IN: SIEGESMUND, S. & MIDDENDORF, B. (ED.): MONUMENT FUTURE: DECAY AND CONSERVATION OF STONE. – PROCEEDINGS OF THE 14TH INTERNATIONAL CONGRESS ON THE DETERIORATION AND CONSERVATION OF STONE – VOLUME I AND VOLUME II. MITTELDEUTSCHER VERLAG 2020.

ULTRASONIC TESTING OF THE DOLOMITE MARBLE STATUE OF SOONG CHING-LING WITH RESPECT TO THE DEPTH OF CRACKS AND DETERIORATION STATE

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Abstract

The marble statue of Soong Ching-ling stands in the memorial square of Soong Ching-ling cemetery in Shanghai, China. The statue has been inaugurated in 1984 and is a Chinese National Monument. Since 2014 many micro cracks appeared on the surface, especially on the head of the statue. To evaluate the deterioration condition of the statue and the depth of the cracks, non-destructive ultrasonic technology was applied. The deterioration state was tested by the USCT (Ultrasonic Computed Tomography) method and the depths of surface cracks were determined.

Based on the USCT, there were no penetrative severe cracks. The depth of the superficial cracks on ~~the~~ top of the head was not more than 50mm. However, a clearly deteriorated, shell-like zone with a thickness from 10 to 50mm was found around the head. Fifteen micro cracks were detected and the depths of those cracks ranged from 0 to 68 mm. The results provided fundamental information to work out a preservation concept.

Key words: Soong Ching-ling statue, dolomite marble, ultrasonic detection, USCT, cracks

1. Introduction

Madam Soong Ching-ling(Jun.1893-May.1981) was the wife of Mr. Sun Yat-sen, the founder of the Republic of China and honorary Chairlady of the Peoples' Republic of China. The marble statue of Soong Ching-ling stands in the memorial square of Soong Ching-ling cemetery in Shanghai, China (Fig 1). The statue was inaugurated in 1984. It stands 2.52 m high on top of a granite basement, which is 1.1 m high above the ground level.

The statue is composed of 4 pieces of Fangshan Hanbaiyu, a valuable and famous dolomitic marble from Fangshan, Beijing.

Since 2014 many micro cracks appeared on the surface (Fig 2), especially on the head of the statue (Fig 3).

Mineralogically it consists of approximately 92-97% dolomite($CaMg(CO3)2$): Minor amounts of quartz and muscovite have also been identified.

Inspection under the in-situ microscope shows different stages of disintegration of the crystal fabric on the surface, and even the formation of small marble spalls(Fig 4).

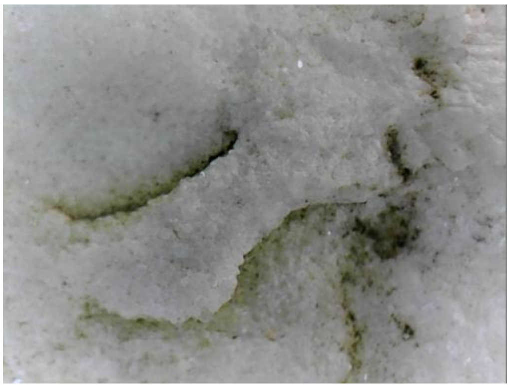
A comprehensive conservation and compatible maintence concept is needed to check the weathering process. But first of all, the deterioration condition of the statue and the depth of the cracks had to be evaluated. Non-destructive ultrasonic technology was applied. The deterioration condition was tested by USCT method and the depths of surface cracks were determined.

Fig 1: Marble statue of Ms. Song in Shanghai

Fig 2: Crack under microscope
The width of the micrograph is is 1cm

Fig 3: Progressive crack on the head

(a)



(b)

Fig 4: Disintegration of crystal fabric (a) and development of spall (b)
The width of the micrograph is 1cm

2. Principle and method of ultrasonic testing

2.1 Ultrasonic wave and natural stone

Ultrasonic waves are mechanical waves which can spread in solid, liquid and gas mediums. They may be differently attenuated when propagating in different mediums, and also have different velocities in different mediums. The velocity and the attenuation are the two most important parameters in ultrasonic testing.

For the ultrasonic testing of stone, the favourable frequency range is 20kHz-1000 kHz. The velocity and attenuation of ultrasonic waves in stone depend among other factors on the density, water content and cracks. The amplitude and velocity of the first wave received are positively correlated to the mechanical strength of the stone, and the mechanical strength directly responds to the weathering condition of the stone.

Therefore ultrasonic testing is an appropriate method to detect the position and trend of weathered zones band and cracks inside a stone.

There are many reasons for some cracks, crazings, and splits on the surface and in the interior of stone sculptures. Ultrasonic waves may go directly through a crack if the fracture surfaces are still in contact with each other with little effect on the velocity but with a distinct attenuation of the amplitude. For the situation that the fracture surfaces are completely apart from each other, the waves bypass the crack and the transit time increases. Due to the open split that runs through the stone, the wave will not be received on the other side.

For evaluating the stone weathering level, we use the P-wave velocity v normalized with respect to the velocity of an unweathered sample V_0 as shown in table 1, which is normally used by conservators. For the Fangshan Hanbaiyu marble V_0 is about 4500 m/s.

Table 1. Normalized velocity ratios for the definition of stone weathering levels

Weathering Level	V_i/V_0
Not Weathered	≥0.9
Void ratio increased	0.75-0.9
Floor level of weathering	0.75
Slightly weathered	0.5-0.75
Moderately weathered	0.25-0.5
Severely weathered	≤ 0.25

2.2 Crack depth detection

In case of open cracks the ultrasonic waves run from the emitting probe to the end of a crack, and then back to the receiving probe. Assuming that the crack is perpendicular to the surface and the ultrasonic waves progagate with constant velocity, the depth can be easily calculated.

We measure the ultrasonic transit times between points A and B for the path ACB and between points D and F for the path DCF, and also the distances AE and DE for mode A. For mode B, the respective transit times are for the paths ACB and and ACE and the distances AD and DB as shown in Fig 5. The choice of mode A or B depends on the field situation. The data is evaluated with respect to the crack depth by Equation 1 (mode A) or Equation 2 (mode B). Both equations can be deduced by geometrical reasoning from the sketches in Fig. 5.

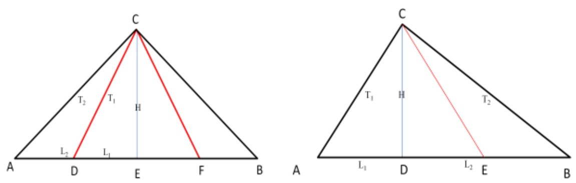


Fig 5: Crack depth detection modes

$$H^2 = \frac{{T_1}^2({L_2}^2 - {L_1}^2)}{{T_2}^2 - {T_1}^2} - {L_1}^2$$

T_1 - ultrasound wave time DCF; T_2 - ultrasound wave time ACB
L_1 - distance DE; L_2 - distance AE
H - height of the triangle, depth of the crack

Eq 1: Crack depth equation of mode A

$$H^2 = \frac{{T_1}^2({L_2}^2 - {L_1}^2)}{4({T_2}^2 - T_1 T_2)} - {L_1}^2$$

T_1 - ultrasound wave time ACE; T_2 - ultrasound wave time ACB
L_1 - distance AD; L_2 - distance BD
H - height of the triangle, depth of the crack

Eq 2: Crack depth equation of mode B

2.3. Ultrasonic CT method

The principle of ultrasonic CT is shown in Fig 6. Abundant data of wave time are collected by fanshaped testing. S_1-S_n are the emitting points, R_{11}, R_{12}…R_{ni}, R_{nj} are the corresponding receiving points.

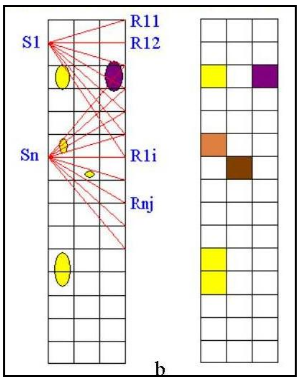


Fig 6. Principle of ultrasonic CT

Hypothesize that there are N testing line in the section plane, and the section plane may be separated to M grids on request of calculating accuracy. The result will be got by solving the matrix equation below:

$$\begin{bmatrix} l_{11} & l_{12} & \cdots & l_{1M} \\ l_{21} & l_{22} & \cdots & l_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ l_{N1} & l_{N2} & \cdots & l_{NM} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ \cdots \\ S_M \end{bmatrix} = \begin{bmatrix} t_1 \\ t_2 \\ \cdots \\ t_N \end{bmatrix}$$

l_{ij} - length of path i in unit j;
$S_j=1/V_j$ - slowness of unit j;
t_i - wave time of path i.

Eq 3 USCT matrix equation

The velocity V_j of ultrasonic wave in each unit the section is given by the reciprocal of each S_j.

3. Detecting of the statue

3.1. Detecting for the depth of the cracks

There were 77 micro cracks observed on the surface of the statue. 15 of them were chosen for testing with either mode A or B, depending on the position of the crack.

The ultrasonic device used was a Proceq PunditLab+, with the precision of 0.1μs and the probes were Proceq 40 17-B 54KHz conical probes(Fig 7), with the contact diameter area of 4mm, that ensures the precision of the contact points and the accurcy of testing results. Fig 8 shows examples of cracks detected. Table 2 shows the calculated depth results of fifteen cracks and the depth ranged from 0 to 68mm.

Fig 7: Probe for crack depth detection

Fig 8: Cracks in the marble of the Soong Ching-ling statue

3.2 USCT testing of the head

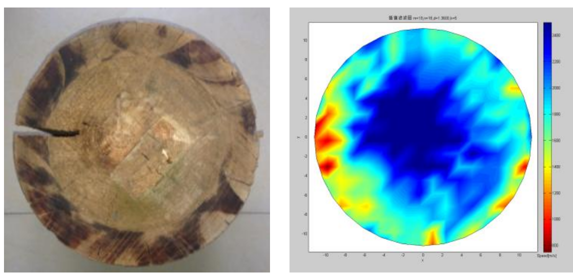
The authors have developed a USCT system that can be used for testing wood and stone structures. It comprises a Proceq Pundit Lab+ non-metal ultrasonic device, an amplifier between the receiving probe and the detector, a sensor diameter convertor, a multi sensor fixator and the USCT analysis software. We have 20 Sonotec L40 54kHz sensors of diameter 50 mm, and the convertors transmit the diameter to 10 mm when contacted the tested object. That makes the coordinates of each contacting points more precise. Non couplant is used for testing thus avoiding the penetration of couplants into the object through open cracks.

Table 2: Crack depth data

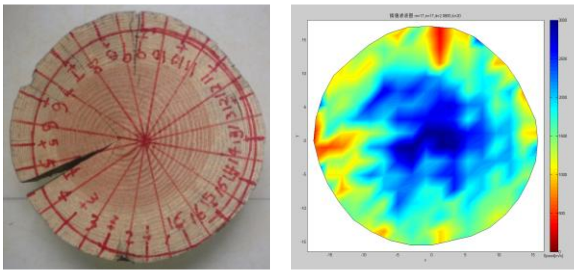
Number	Direction	Mode	Wave time(μs)		t_2/t_1	H(mm)
			t_1	t_2		
Blank	Horizontal	A	34.5	69.3	2.009	0
1-1	Horizontal	A	37.9	66.2	1.747	34
1-2		A	38.2	72.1	1.887	21
1-3		A	42.4	72.1	1.700	38
2	Vertical	A	36.9	56.5	1.531	55
3		B	20.8	31.4	1.510	0
4	Horizontal	A	43.3	75	1.732	35
5	Vertical	A	36.9	54.1	1.466	63
6	Vertical	B	34.3	47.8	1.394	30
7		B	37.8	57.5	1.521	0
8		B	34.5	49.6	1.438	22
9		B	21.4	32.8	1.533	0
10	Vertical	B	21	31.3	1.490	5
11		B	25.3	35.1	1.387	19
12	Horizontal	B	38.8	51.1	1.317	45
13	Vertical	B	19.2	28.8	1.500	0
14	Horizontal	B	24.9	33	1.325	26
15-1	Horizontal	A	45.2	75.8	1.677	40
15-2		A	42	72	1.714	37
15-3		A	41.5	75.8	1.827	27

Laboratory tests were made with several wood and limestone samples, and the USCT images correspond very well with the visible appearance of the samples commendably. Fig 9 shows four of them. All the equipments can be packed into one suitcase and easily transported for on-site testing. Fig 10 shows on-site USCT testing.

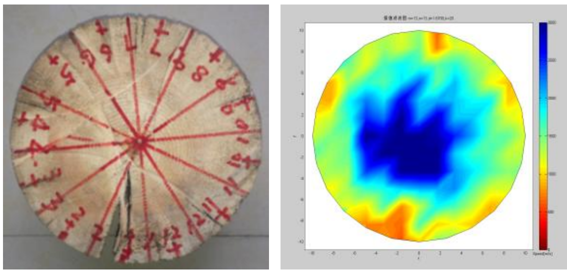
For the on-site testing of the statue, a section of the cranial region of the statue was chosen as shown in fig 11, and sixteen probes were used. Fig 12 shows the USCT detecting system and USCT images. The ultrasonic velocity in fresh marble similar to the material of the statue is about 4500m/s, and the measured velocities shown in the result images range between 1000-4500m/s



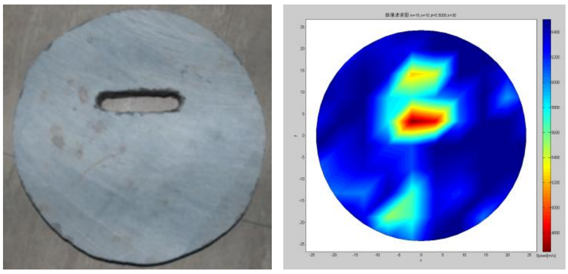
a. Φ 22cm wood sample and corresponding USCT image



b. Φ 28cm wood sample and corresponding USCT image



c. Φ 22cm wood sample and the corresponding USCT image

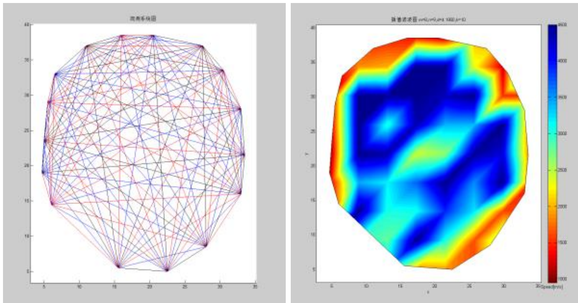


d. Φ 55cm limestone sample and corresponding USCT image

Fig 9: Laboratory samples and corresponding USCT images

Fig 10. On-site USCT testing

Fig 11: USCT testing section



a.USCT testing array b. USCT image

Fig 12: USCT testing

According to the USCT results no penetrative severe cracks were found. The depth of the superficial cracks on the top of the head was not more than 50 mm. However, a clearly deteriorated zone with a thickness from 10 to 50 mm, caused by the disintegration of the crystal fabric, was found around the head.

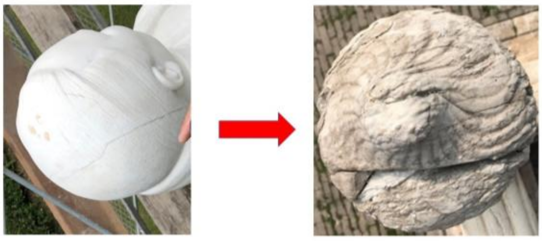
4. Conclusion

According to the observation, almost all of the 77 cracks should be developed from the stone interlayers. The depth of 15 cracks has been detected and the results are between 0-68mm. By UCT, a losen zone with thickness up to 50mm has also been found.

For the reason of the statue has just been exposed to the natural environment for only 35 years, the marble should be in the early stage of deterioration, that is surface crystal fabric loosing and surface cracks developing.

If no effective measures are taken, the deterioration level of the statue may increase quickly, perhaps even seriously in the next 50 years producing a similar state as the marble railing of Tian'anmen-Qing Dynasty monument (Fig 13).

It is absolutely necessary to fill cracks and crystal gaps with suitable materials to slow down the deterioration process.



Head of the Statue Marble railing of Qing Dynasty monument

Fig 13: Lack of effective protection leads to serious deterioration

Acknowledgement

This research was financially supported by the Honorary Chairman Soong Ching-ling Mausoleum Of The P.R.C. and by National Natural Science Foundation of China (No 51978472).

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