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ULTRASONIC VELOCITY MEASUREMENTS FOR THE LONG-TERM MONITORING OF THE DEGRADATION OF MARBLE COLUMNS IN THE CLOISTER OF THE CHURCH OF SAINT-TROPHIME IN ARLES (FRANCE)

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Abstract

The cloister of the church Saint-Trophime in Arles is composed of two romanesque and two gothic galleries with 62 columns made of different white or coloured marbles. The stone is affected by many degradation features including contour scaling, superficial granular disintegration and internal disintegration. Some columns showing a good aspect are in fact decayed in depth whereas others that show superficial damage may have a sound and hard core. A first thorough ultrasonic investigation performed in 1993 had allowed to classify the state of preservation of the columns. Within the frame of the general preliminary study to the restoration of the cloister, ultrasonic measurements were undertaken on the columns again in 2009 in order to provide an update of their condition and to get information on the evolution of their degradation over 16 years. The analysis of the results allowed to classify the columns into damage classes and to compare ultrasonic velocities between 1993 and 2009. Over 16 years the degradation has significantly changed for many columns distributed in different parts of the cloister. This work shows how the ultrasonic velocity measurements and its ability to quantify physico-mechanical conditions for natural stone, allow for a long-term, reliable monitoring of change, degradation or consolidation by conservation intervention.

Keywords: marble, monitoring, ultrasonic velocity, marble degradation

1. Introduction

Located in the south of France, the cloister of the church Saint Trophime of Arles is a masterpiece of architecture built between the 12th and the 14th Century. Its restoration has started in 2012 spring and it should be achieved within 2 years. Many studies have been undertaken before carrying out this restoration work. The earliest were conducted more than 15 years ago. Some investigations are still in progress while black crusts are beginning to be removed from the columns and capitals, uncovering colored products that require identification. A few years ago, a scientific committee composed of archaeologists, conservators and conservation scientists from national and international institutions (World Monuments Fund) was raised around the architect in charge of the restoration, François Botton, to discuss about complementary investigations, restoration tests, methodological approach and objectives with the city authorities and the national authorities responsible for the conservation of Cultural Heritage.

Within this framework, a particular attention has been paid on the columns and their state of conservation. The cloister is composed of two Romanesque (north and east) and two Gothic (south and west) galleries, opened to a central courtyard by arcades. The 62 columns of the arcades are made of different white or coloured marbles. There are various re-used materials in the Romanesque galleries whereas only one type of white marble without any trace of re-use constitutes the Gothic columns. The stone is affected by many degradation features including contour scaling, superficial granular disintegration, black crust and internal disintegration. Some columns showing a good aspect are in fact decayed in depth whereas others that show superficial damage may have a sound and hard core. Water and atmospheric pollution are involved in the degradation process. Run-off waters during rain events have played a role in the degradation but Samson-Gombert (1994) who managed a one-year study on the water assessment in the cloister, clearly identified two other important sources of water: capillary rising damp from the ground and percolation in the stone masonry starting from the terraces surmounting the cloister galleries.

A first thorough ultrasonic investigation performed in 1993 allowed to classify the state of preservation of the 62 columns (Simon et al., 1994). Within the frame of the general preliminary study to the current restoration of the cloister, *in situ* ultrasonic measurements were undertaken on the columns again in 2009 to provide an update of their condition and to get information on the evolution of their degradation over 16 years. This paper presents the results of the new ultrasonic velocity measurements and a comparison of the 1993 and 2009 measurements.

2. General context

The diameter of the columns varies from 11.6 to 17.4cm with an average value of 14.6cm. The stone material is mainly a fine grained marble but several columns are specific coloured marbles (Tab.1). Various deposits (black crust, white lamellar encrustations, shiny patina, waterglass treatment…) have been observed at the surface of the columns. In-depth investigations were made on the nature of these surface deposits (Vergès-Belmin and Simon 1994). A sacrificial whitish limewash was applied between 1993 and 2009 on surfaces affected by water run-off (Fig.1). Ethyl silicate consolidation was performed on the most damaged areas. Facings of japanese paper were applied using carboxymethylcellulose and methyl metacrylate resin as a provisional glue on most of the scales and disintegrated areas. Other stone deterioration patterns (Fig.2) are also visible on the columns (erosion, contour scaling, blistering…). Several columns do not show any visible superficial degradation feature excepted soiling (Tab.1). Among them, 5 columns (61, 70, 72, 73, 75) were substituted by new ones in 1841/42 by architect Renaux because of cracks resulting from a local overloading.

In 2003/2004, a decisive restoration campaign was carried out to make waterproof the terraces of the four galleries and to improve the drainage of the water collected on the stone pavement of these roofs. A drainage gallery was integrated into the terrace roofs upon the galleries all around the cloister and vertical gutters were set up at the corners to evacuate rainwaters directly out of the cloister by the way of subterranean drivings (Botton 2006). Thanks to this efficient intervention, rainwater run-off and percolation from the terraces through the masonry were stopped and one of the main sources of water for capillary rise from the courtyard was eliminated.

Features	**Column**
Contour scaling (and facing)	10 11 12 14 15 22 23 25 26 32 33 35 36 37 49 58 60 62 85 88 94 96 102 104
Sacrificial limewash	12 23 32 34 36 58 60 72 74 82 84 88 89 92 94 96 97 98 99 100 101 102 105 106 107
Differential erosion	21 25 34 36 47 49 51 62 70 72 88 90 92 94 98 100 102
Shiny patina (bold letters for columns without any visible degradation features excepted soiling)	11 12 13 14 15 **21** 22 25 32 34 35 47 **48 50** 51 **52** 58 **59 61** 62 63 **70 71 72 73** 74 **75 82** 83 **84** 85 91 92 **93 95** 96 **97 99 101** 102 103 104
Black crust	24 26 33 37 89 90 91 93 103 105
Marble different from white fine grain marble	13, 23, 62 griotte marble 21 25 32 58 coarse grained marble 47 51 74 Pavonazzetto breccia

Table 1. Main visual features about deposits and alteration in 2009.

Figure 1. Limewash application on external faces of columns 94 (on the left) and 74 (on the right).

Figure 2. Granular disintegration pattern underneath sacrificial limewash (column 94, on the left side) and contour scaling (column 15 on the right side). Facings put on the scaling area have been removed in 2010 (photo 2010).

3. 1993 campaign

The first thorough ultrasonic investigation performed in 1993 was undertaken with a portable device USG 20 (Krompholtz Geotron Electronik, FRG) working at 250kHz. The methodology has been described in detail by Simon *et al.* (1994). The accuracy was assumed to be ±10%. Modelling clay was used as a coupling material between the stone and the sensors. Measurements were performed 15cm from the top and the base of the cylindrical columns, in parallel and perpendicular direction to the gallery respectively. The average velocity calculated from the four transmission times was used to attribute the column to a specific damage class.

The average velocities ranged from 800 to 6100 m/s and the columns were classified into 5 damage classes from complete structural deterioration (class IV ≤1500m/s) to unweathered marble (class 0 >5000m/s) according to a slightly modified version of velocity–porosity correlation of Köhler (1991 in Ahmad *et al.* 2009). No significant difference was put in evidence between measurements realised at the bottom or at the top of the columns. No difference also appeared for the measurements performed parallel and perpendicularly to the gallery. The velocities described a very complex picture of the preservation conditions (Fig.3). Nevertheless the lowest values were measured on the columns of the west gallery which is the youngest one, with an average velocity of 2500m/s and on those of the southern gothic gallery (3090m/s). The columns of the oldest north gallery were in the best state of conservation with an average velocity of 4800m/s and the columns of the Romanesque east gallery were also in a rather good general condition with an average velocity of 4340 m/s. The five columns (61, 70, 72, 73, 75) replaced in the east gallery during 1841 restoration work were in very good state (damage class 0). Some columns without evidence for any replacement showed also very high velocity higher than 5000m/s. A few columns (11, 22, 26, 91) with ultrasonic velocity higher than 6000 m/s might be dolomite marble. In general, velocity was higher on interior and more sheltered than exterior and more exposed columns (average velocity 4210 vs 3430m/s). The smaller the surface covered by direct water run-off or percolation traces is, the higher the ultrasonic velocity (Simon *et al.* 1994).

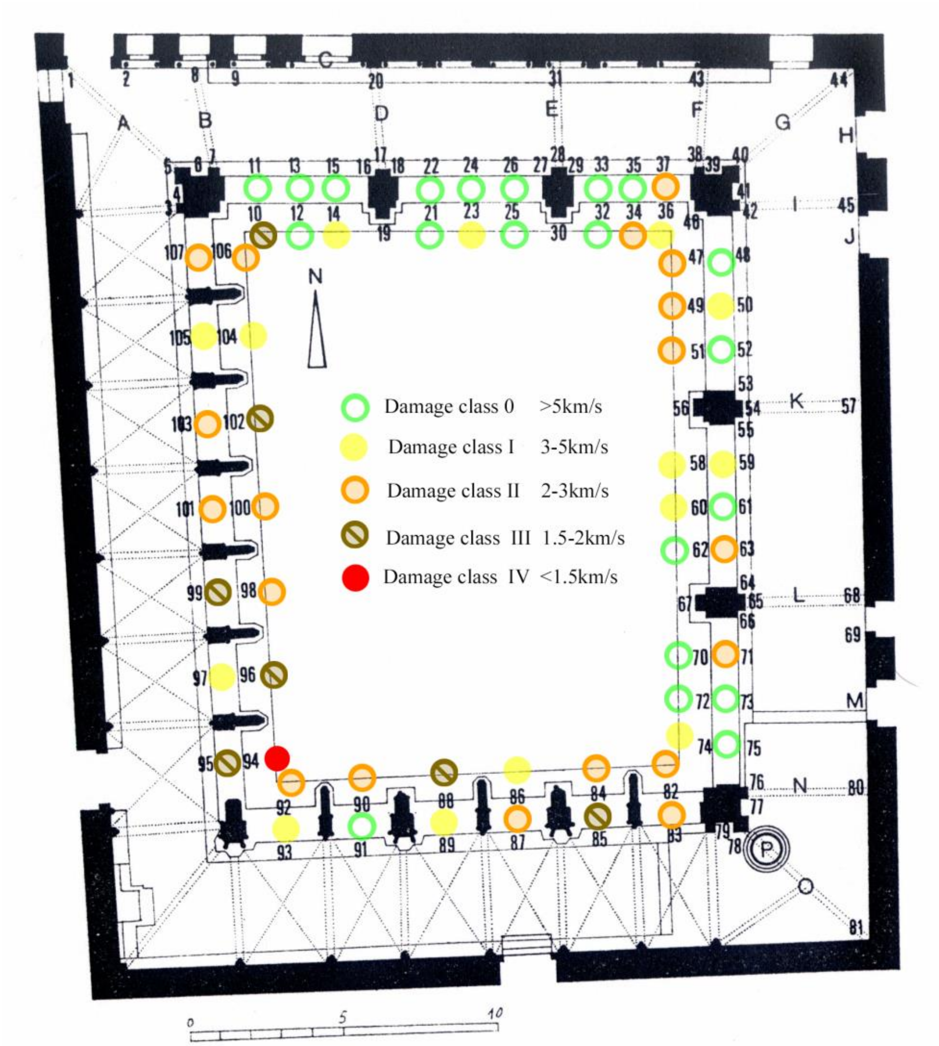

Figure 3. Mapping of the different classes of damage attributed to the 62 columns of the cloister in 1993 (Simon *et al*., 1994).

4. 2009 campaign

This second campaign was made with another transportable ultrasonic equipment (Au 2000, CEBTP) working at 54kHz with an assumed acuracy of ±10%. Pieces of bicycle wheel inner tube were used to improve the contact between the transmitter and the receiver on the stone surface. The calibration of the device was controlled with a resin cylindrical bar having a known travel time (29.3µs). The delay induced by the interposition of pieces of inner tube of bicycle on both extremities of the bar was subtracted afterwards from each travel time measurement to obtain the actual transmission time through the stone material. On account of the previous results and not to waste time, only measurements perpendicular to the gallery were performed, exactly at the same spots as 1993 at the bottom and the top of each column.

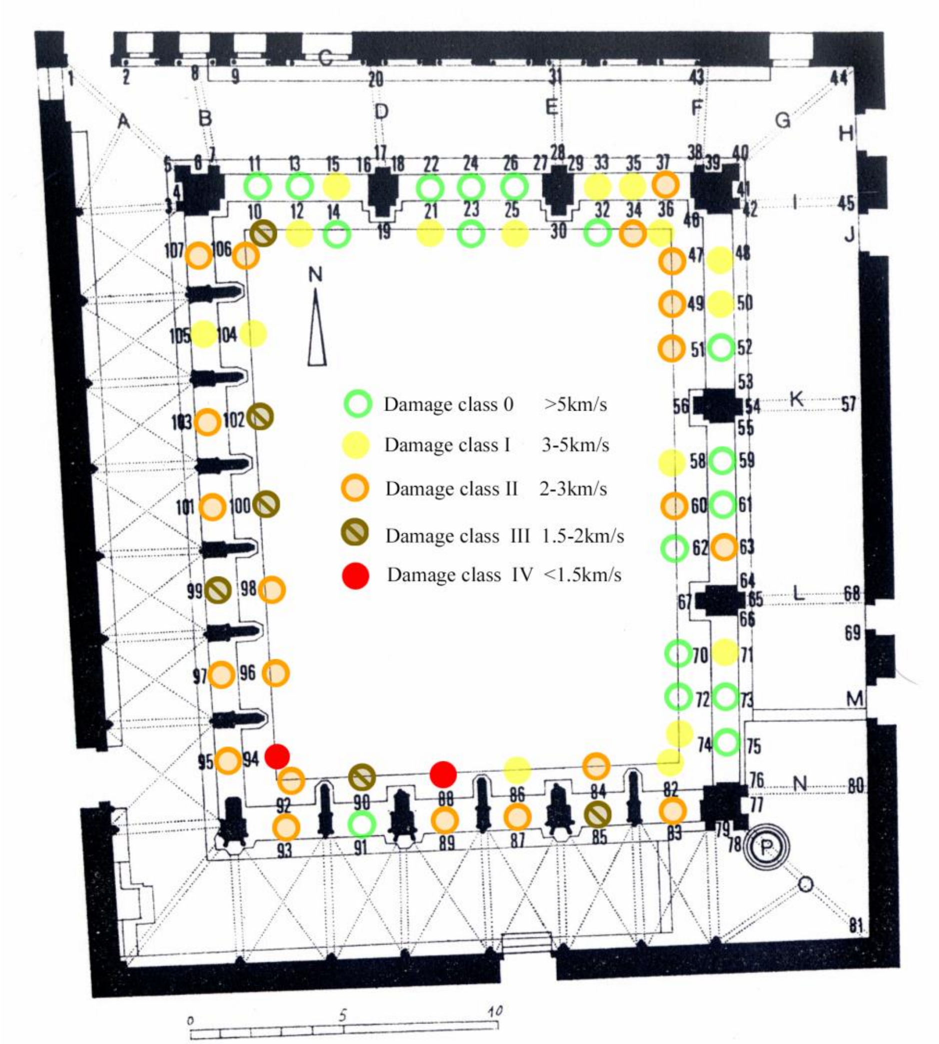

Figure 4. Mapping of the different classes of damage attributed to the 62 columns of the cloister from the ultrasonic velocities measured in 2009

The ultrasonic velocities ranged from 650m/s to 7100m/s (Fig.4). Damage class 0, meaning no damage, still characterized the columns 61, 70, 72, 73, 75 replaced in 1841/42 in the eastern gallery. The highest average velocity was still measured on the columns of the oldest northern gallery (4715m/s) and afterwards on the ones of the east gallery (4500m/s). The younger galleries still showed weaker materials; the average value of the southern gallery was 2770m/s and the lowest average velocity remained for the youngest western gallery (2370 m/s).Velocity was still higher on interior and more sheltered than exterior and more exposed columns (average velocity 4100 vs 3390m/s).

5. Long-term monitoring from 1993 to 2009

The velocities measured in 1993 and 2009 on the columns are significantly correlated (Fig.5). The comparison between the 2 campaigns is relevant in spite of the difference of equipment and frequency. The fact that the correlation is not very good (regression coefficient 0.80) indicates an evolution of these velocities during this period.

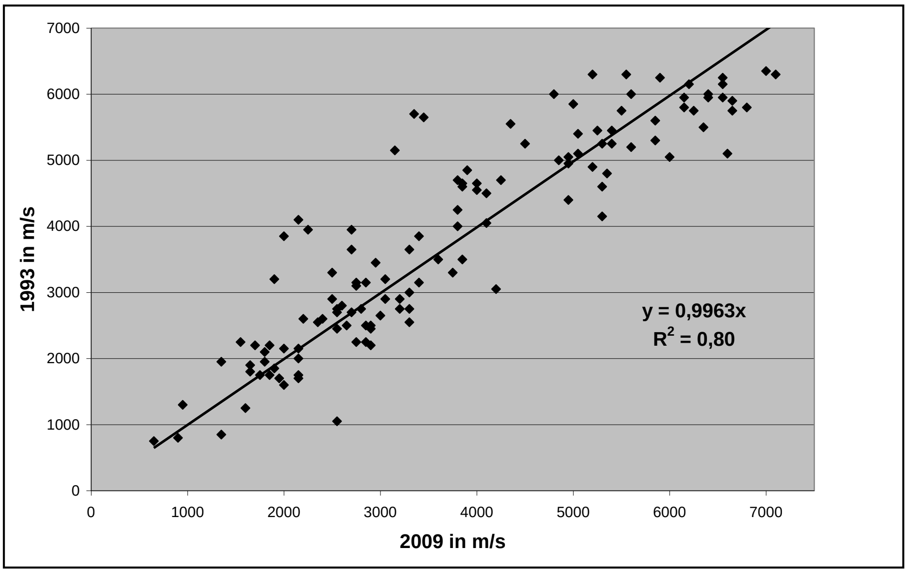

Figure 5. Correlation curve of 1993 measurements vs 2009 measurements for the 62 columns.

		V_{us} (m/s) 1993	V_{us} (m/s) 2009
Gallery	*West*	2500 *(Δv1245)*	2370 *(Δv930)*
	South	3090 *(Δv1145)*	2770 *(Δv1145)*
	East	4340 *(Δv1340)*	4500 *(Δv1445)*
	North	4840 *(Δv1370)*	4715 *(Δv1430)*
Location	*Interior*	4210 *(Δv1550)*	4100 *(Δv1730)*
	Exterior	3430 *(Δv1440)*	3390 *(Δv1455)*

Table 2. Average ultrasonic velocity of the columns in the different galleries and according to their internal or external position (1993 and 2009 campaigns). (*Δv standard deviation)*

The overview of the average ultrasonic velocity of columns in each gallery according to their location (external and internal position with respect to the courtyard) shows that there has been no significant change during the 16 years period (Tab.2). The columns which were in good condition (intern position and located in the oldest Romanesque east and north galleries) in 1993 are still well preserved after 16 years.

Nevertheless several columns have moved toward another class of damage (Tab.3). Fourteen columns have changed for a higher class of damage: the column 88 from class

III to IV, columns 90 and 100 from class II to III and columns 60, 89, 93, 97 from class I to II. Seven columns undamaged in 1993 (class 0) have moved toward damage class I. On the opposite, seven columns have changed for a lower class of damage: columns 95 and 96 have moved from class III to II, columns 71, 82 from class II to class I and columns 14, 23, 59 from class I to class 0. Their state of conservation would have improved within the last 16 years. The fact that 20 columns have changed for another class of damage between 1993 and 2009, provides an indication that the cloister has not been a stable environment for the columns during this period.

Damage class	**1993**	**2009**
Damage class **IV**	94	94 88
Damage class **III**	10-85-88-**95**-96-**99**-102	10-85-90-**99-** 100-102
Damage class **II**	34-37-47-49-51-63-**71-82-**83-**84-**87-90-92-98-100-**101-**103-106-107	34-37-47-49-51-60-63-83-**84-**87-89-92-**93**-(*95*)-(*96*)-**97**-98-**101**-103-106-107
Damage class **I**	14-23-36-**50-**58-**59-**60-74, 86- 89-**93-97-**104-105	12-15-**21**-25-33-35-36,-**48** -**50**-58-(**71**)-74-(**82**)-86-104-105
Damage class **0**	11-12-13-15-**21**-22-24-25-26-32-33-35-**48-52-61**-62-**70-72-73-75**-91	11-13-(14)-22-(23)-24-26-32-**52-**(*59*)**-61**-62-**70-72-73-75-**91

Table 3. Ranking of the 62 columns of the cloister into the different damage classes according 1993 and 2009 campaigns (underlined numbers show columns which have moved to a higher class of damage - Numbers within brackets indicate columns which have moved to a lower class of damage - in bold, column without any superficial degradation feature).

In fact, the calculation of the difference of ultrasonic velocity Dv = $(V_{2009} - V_{1993})*100/V_{1993}$ provides more detailed information on the evolution of the columns. Dv varies between – 49% up to +39% (Tab.4). From 1993 to 2009, 16/62 columns show a velocity reduction of more than 10%. 8/15 of these columns are located in the south-west corner of the cloister in internal as well as external location (Fig.6). Among them, intern columns 89 and 97 show the worst evolution with a Dv between -40 and -49%. Extern column 90 has lost -36% of its velocity. Five other ones (35, 50, 88, 93 and 100) have lost between -20 and -29% and height (12, 15, 21, 25, 33, 60, 98, 101) only -10 to -19%. Twenty nine columns have not been significantly affected by any change, among them the 5 columns placed during Renaux's restoration in 1841/42. The expected drying of marble due to significant improvements of the water collection system in the cloister may account for a limited decrease of the ultrasonic velocity of many columns. As a matter of fact, it is known that ultrasonic velocity is higher on wet stones than on dry ones (Weiss *et al.* 2002; Ahmad *et al.* 2009). Nevertheless this drying cannot explain alone the huge reduction of velocity which points out a worsening of the state of conservation of several columns 16 years after the first campaign of ultrasonic measurements.

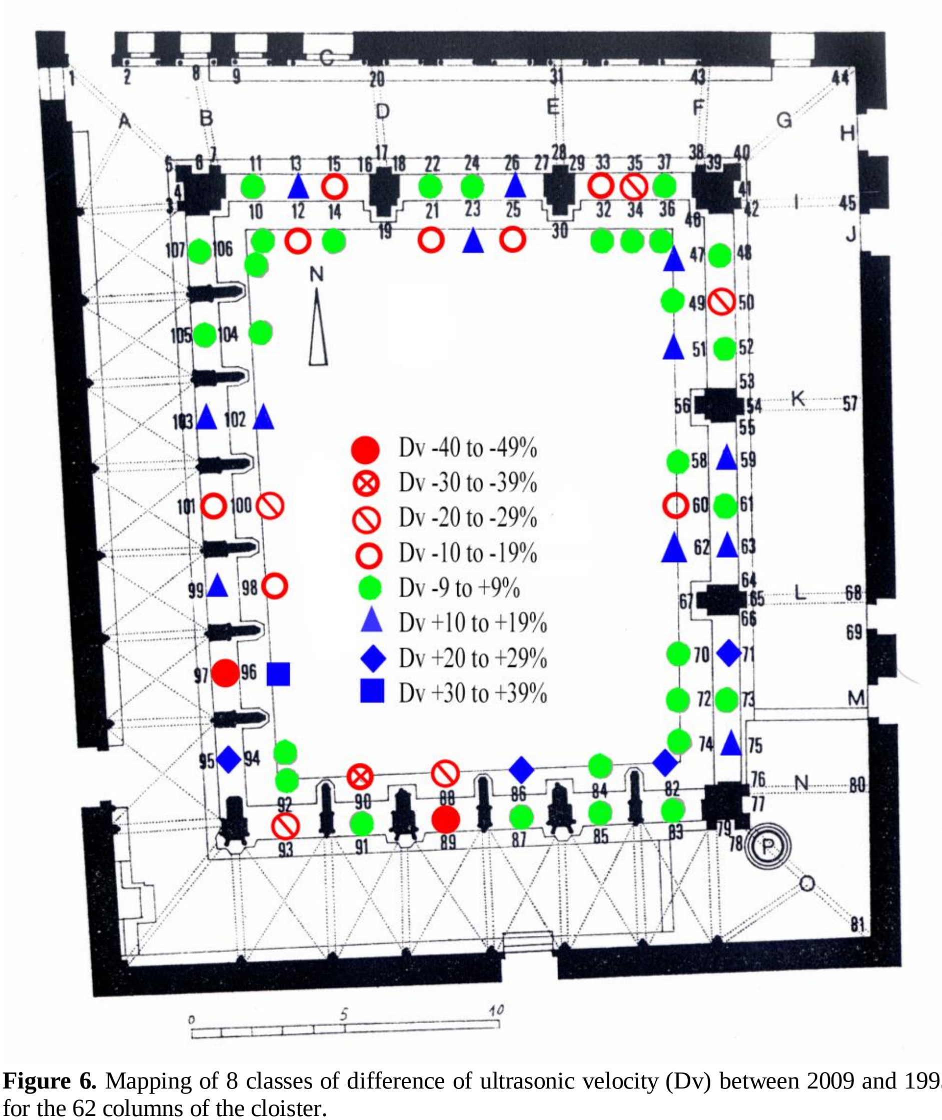

Figure 6. Mapping of 8 classes of difference of ultrasonic velocity (Dv) between 2009 and 1993 for the 62 columns of the cloister.

Ultrasonic velocity of seventeen columns has increased in the range +10% - +34%. These columns belong to the damage classes 0, I, II and III. The phenomenon concerns 7 intern or extern columns of the east gallery, 5 from the west one, 3 from north and 2 from south (Fig.6). This increase is not specifically linked to the application of the sacrificial limewash or the application of facings on scaling parts of the columns (Tab.4) after the 1993 campaign. The ultrasonic devices working respectively at 54 (2009) and 250kHz (1993) have investigated the internal disintegration (microcracking) of marble and not at all the superficial hardening or protective effect of restoration interventions carried out after 1993. In their review, Ahmad *et al.* (2009) pointed out that investigations on the effect of these surface treatments as well as superficial degradation processes required much higher transmitter frequencies (>2000kHz). The evolution toward a higher ultrasonic velocity can not be linked to any water content increase. It should be interpreted as an improvement of the material condition and could result from the reduction of water content within the masonry since 2003/2004 restoration work which intended to reduce rising damp, rainwater run-off and percolation from the terraces. The drying phase induced by this work may have had many consequences on the marble properties for the most exposed columns to water, e.g. a partial filling of pores due to calcite and soluble salts crystallization or an increase of mechanical strength. Closure of microcracks consecutively to modification of loading of the columns after restoration work in the upper part of the building (terraces) is also possible. Study of marble samples and laboratory experiments would be necessary for a deep understanding of the cause of this increasing of velocity.

Difference of velocity Dv	**Column**
-40 to -49%	<u>89</u>-<u>**97**</u>
-30 to -39%	90
-20 to -29%	*35*-**50**-<u>*88*</u>-**93**-<u>100</u>
-10 to -19%	<u>*12*</u>-*15*-**21**-<u>*25*</u>-*33*-<u>*60*</u>-<u>98</u>-<u>**101**</u>
+9 to -9%	*10*-*11*-*14*-*22*-24-<u>*32*</u>-<u>34</u>-*36*-*37*-**48**-*49*-**52**-<u>*58*</u>-**61**-**70**-<u>**72**</u>-**73**-<u>74</u>-83-<u>**84**</u>-*85*-87-91-<u>92</u>-<u>*94*</u>-*104*-<u>105</u>-<u>106</u>-<u>107</u>
+10 to +19%	13-<u>*23*</u>-*26*-47-51-**59**-*62*-63-**75**-<u>**99**</u>-<u>*102*</u>-103
+20 to +29%	**71**-<u>**82**</u>-86-**95**
+30 to +39%	<u>*96*</u>

Table 4. Difference of velocity from 1993 to 2009 (underlined numbers indicate columns which were partially protected with a sacrificial limewash between 1993 and 2009 – in bold column without any superficial degradation features).

In conclusion, this monitoring performed almost over two decades emphasizes the need to improve the conservation state of the columns and justifies both the work undertaken in 2003/2004 to manage the water drainage and the restoration work started in 2012. It offers a very useful tool and an efficient methodology for a regular survey of the condition of the material. The non-destructive character of ultrasonic velocity measurements and its ability to quantify physico-mechanical conditions for natural stone, allows for a long-term, reliable monitoring of change, degradation or consolidation by conservation intervention.

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