damaged bricks were replaced, joints were re-pointed. The rubble stone path leading to the gate was also restored. Works on the bastion above the Dark Gate were

carried out the same year; cannon openings above the central aisle were restored, but hydro-isolation was not installed.

Mapping of the stone façades was carried out in the fall of 2007, in order to evaluate stone damage and help develop a strategy for stone conservation and restoration. Due to the lack of funding, conservation and restoration of the stone of the Dark Gate were not carried through to this date.

Methodology

This study commenced with detailed study of the Monument: survey, classification, and registration of lithological types and weathering forms. Mapping models used in the study included rock type mapping and weathering form mapping. Determination of damage categories on built stone blocks made it possible to calculate damage indices.

Field observation of the Dark Gate was done in November–December 2007. For lithological mapping of built stone, macroscopic observation was carried out in situ. In order to examine microfacies of built stone, five

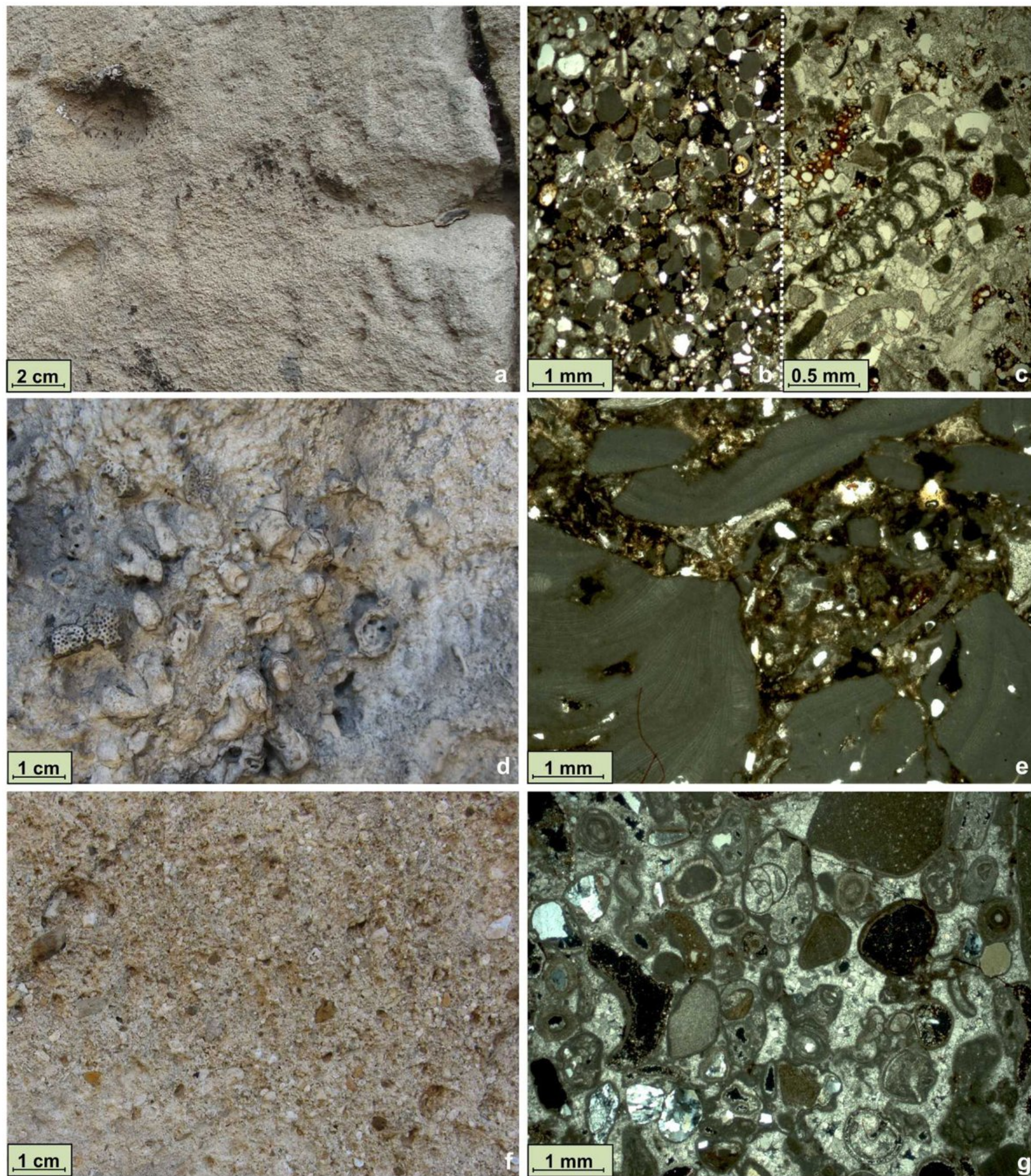


Fig. 2 Images and photomicrographs of stones built in the Dark Gate: (a–c) Grainstone; (d–e) Algal rudstone; (f–g) Rudstone

structurally different samples were taken from the Monument for petrographic study. Petrographic analyses were performed on thin sections, using a Leica DMLSP microscope for polarized light that was connected to a Leica DC 300 digital camera. Classification of built stone was done according to textural characteristics (Folk 1959, 1962; Flügel 2004)

Weathering mapping was carried out using the internationally accepted classification scheme developed by the Aachen working group “Natural Stones and Weathering” (Fitzner et al. 1995) in scientific literature known as

Fitzner’s model mapping. The standard classification scheme was modified to fit the size of built stone blocks in Dark Gate. A correlation scheme was developed for the monument in which all observed weathering forms were related to damage categories (Table 1). Terminology of weathering forms was adapted according to ISCS Glossary (ICOMOS-ISCS 2008).

For determination of damage categories, intensities of weathering forms were correlated with the average size of stone blocks, function of structural elements and monument’s defined cultural value (Fitzner and Heinrichs 2002).

Based on the correlation scheme, damage categories were determined separately for each group of weathering forms which are present on the monument façades (loss of stone material, discoloration/deposits, detachment and fissures/deformations). State of each stone block was documented by taking photographs and noting present categories of weathering forms according to groups, main and individual weathering forms and damage categories. Final damage categories were derived by jointly considering all weathering forms of the four groups. The selected damage categories are: very slight damage (1), slight damage (2), moderate damage (3), severe damage (4), and very severe damage (5; Table 1). They were noted on the architectural drawings of façades and evaluated quantitatively. From maps of damage categories and area percentage of very slight (B), slight (C), moderate (D), severe (E), and very severe damage (F), damage indices—linear damage index DI_{lin} (1; Fitzner et al. 2002a) and progressive damage index DI_{prog} were calculated (2; Fitzner et al. 2002b):

$$\frac{B + (2 \cdot C) + (3 \cdot D) + (4 \cdot E) + (5 \cdot F)}{100} = DI_{lin}, \quad (1)$$

$$\sqrt{\frac{B + (4 \cdot C) + (9 \cdot D) + (16 \cdot E) + (25 \cdot F)}{100}} = DI_{prog}. \quad (2)$$

Damage indices were first calculated for the whole gate. Then the gate was divided by two axes—first separating the south and north façade and second dividing according to longer axes the gate in half to zones oriented to east and west. Damage indices were calculated for every zone separately in order to evaluate weathering rates according to monument's orientation.

In 2014, re-evaluation was done in order to verify the condition of the stone and assess degradation rate over the past 7 years. Documentation created in 2007 was compared with the stone condition by direct examination in situ and also by taking new photographs and comparing old and new photo documentation. Changes in final damage categories were noted and mapped. On the base of re-evaluation of damage categories, new damage indices were calculated.

Results

Lithological mapping

Results of petrographic macroscopic observation in situ and microscopic microfacial analyses on built stone samples reveal that three facies type of limestone were used for construction of the Dark Gate. The rocks are differentiated according to macroscopic visible component, fabric and

color, as well as structural features and biogenic detritus in thin sections. There are: Grainstone microfacies, Algal rudstone microfacies, and Rudstone microfacies. Algal rudstone microfacies is separated from Rudstone microfacies due to predominant algal detritus content. Furthermore, these three microfacies types are limestones mineralogically composed of calcite (CaCO_3), with very small amounts of silici-clastic input. They are autochthonous limestone, of Miocene age. Today, pure algal, algal-bryozoan, and algal-detrital varieties of limestone can be distinguished within the limestone beds below the fortress (Pantić 1988).

Grainstone microfacies (biosparite) is the dominant type of built stone. It is light gray in color and massive texture (Fig. 2a). It is predominantly composed of densely arranged fragmented microfauna. Generally, all bioclasts are the uniform size, between 0.2 and 1.5 mm, mostly about 0.5 mm. Densely distributed bioclasts include shallow water, debris of red algae, foraminifera, fragments of mollusks shells and echinoids (Fig. 2b, c). The ooids were also registered in this microfacies. The cores of the ooids are composed of silicic-clastic grains. Ortochem is sparite with interparticle to intraparticle porosity.

Algal rudstone microfacies (algal biomicsparrudite) are white biogenic limestones, poorly cemented with very porous texture, which is characterized by irregular or lenticular voids and channels (Fig. 2d). Macroscopically observed big preserved or fragmented algal allochem, round to nodular or tabular to irregular shape (up to 5 cm in size), provide a rudite character of stone and prefix *algal* in name. These prevailing allochemical compounds are fossil fragments of red algae (*Lithotamnium ramisissimum*; family Corallinaceae) (Fig. 2e). The algal remains are micrite in composition with a well-developed and prominent mesh texture consisting of micron-sized rectangle chambers. Fragments of some other species (diverse association of reef macro- and microfauna) were also recognized and have chambers partially filled with sparry calcite. The algal biomicsparrudite is a poorly consolidated rock with microsparite bounds with large moldic, vuggy, and interparticular porosity.

Last of all built type is Rudstone microfacies represented by coarse-grained rudites regarding their textural features, i.e., the coarseness of the component especially terrigenous component homogeneous distributed throughout the rock (Fig. 2f). Size of these clasts reaches up to 1 cm. Among the sparry varieties of this microfacies, intrasparrudite, biosparrudite to intrabiosparrudite may be distinguished. They are made of simple and complex intraclasts and fossil fragments of shallow-water organisms, ooids with orthochem of sparry calcite (Fig. 2g). The intraclasts are the coarsest allochem (up to 4 mm in size) and correspond to biomicrite, or micrite, regarding their

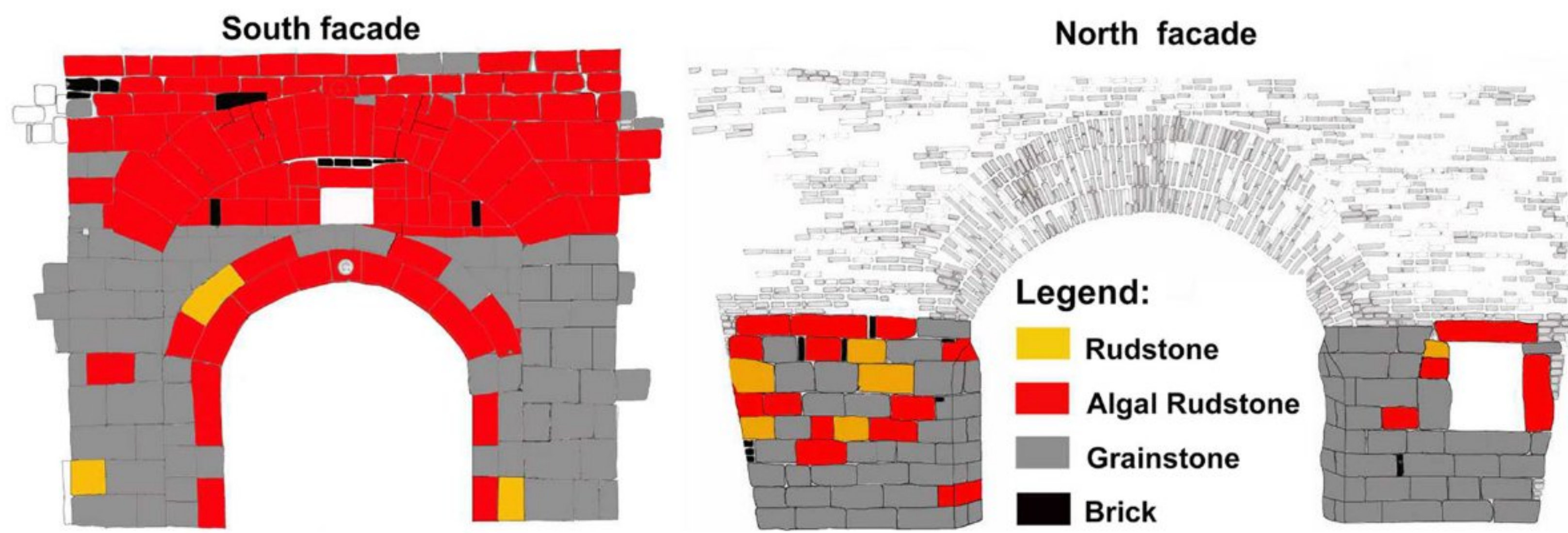


Fig. 3 The results of the lithological mapping of rock types for south and north façades of the Dark Gate

composition. Bioclasts include shallow water, macrofaunal remains, usually completely recrystallized and molds of microfauna as well as algal debris (Fig. 2g). Fossil fragments are densely distributed around various-sized intra-clasts, what in general had the influence on the poorly sorting of intra/biosparrudites. Terrigene components are presented of uniformly distributed quartz/quartzite grains and it built up to 10–15 % vol. rock. The cement is sparite pigmented with iron oxides. Rudstone microfacies have an intergranular and intragranular porosity.

The results of lithological mapping of north and south façades of Dark Gate are documented on Fig. 3a, b. The grainstone microfacies (biosparite) dominates in the lower part south façades, while the algal rudstone are built in the upper part and arch. For the most part of north façade, grainstone microfacies was used, although algal rudstone identified rarely. Rudstone microfacies occur only sporadically, probably used during the latter restoration phases. In addition, brick was also used to fill some gaps and for filling the empty spaces between limestone blocks or gaps caused by completely destroyed blocks.

Mapping of weathering forms

Mapping of Dark Gate’s façades and registration of weathering forms for each built stone block individually enabled characterization of stone degradation according to the type and intensity. It showed that all five groups of damage categories are present on built stone blocks i.e., category “no visible damage” was not observed. As far as groups of weathering forms are concerned, most dominant are loss of stone material, deposits in the form of crusts and detachment (Fig. 4). Loss of stone material is generally presented as surface recession and relief, only occasionally as outburst. Black crusts and white calcite crusts are present on majority of the stone blocks on the south façade. While black crusts are the ones that provoke surface recession, white crusts are thin and uniformly cover the surface of stone blocks. Discoloration is present as chromatic color change due to the oxidation

of Fe-components and due to accumulation of coloring components near the stone surface. This form of degradation was identified in a number of calcarenite blocks on the south façade. Soiling occurs in the form of deposition of weakly bound atmospheric particles of dust, soot, soil, or sludge and is present on the blocks in the lower zones of façades. Biological colonization in the form of microorganisms is present on the ground level where moisture is retained. Detachment is presented in the forms of granular disintegration, contour scaling, and detachment of crusts with stone material. Fissures do not present important feature as they are present only on several individual stone blocks.

In order to assess the degree of damage to the façade and to graphically present mapping results, damage categories were defined and correlated with previously established individual intensities of weathering forms (Fig. 4; Table 1). Blocks rated as ones with heavy and very heavy damage are blocks with a significant loss of material that disrupts the original appearance of the stone element (Fig. 4b, d, f damage category 4 and 5 in Table 1). Moderate damage is manifested on stone blocks where loss of material is superficial (Fig. 4c, e damage category 3 in Table 1). On the blocks with very slight and slight damage, the original stone surface is preserved but discoloration or crusts are present (Fig. 4a, category 1 and 2). Stone blocks without visible damage were not observed.

Results of the weathering forms mapping during 2007 showed that very heavy and heavy damage were present on 28 % of the Dark Gate’s stone surface (9 % very heavy, 19 % heavy; Table 2). The largest part, 43 % of stone surface, was moderately damaged, while 29 % showed slight and very slight damage (22 % slight, 7 % very slight) (Fig. 5–2007 mapping and Table 2).

In 2014, the level of damage changed slightly. Very heavy and heavy damage are now present on 30 % of the stone surface (very heavy 12 %, heavy damage 18 %). Moderate damage affects 42 % of the stone surface, while slight and very slight damage affects 28 % (slight 21 %, very slight damage remained unchanged 7 %) (Fig. 5–2014 mapping). From looking at the south and north



Fig. 4 Weathering forms on the Dark Gate: **a** relief, **b** surface recession and granular disintegration, **c** remains of black crust, discoloration and detachment of crusts with stone material, **d** Surface

recession, flaking and granular disintegration, remains of white crust, **e** contour scaling and flaking, **f** outburst and fissures

Table 2 The damage categories and percentage ratio of decayed stone surface for 2007 and 2014 for the whole façade and related to the gate's orientation

Damage categories	Percentage of the affected stone surface on Dark gate's façade									
	Total (%)		South façade (%)		North façade (%)		East half (%)		West half (%)	
	2007	2014	2007	2014	2007	2014	2007	2014	2007	2014
1	7	7	8	8	3	1	7	6	7	7
2	22	21	20	19	27	27	21	22	24	19
3	43	42	44	42	44	42	40	38	47	47
4	19	18	20	18	16	18	21	20	16	16
5	9	12	8	13	10	12	11	14	6	11

façade, it seems that the north one is slightly more damaged than the south one. This is reflected mostly in stone blocks showing very slight damage; 8 % of the surface

with very slight damage on the south façade did not change in 2014, comparing to the north one. On the north façade slight damage was present on only 3 % of the surface in

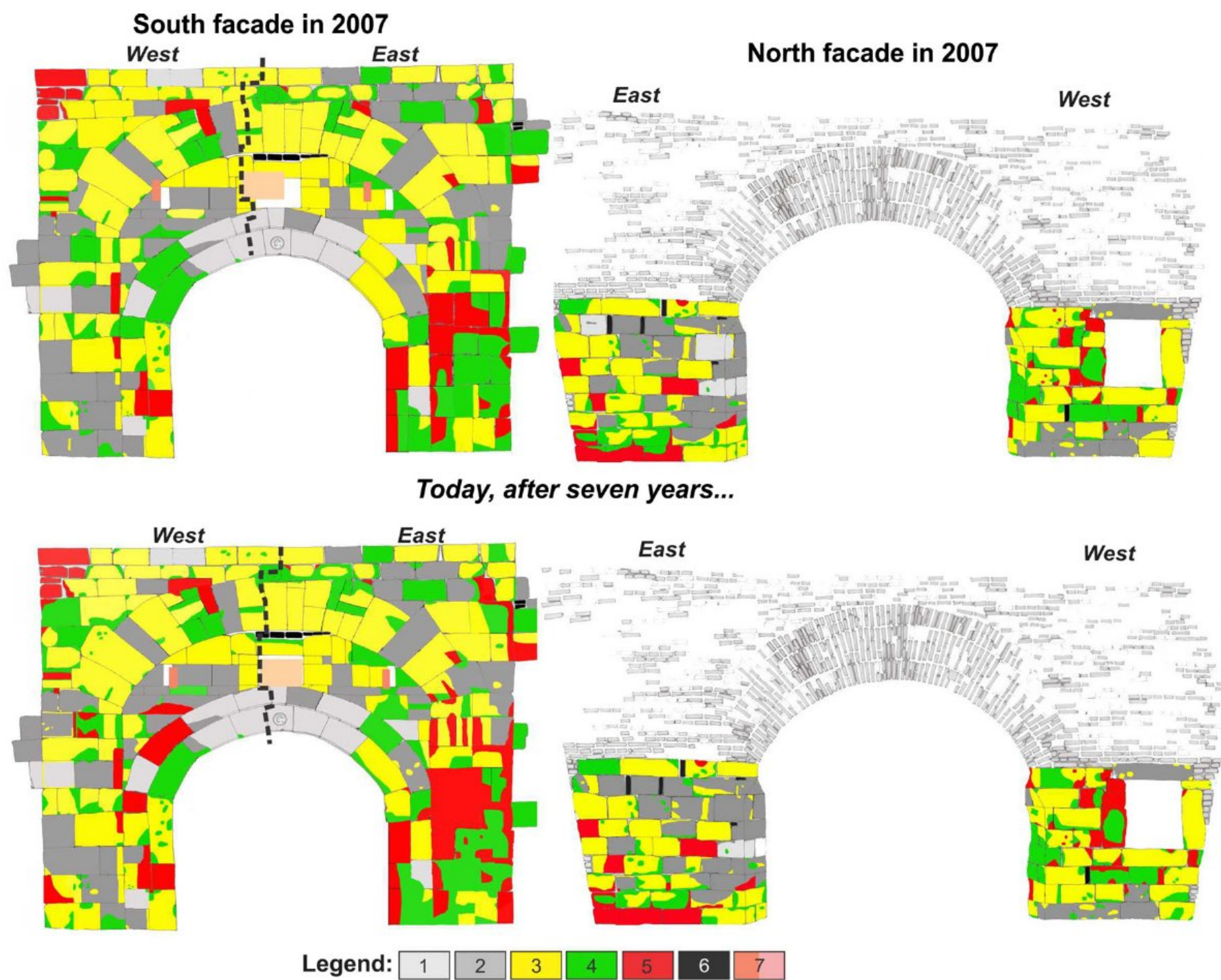


Fig. 5 Mapping of damage category on the Dark Gate; 1 very slight damage; 2 slight damage; 3 moderate damage; 4 severe damage; 5 very severe damage; 6 bricks; 7 open gaps or mortar surface

Table 3 Linear and progressive damage index for 2007 and 2014 for the whole façade and related to the gate’s orientation

Damage index	Dark gate’s façade									
	Total		South		North		East half		West half	
	2007	2014	2007	2014	2007	2014	2007	2014	2007	2014
DI _{lin}	3.01	3.07	3.00	3.09	3.03	3.13	3.08	3.14	2.90	3.05
DI _{prog}	3.18	3.25	3.17	3.28	3.18	3.28	3.26	3.33	3.05	3.28
DI _{lin 2014} –DI _{lin 2007}	0.06		0.09		0.10		0.06		0.15	
DI _{prog 2014} –DI _{prog 2007}	0.07		0.11		0.10		0.07		0.23	

2007 and in 2014 this number dropped to 1 % (Table 2). When damage categories are considered by dividing façades vertically to the east and west half, percentages of heavy and very heavy damage implicate that the east oriented half has suffered more damage than the west half (32 % in 2007 going to 34 % in 2014 for the east half, 22 % going to 27 % for the west half) (Table 2).

Damage index

For the entire monument high damage indices have been determined on the base of weathering forms and damage

categories (Table 3). According to results of mapping on the Dark Gate in 2007, linear damage index for the total façades was 3.01, and uniform values of damage indices to the north and south façades were noted. However, comparing the east and west part of gate, it can be seen that the linear index has higher value on the eastern façade than on the western façade. The progressive damage indices show the same trend but more pronounced differences in values, especially among western and eastern façade (Table 3).

In 2014, linear damage index for the entire monument is augmented to 3.07 and progressive damage index to 3.25 (Table 3). Damage indices calculated for façades according

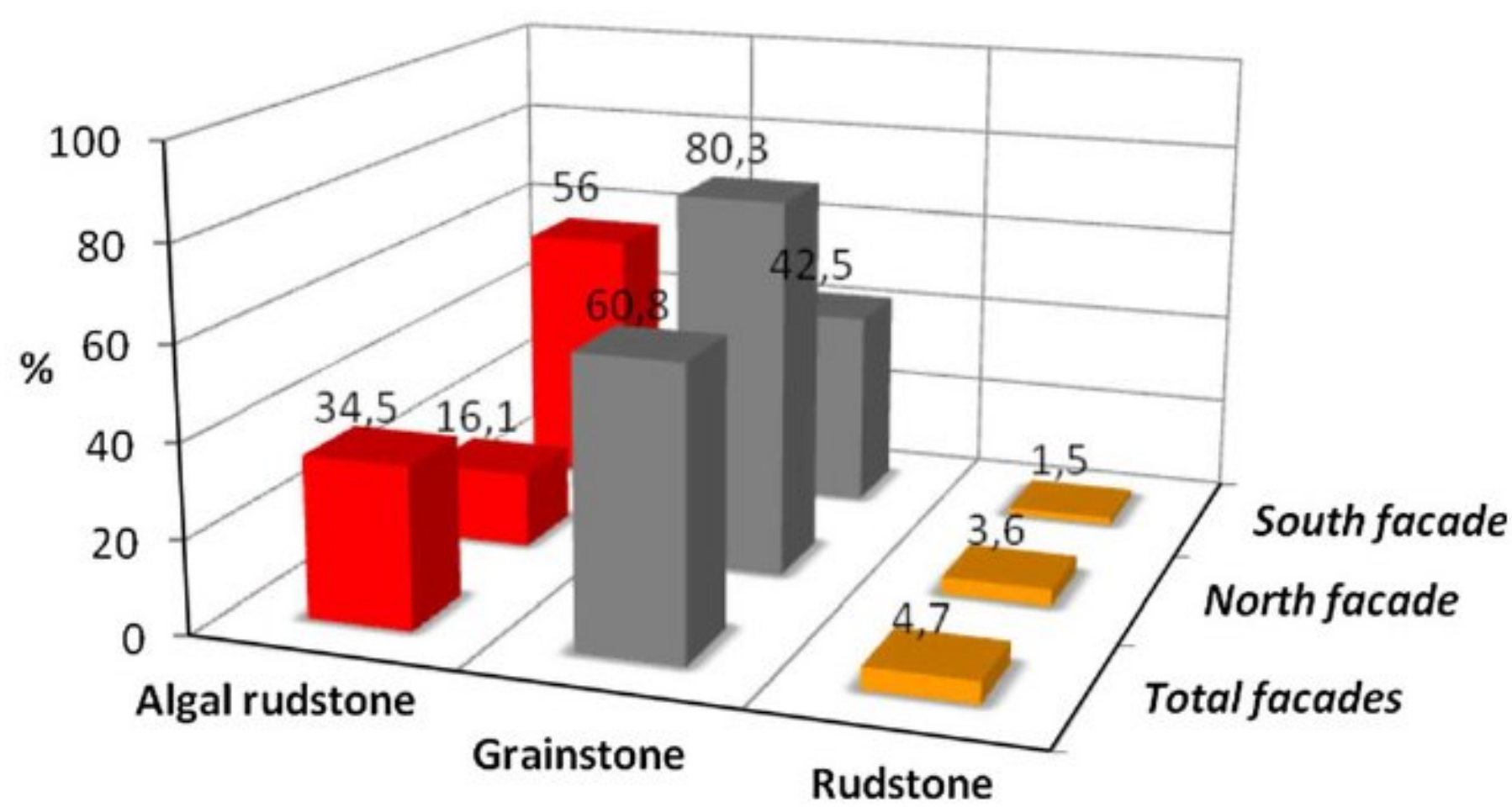


Fig. 6 The percentage amount of built rock type of the Dark Gate

to gate's orientation to the south and north, do not differ considerably among themselves and from the damage indices for the whole gate. Only when the gate is considered by its east and west oriented halves, can be noted that the western façades shows lower values of both damage indices types, than the calculated values for eastern façades.

Discussion

Results of petrological analyses and lithological mapping of built stone blocks revealed the quantified distribution of three different microfacies of limestone (Fig. 6). The grainstone microfacies were predominantly used rock on the Monument Dark Gate. The northern portal on the gate is architecturally simple in style and 80 % composed of grainstone microfacies, with scarce presence of algal rudstone and minor number of rudstone blocks. The style and building technique used for the southern façade was significantly different. The southern portal is made of profiled stone blocks of algal rudstone and grainstone in almost same prevalence. Their distribution in this portal imply an organized building technique. While the soft and easy workable algal rudstone was used for upper part and arch of the portal, hard and compact grainstone was built in lower parts of façade. Content of rudstone microfacies on both façades and for entire gate is very low, and it implies the possibility of its use in later restoration phases, probably for replacement of completely destroyed blocks.

When lithological maps are compared with weathering features, it is evident that algal rudstone microfacies are characterized by loss of stone materials in forms of surface recession and outburst, while grainstone microfacies is marked by relief loss of stone materials and detachment of crust following by granular disintegration and flaking. If we compare lithological maps with damage category maps, it is clear that category of damage cannot be linked to the one type of stone. All damage categories are equally

present on all three stone types; therefore it is not possible to differentiate between their susceptibility to degradation.

Correlations among intensity of weathering forms and damage category in relation to orientation of gate parts reveal very interesting data. Looking at the façades oriented to south and north and their results of mapping damage category, no significant difference can be noted. The distribution of damage category is almost random on both façades. What is obvious from looking at the weathering maps, as well as at damage category, is that the half of the gate oriented to the east is more damaged than the half oriented to the west (Fig. 5 and Table 3).

This could be explained by the gate position inside of the fortification; the gate is leaning on the slope which descends from the Upper Town of the fortress. This slope is permanent source of moisture/water for eastern side of gate. Water draining from the slope causes higher moisture content in the walls on the eastern side of the gate in comparison to the western side (Fig. 7a). It has already been mentioned that these built limestones have high porosity which enables water to penetrate into the inner parts of blocks. Pore communications and their size enable water circulation through all gate construction not only from slope, but also groundwater and rain water, too (Fig. 7b). Percolating rain water in sheltered stone blocks is related to the destroyed waterproofing layers above the gate. Although the upper part of the gate is more influenced by wind that results in the faster drying process, the lower part of façades is influenced by the groundwater rising up. Additionally, gate position close to the Sava river (only 50 m away) also contributes to the higher moisture influence on stone surface and rising velocity of decay processes. All of these sources of moisture/water caused dissolution of poorly cemented algal rudstone and sparite cement of grainstone. It resulted in crumbling, granular disintegration, or occurring of thin white crust on stone surface as consequence of redeposited dissolved calcite. Over prolonged periods, repeating of cycles of dissolve, wetting–drying and freeze–thaw caused continual increasing intensities of decay and very heavy damage in different forms of loss of stone materials (surface recession, relief, and outburst).

The present state of the gate is result of the complex action of the above-mentioned natural factors but some other agents too. On the present appearance of the gate anthropogenic factor has undoubted influence. The selected mode of cleaning in the past has surely contributed to the increase loss of stone material from block's surface. Because of that, the state of the gate in 2007 provided an initial level of concern and served as a baseline for evaluating the decay rate over the past 7 years.

Decay rate and damage category was synthesized by linear and progressive damage indices. As it can be seen on



Fig. 7 a The position of Dark Gate and the direction of water draining from slope; b directions of water moving down slope and rising from the ground

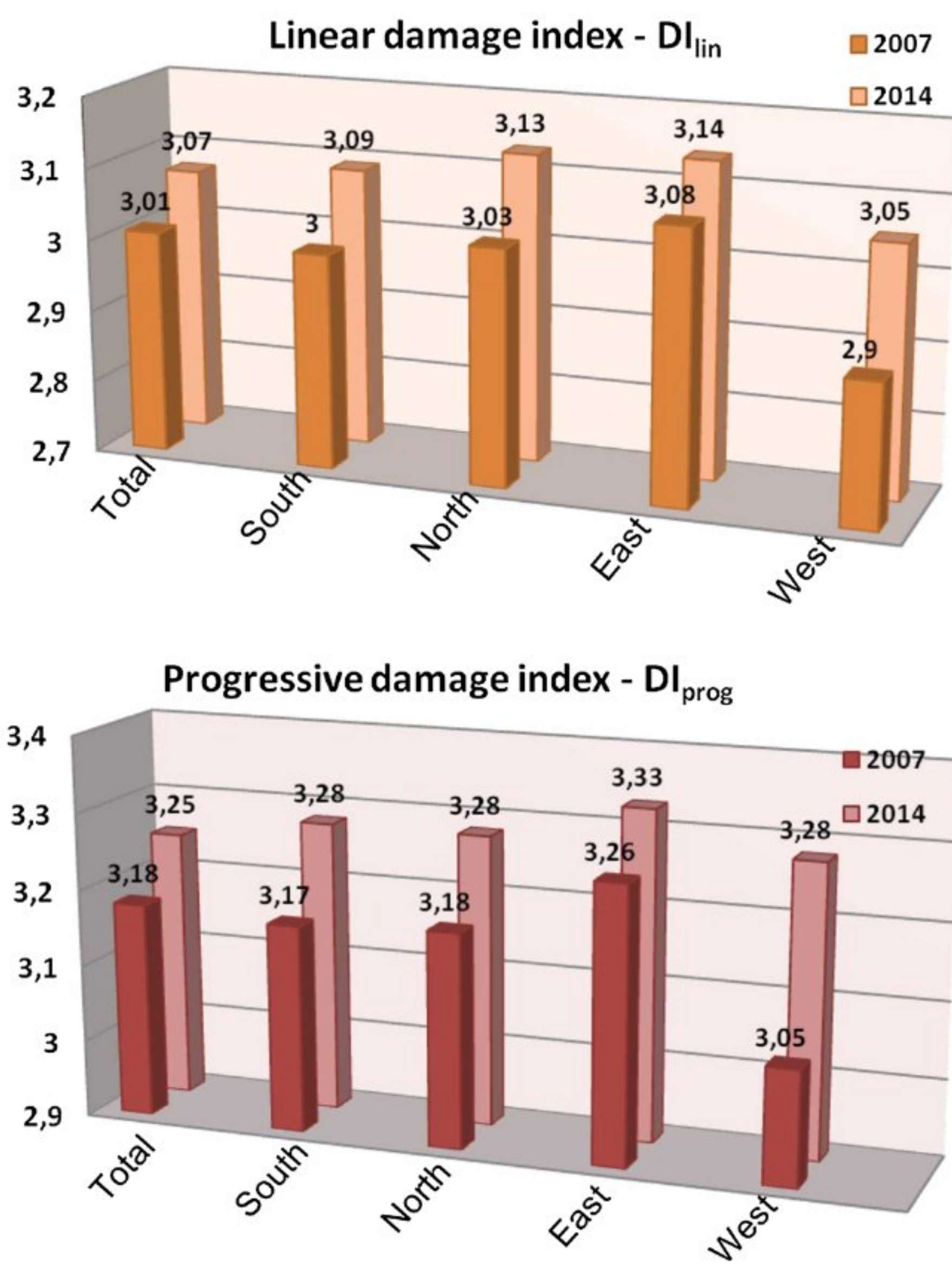


Fig. 8 Comparison of the calculated damage indices values

Fig. 8a, b, their values are in relation to gate’s orientation, too. The values of linear damage indices display insignificant differences between 2007 and 2014 for the entire gate as well as north and south façades. Nevertheless, the difference of linear damage indexes from 2007 to 2014 is significantly higher on the eastern part of the gate in comparison to western one (Fig. 8a). It is additional,

quantifiable evidence that the eastern side is more damaged due to its position and contact with the slope (Fig. 7b).

Generally, comparing progressive damage indices for 2007 and 2014, high rate of damage progression is evident—progressive damage index for the whole gate increased by 0.07 in only 7 years (Fig. 8b). Among north and south façade, there is no difference in values of damage progression, but this progression is significantly higher on the western side of the gate (0.23; see Table 3) than to eastern side (0.07).

This difference can be explained by chosen intensity class of weathering forms and its correlation to damage category. On the western half of the façade, the percentage of slight damage decreased by 5 %, from 2007 to 2014, while at the same time percentage of very heavy damage increased by the same 5 %. On the other hand, progressive damage index on the west side is coming close to the one on the east side (Table 3). This seemingly illogical inconsistency lies in the classification scheme of weathering forms (Table 1), i.e., in the intensities related to damage categories. According to chosen classification scheme in our study, loss of material higher than 5 cm in depth, or 1,000 cm³ in volume is considered as very heavy damage. Although the loss of material on some stone blocks was rated as very heavy damage in 2007, it is evidently progressing during the past 7 years (Fig. 9). However, this progression could not be noted on damage map for 2014, due to defined ranges of intensity—a class does not allow for this progression to register. It should be noted that classification scheme was developed in the frame of 2007 condition survey which had the objective to estimate the urgency for conservation and to help identify stone blocks in need of more extensive restoration work. Nevertheless, damage progression is evident and the ranking of the monument corresponds to the increasing need and urgency of preservation measures.



Fig. 9 Evident increase of stone decay on southern façade of the Dark Gate

Conclusion

The mapping of weathering forms on the stone built façades of the Dark Gate implies a wide range of damage at the monument. The main weathering type that occurred on limestone blocks were loss of stone material in forms of surface recession, relief, and outburst. All of them were followed by granular disintegration, flaking, and crust detachment.

Considering the age of the monument, its position in fortification and exposure to influences of different natural and anthropogenic factors, the present state of the monument shows a high susceptibility of these limestones to decay processes. The main cause of stone damage is definitely moisture/water and its percolation through the entire gate. The higher damage level on eastern side was caused by gate position (leaning on the slope). This claim was confirmed by the higher values of damage indices for the eastern façade in relation to western façade. Comparing the damage index values for north and south façade as well as east and west part of gate, the eastern part shows the heaviest damages. In contrast, progression rate of damage indices from 2007 to 2014 is the highest for the western part. This phenomenon was the consequence of intensity range of weathering forms and corresponding damage categories (heavy and very heavy category). Adjacent to evidence of increasing decay on some blocks, this did not reflect in the damage categories or the progression of damage indices because these blocks were placed in heavy or very heavy category during 2007.

Finally, high values of damage indices (>3) point out the need and urgency of intervention. Their application allows one to locate the zone and cause of decay, too. Damage categories mark those parts of Dark Gate where future interventions have to be applied. Significant differences of damage indices values from 2007 and 2014 show

that during the period of 7 years, the decay rate has a notable progression. The results of re-evaluation indicates not only main zone of damage and causes of decay, but also they point to the need of precisely considering and completing a correlation scheme (intensity—damage category) for weathering mapping as essential phase in restoration project, especially for purposes of assess weathering progression.

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