ULTRASONIC PULSE VELOCITY – A TOOL FOR THE CONDITION ASSESSMENT OF OUTDOOR MARBLE SCULPTURES

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ABSTRACT

Conservation of outdoor stone sculptures requires planning, which besides visual inspection should be based on physic-mechanical stone parameters. Diagnosis with a non-destructive, cheap and reliable method can be performed with ultrasonic pulse velocity (UPV).
This paper presents the diagnostic study of 25 Carrara marble sculptures with ultrasonic pulse velocity testing in order to sustain a conservation plan. Measured values were converted into damage classes, which were mapped on the front and back side views of each sculpture. This diagnosis study allowed to quantify weathering and gives input to the conservation team, who can establish sustained priorities for the conservation plan. If conservation products are to be applied on the sculptures, ultrasonic pulse velocity should be used to assess the effectiveness and durability of treatments.

INTRODUCTION

Conservation of outdoor stone sculptures requires planning, which besides visual inspection should be based on physic-mechanical stone parameters. Diagnosis with a non-destructive, cheap and reliable method can be performed with ultrasonic pulse velocity (UPV).

Ultrasonic pulse velocity has been widely used to evaluate the damage of stone [1]. Classification systems that categorize stone damage based on UPV were developed and applied to quantify damage particularly in marble. This study aims at assessing the damage level of 25 outdoor sculptures with UPV in order to sustain a conservation plan.

The marble sculptures represent emperors, kings, prince-electors and margraves from Prussia (ancient German empire, corresponding nowadays to Berlin and Brandenburg States) within the period from 12th to the 19th century.
The sculptures were produced between 1988 and 1901 by the will of the German emperor Wilhelm II and were presented in the Siegesallee (Victory Avenue), Berlin, together with other busts. Over a century the sculptures went through two World Wars, a period of neglection and a period of rescue (Table 1).

Table 1: Historical overview [2] of main events that occurred to the Siegesallee Sculptures.

1988-1901	Placement of the sculptures in the Siegesallee on behalf from the emperor Wilhelm II.	
1918	Decay due to revolutionary disturbances	

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1920's	Further decay	
1939-1945	Decay caused by the war	
1950	In August, 28 standing figures and 52 busts are provisory placed in the Meißner wing of the Palace Bellevue.	
1954	The major part of the sculptures is buried in the Southeast wing of the Palace Bellevue.	 (Photo Landesdenkmalamt [2])
1978/79	In winter the sculptures are excavated and provisory placed in the parking place from the Palace Bellevue. Written documentation states that the 26 standing figures and 40 busts after excavation are in astonishing good state of conservation.	 (Photo Landesbildstelle Berlin [2])
1979	After excavation, the sculptures are displayed provisory in the Berlin lapidarium yard (Halleschen Ufer).	 (Photo Landesbildstelle Berlin [2])
1981	The sculptures are displayed in an exhibition room from the lapidarium.	 (Photo Bildarchiv Preußischer Kulturbesitz [2])

Since 2009	The State of Berlin sells 26 standing figures and 40 busts to the Citadel Spandau, where they are transported into and provisory displayed in the yard.	

Presently, the sculptures belong to the Citadel Spandau, where they will be permanently exhibited from 2012 onwards. The aim of this study is to assess the level of deterioration of 25 marble sculptures with ultrasonic pulse velocity, having in mind three goals:

1. Non-destructive inventory of the state of conservation, based on damage classes for marble, to support the establishment of priorities and settle treatment strategies in accordance to the level of deterioration.

2. Allow a future assessment of conservation treatments' effectiveness, namely of consolidant products.

3. Allow a future assessment of conservation treatments' durability, specifically the kinetic of weathering during long term periods.

EXPERIMENTAL

Cultural heritage made of marble displayed outside decays as a function of several factors. Different deterioration processes can act on the surface level (giving rise to the formation of crusts or scaling) or in association with material loss. Fuchs noticed already in 1829 the damage caused by temperature changes in marble grains [3]. Loosening grains result especially from the anisotropy of thermal dilatation from calcite. The thermal stress leads to higher porosity, which enhances the capillary transport of solutions [4].

Changes in marble condition can be assessed by ultrasonic velocity, as this parameter depends on the stone's density, porosity and water content. It can consequently be related to the stones' compactness and to its conservation conditions [5, 6]. Measuring ultrasonic velocity before and after a conservative treatment allows to evaluate the efficacy of the applied product in improving substrate intergranular cohesion to be evaluated [7, 8].

Köhler [9] and Galan et al. [10] suggested classification systems for marble that categorizes stone damage into five classes according to ultrasonic pulse velocity values. These systems are based on a correlation between ultrasonic pulse velocity and porosity for marbles, being these properties inversely proportional. These damage classes were further adapted by [11], and are used in this study (Table 2).

Table 2: Classification of marble damage based on velocity-porosity correlation after [11]

Ultrasonic pulse velocity V_p [km/s]	Description	Damage class
> 5	Fresh	0
3 – 5	Increaseing porosity	1
2 – 3	Progressive granular disintegration	2
1,5 – 2	Danger of breakdown	3
< 1,5	Complete structural damage	4

The inventory consists on mapping the front and back sides of each sculpture with several ultrasonic pulse velocity measurements. The precise measured spot and the surrounding area are then colored in accordance to the corresponding class of damage. Superficial cracks are also mapped. As the sculptures' size ranges from 1.5 x 1.5 x 3.0 m, per figure ca. 30 measurements were performed as suggested by [11]. Each ultrasound measurement is the average of 4 to 6 determinations.

For each sculpture the velocity in dependence of distance was measured. By plotting ultrasonic velocity as a function of the measuring distance, it is possible to have an idea if the weathering profile is homogeneous or not. Therefore, the inventory of each sculpture includes the velocity-distance graphs.

A table with the sculptures' identification (name, author and production date) and correspondent measurement data (place, date, number of measurements, average UPV, average standard deviation and average damage class) is also included in the inventory.

Longitudinal ultrasonic waves in the direct transmission method were measured with the portable measurement device USG 20 (Geotron Elektronik, Germany), operated with a point-shaped 46 kHz-vibrator (UPG-T) and receiver (UPE-T). The accuracy of measurements is assumed to be ± 10%. During the measurement the coupled pressure was steadily increased until the measured transmission time was constant and therefore independent from the pressure applied [12 - 14]. Transducers were coupled to the surface with a suitable elastic material.

RESULTS & DISCUSSION

The interpretation of results is mentioned for 26 figures as within the 25 sculptures one (margrave Johann I and margrave Otto III) is made of two figures.

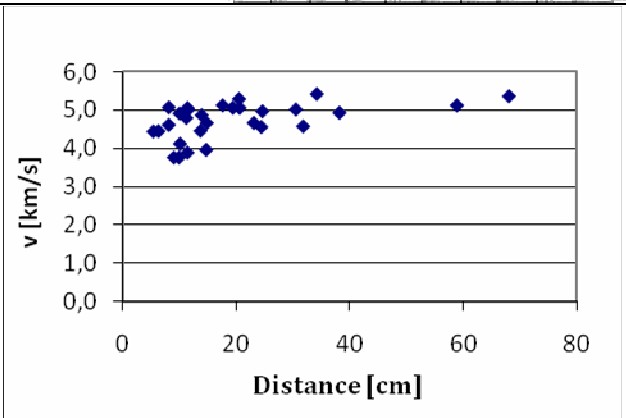
Within 26 figures investigated (Table 3), 5 have average UPV value lower than 3,0 km/s; 17 have average UPV value between 3,0 und 3,9 km/s; and 4 have average UPV value higher than 4,0 km/s. According to these results, 80 % of the stand figures fall into the weathering class 1 and 20% in the class 2. These classes correspond to a marble with growing porosity and a marble with loosening grains.

Table 3: Ultrasound average value (v_{avg}), standard deviation (σ v), **range of deviation (dv)** and average damage class (SK_{avg}) for 26 figures

	Production date	**v_{avg} (km/s)**	**σ v (km/s)**	**dv (km/s)**	**SK_{avg}**
Emperor Karl IV	1899	3,0	0,7	3,0	1
Emperor Sigmund	1900	2,8	0,8	3,7	2
Emperor Wilhelm I	1901	3,1	0,6	2,9	1
King Friedrich I	1900	3,3	0,7	3,0	1
King Friedrich Wilhelm I	1900	2,8	0,6	2,5	2
King Friedrich Wilhelm II	1900	2,8	0,6	2,7	2
King Friedrich Wilhelm III	1901	3,9	0,7	3,1	1
Prince-elector Albrecht Achilles	1900	4,8	0,7	1,7	1
Prince-elector Friedrich I	1900	3,7	0,5	2,1	1
Prince-elector Friedrich II	1898	3,2	0,4	1,5	1
Prince-elector Friedrich Wilhelm	1901	2,6	0,6	3,0	2
Prince-elector Georg Wilhelm	1899	4,6	0,6	2,8	1
Prince-elector Joachim I	1900	3,2	0,4	1,7	1
Prince-elector Joachim II	1900	3,5	0,7	3,3	1
Prince-elector Johann Cicero	1900	3,9	0,9	2,0	1
Prince-elector Johann Georg	1901	4,4	0,6	2,3	1
Prince-elector Johann Sigismund	1901	3,9	0,7	2,7	1
Margrave Albrecht II	1898	2,6	0,7	3,3	2
Margrave Heinrich das Kind	1900	3,2	0,7	2,5	1
Margrave Johann I	1900	3,1	0,7	1,4	1
Margrave Johann II	1900	3,2	0,4	1,8	1
Margrave Otto I	1898	4,8	0,4	3,8	1
Margrave Otto II	1898	3,7	0,6	3,9	1
Margrave Otto III	1900	3,8	0,6	2,6	1
Margrave Otto von Wittelsbach	1899	3,2	0,7	2,6	1
Margrave Waldemar der Große	1900	3,1	0,5	2,5	1

Besides the ultrasonic average values, a closer analysis of the figures allows to locate fragile surfaces, with UPV values within the classes 3, 4 and 5, namely:

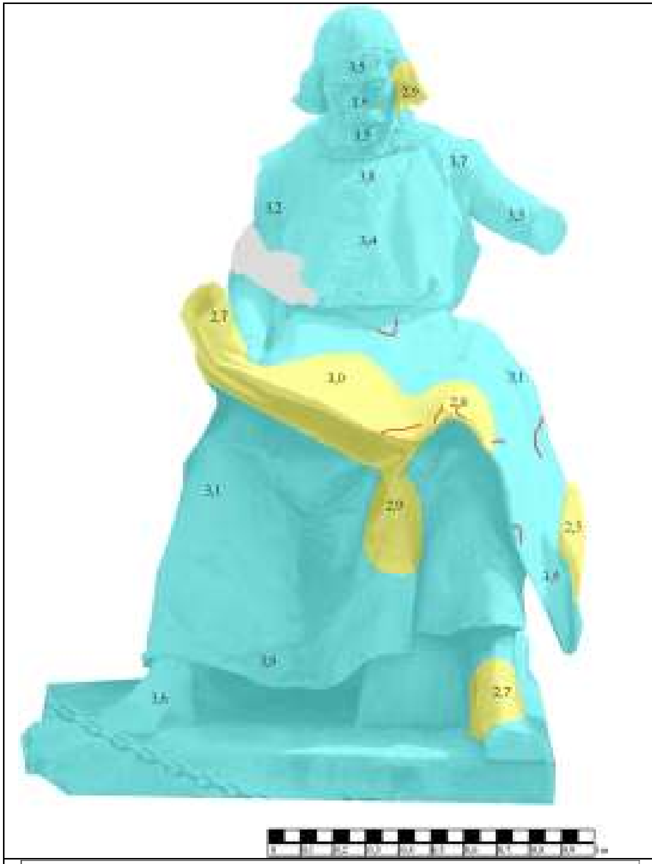
- 3 figures have surfaces which fall into the class 0 and class 1 (see e.g. Fig. 1)
- 10 figures have surfaces which fall into the class 0, class 1 and class 2 (see e.g. Fig. 2)
- 8 figures have surfaces which fall into the class 1, class 2 and class 3
- 5 figures have surfaces which fall into the class 2, class 3 and class 4 (see e.g. Fig. 3)

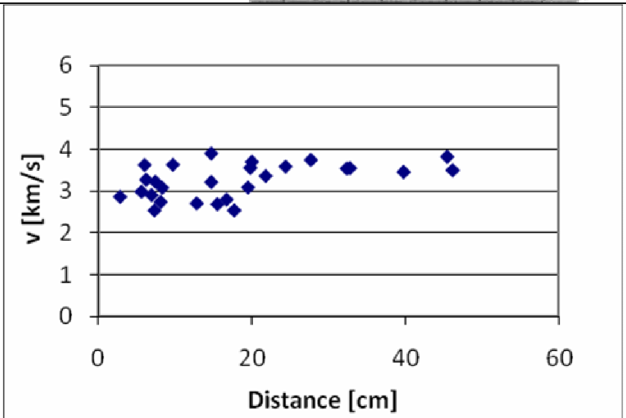


Condition is good.

Name	Prince-elector Albrecht Achilles	Date	August 09
Author	Otto Lessing	n	30
Production date	1900	v_{avg} (km/s)	4,8
Material	Carrara marble	σ v/dv (km/s)	0,7 / 1,7
Place	Citadel Spandau	SK_{avg}	1

Figure 1: Prince-elector Albrecht Achilles has average damage class 1. Some areas have damage classes 0 and 1.

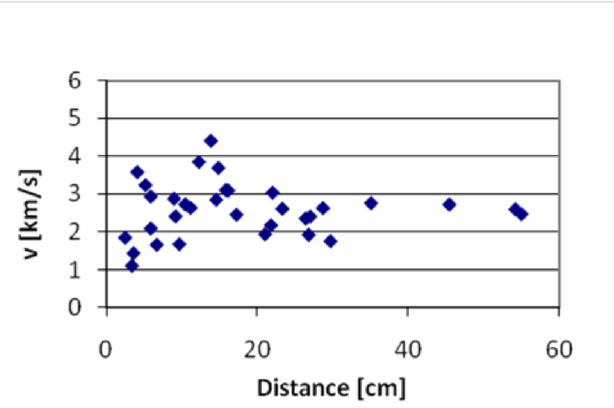




Moderate condition. Fissures should be protected from impacts or loads during transport.

Name	Margrave Johann I	Date	August 09
Author	Max Baumbach	n	27
Production date	1900	v_{avg} (km/s)	3,2
Material	Carrara marble	σ v/dv (km/s)	0,4 / 1,4
Place	Citadel Spandau	SK_{avg}	1

Figure 2: Margrave Johann I has average damage class 1. Some areas have damage classes 1 and 2.



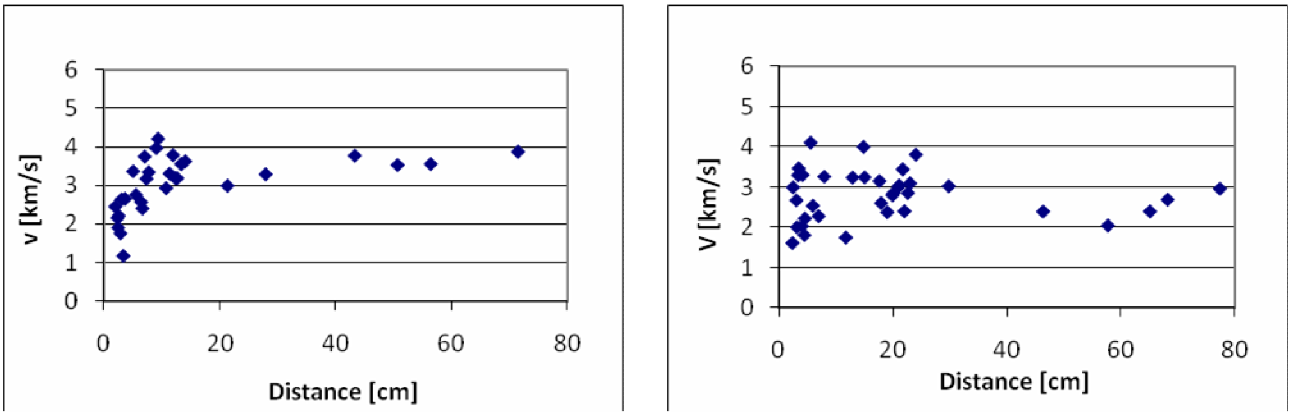
Moderate to severe condition. Exposed areas in damage classes 3 and 4 should be protected from impacts or loads during transport.

Name	Margrave Albrecht II	Date	August 09
Author	Johannes Boesse	n	33
Production date	1898	v_{avg} (km/s)	2,6
Material	Carrara marble	σ v/dv (km/s)	0,7 / 3,3
Place	Citadel Spandau	SK_{avg}	2

Figure 3: Margrave Albrecht II has average damage class 2. Some areas have damage classes 1, 2, 3 and 4.

The 13 figures that have surfaces which fall into the class 3 and class 4 should be very carefully transported to the new exhibition room of the Citadel Spandau. The mapping allows to locate clearly which areas are more fragile and need to be protected during transport. Several cracks should be observed during and after transport, in order to assure that they do now grow.

The velocity-distance graphs allow to address the question whether the weathering progress is homogeneous or not [15] and recognize the inner weathering, which is common for crystalline marbles. From the 26 investigated figures, 23 have the outer surface more weathered than the inner core. There are 3 figures however, which seem to have inner-core weathering (Figure 4). For these 3 figures a consolidation treatment might be considered.



Emperor Karl IV with weathered surface   King Friedrich Wilhelm I with in-depth weathering

Figure 4: Distance-velocity graphs of sculptures showing marble weathering at surface level (left) and marble with in-depth weathering (right).

For outdoor sculptures, there is no direct correlation between the age (time of exposition) and decrease of ultrasonic pulse velocity. The decrease in ultrasound velocity is due to increasing weathering that can be due to negligence, interventions which are technically wrong, microclimatic factors or other surrounding aspects with direct influence, not directly depending on time.

For marble sculptures it was noticed by Simon [16] that the range of deviation in UPV increases with age. Noticeable is a significant scattering for sculptures which were produced around the 1900s. At this period, an increasing interest in statuary marble in Europe went with a quality decrease of the delivered marble [16]. The Siegesallee sculptures are ca. 110 years old and the scattering of their range of deviation (maximum-minimum values) in UPV agrees well with the tendency previously noticed by [16] (Figure 5).

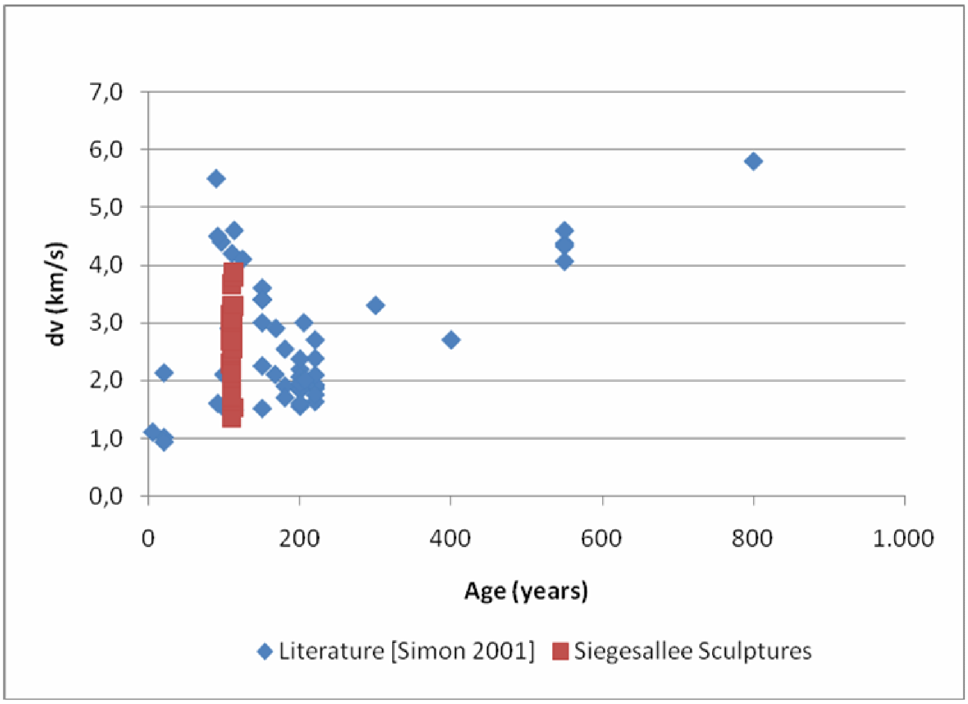


Figure 5: Range of deviation (dv [km/s]) of ultrasonic data collected from Siegesallee sculptures and data from [16] in relation to the sculptures' age.

CONCLUSIONS

Around 30 ultrasonic measurements per sculpture were performed, as suggested for in situ measurements of large sculptures [11]. A list of priority with the needed conservation measures can now be established with the support from the conservation and curatorial teams. Suggested measures are the careful transport of the sculptures to the future exhibition room, taking into account the fragile areas (damage classes 3 and 4) that were found in 50% of the cases.

Further measures as stabilization of cracks, localized or full consolidation treatment are to be discussed and if appropriate, they shall be carried out after testing of products and assessment of their effectiveness with ultrasonic testing. If the 3 sculptures with in-depth weathering are to be consolidated, ultrasonic tomography should be used for the assessment of product effectiveness.

Measurements in the Citadel Spandau were documented in such a way to allow their repetition in future campaigns. If monitoring is required, it should be taken into account that the ultrasonic velocity is dependent on, among others, the degree of water-saturation of the pore space. Therefore, it should be carried out during comparable environmental conditions, e.g. not immediately after rain fall.

Ultrasonic measurements proved to be a fast, economic and reliable tool for diagnosis and planning conservation treatments. The use of this non-destructive technique is recommended for future monitoring campaigns, namely for the evaluation of short-term and long-term performance of conservation products.

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