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Coordinated application of structural strengthening injections with GPR method for restoration of historical artifacts: example study of Bodrum castle

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Abstract

Shallow geophysical methods are increasingly used for non-destructive assessment of structures and in line with this a variety of methods have come to the forefront for research of cultural heritage buildings. However, correct selection of geophysical method and targeted studies with historical structural knowledge will be effective and beneficial for restoration of cultural heritage structures. In this article, the GPR method was chosen with the aim of obtaining data forming the basis of injection studies to strengthen the fortification walls of Bodrum (*Halikarnassus*) Castle and to identify small anomalies (nearly centimeter size). The aim of the study was first to identify the locations of structural problems like cavities or degradation formed in the walls of the historical castle to effectively apply the injections and secondly to reveal the effect of the injections. GPR data identified cavities before injection and checks were performed at intervals after the injection to identify the effect of the injection and the best drying duration.

Keywords: structural strengthening injections, fortification wall, cavity, GPR

1. Introduction

The most important aim of restoration studies is to transfer many historical and archeological architectural artifacts that have reached the present from the past to future generations. In Turkey, as throughout the world, renovation and strengthening studies of historical artifacts are completed with joint studies involving many scientific branches such as architecture, restoration, art history and structural engineering (Annan 2003; Daniels 2004; Carcione 1996). Due to developing technologies, studies called shallow geophysical methods, generally based on electromagnetic methods, provide high sensitivity non-destructive solutions and have become indispensable for restoration studies (Pérez-Gracia *et al.* 2008; Gracia *et al.* 2007; Pérez-Gracia *et al.* 2013; Kanli *et al.* 2015).

Ground penetrating radar (GPR) is the most important and promising non-destructive (NDT) geophysical method with a broad area of use from geology and environmental studies to structural engineering (Pieraccini *et al.* 2005; Pérez-Gracia *et al.* 2008, 2013; Gracia *et al.* 2007; Kanli *et al.* 2015). Additionally, it is commonly used in many areas such as modern and historical bridge piers, road and railway research and tunnel studies (Annan 2003; Liu *et al.* 2007; Wai-Lok *et al.* 2018). As the GPR method includes receiving and transmitting antennae, they can be moved over the area of application providing reliable results with rapid and high data intensity over broad areas. Radar waves cannot penetrate metal material due to the nature of electromagnetic waves; however, they can easily pass through and reveal other structural elements (cement, stone, brick etc.). As a result, metal formations can be easily identified within structural materials. There are antennae with difference frequencies produced for different depths that can be obtained commercially. A low frequency antenna transmits waves that penetrate deeply

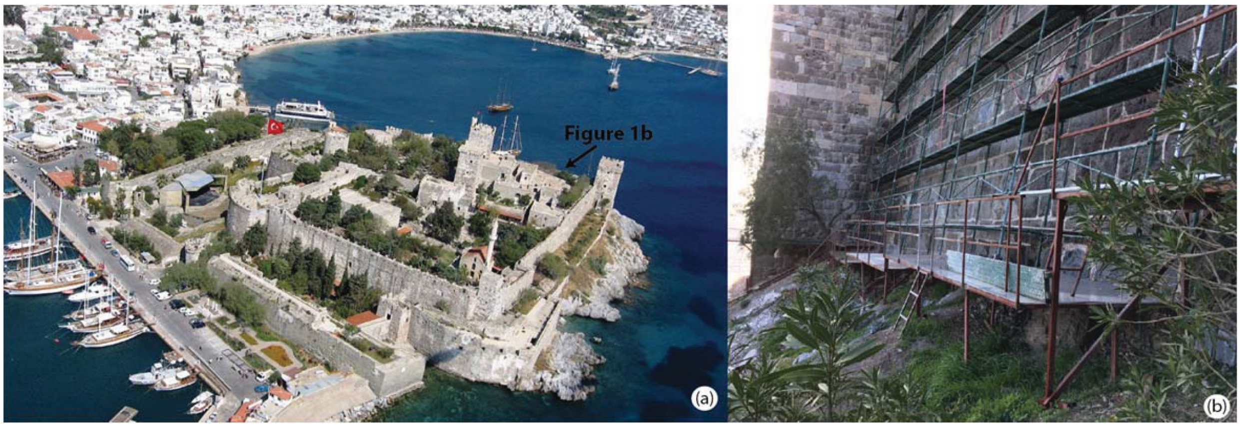

Figure 1. (a) General appearance of Bodrum Castle and (b) the fortification wall in the study.

with lower depth resolution, while a high frequency antenna provides radar waves with high depth resolution that penetrate shallow depths. The use of a high frequency can determine invisible elements, such as areas with iron reinforcement in general, cavities, damp, layering and disintegration, in cement and stone wall-type structures. Among non-destructive (NDT) methods with easy and rapid use, GPR is a very appropriate method to research historical artifacts.

The GPR method, called structural radar (1–2.3 GHz), is based on very high frequencies reaching shallow depths (0–200 cm). It provides rapid and high resolution (0.5–2 cm horizontal resolution) and is used with the aim of researching many structures with archeological and historical importance without causing destruction (Yalciner *et al.* 2017).

Bodrum Castle, where the study was completed, was constructed by the Knights of St. John (Knights Hospitallers) from 1406–1522 on a rocky peninsula surrounded by sea on three sides between two piers. Construction of the castle used stones from one of the seven wonders of the ancient world, the Mausoleum at Halicarnassus, which had been destroyed in an earthquake. The castle contained French, Italian, English, German and Spanish (Yılanlı) towers. After the island of Rhodes was taken by the Turks in 1522, the knights abandoned Bodrum and surroundings on 5 January 1523. Used as a prison since 1895, the castle was bombed by the French and English during World War I from 26–28 May 1915 and was abandoned in semi-destroyed form (figure 1a). Fortification walls considered to be for strengthening during the restoration of Bodrum Castle had the GPR (1.6 GHz antenna) method applied (figure 1b). The target was to identify cavities and disintegration within the fortification walls using the GPR method and to provide information before injections with the aim of strengthening. Then the efficacy of the injections was tested.

2. GPR method and field studies

GPR is a method commonly applied for research of archeological and historical structures (Carcione 1996; Daniels 2004; Pieraccini *et al.* 2005; Pérez-Gracia *et al.* 2008, 2013 Solla *et al.* 2011). GPR antennas transmit waves (1–60 ns) at short electromagnetic beats in the interval VHF/UHF band (30–3000 MHz). The beats are conducted toward the investigated environment. The reflections of these beats produce interfaces between regions with different electromagnetic characteristics (Pérez-Gracia *et al.* 2000). Part of the energy produced returns to the receiver antenna at the surface while the remainder is diffused. The receiver antenna includes an electronic circuit called a 'demodulator linked to amplifier and receiver circuit', which digitizes the electromagnetic waves and sends them to the main control unit. Each wave obtained is accepted as a trace. In this way, waves returning to the antenna as it measures and is moved are defined as traces in the main unit and transformed into profiles. On the profiles, the transmission-return time, defined as the travel time, is used to complete depth calculations (if the speed of the environment is known). In situations where the depth is known, such as castle walls, the speed of the environment may be similarly determined. In spite of this, this value may change linked to variations in the materials (Annan 2003; Pérez-Gracia *et al.* 2008). Due to the contrast between the dielectric constant in air and unweathered limestone variations are expected in fractured or damaged regions. Air in fractures will probably produce an increase in the mean wave speed. The mean speed of the wave in the environment is linked to different phases (solid or mineral compounds, fluid – generally water – and gas or air). Combinations of phases determine the electromagnetic behavior of the soil, including the wave speed (figures 2a–d). The speed in air is higher than in minerals so the speed is expected to increase in the presence of many fractures. In this way, damaged regions may be defined

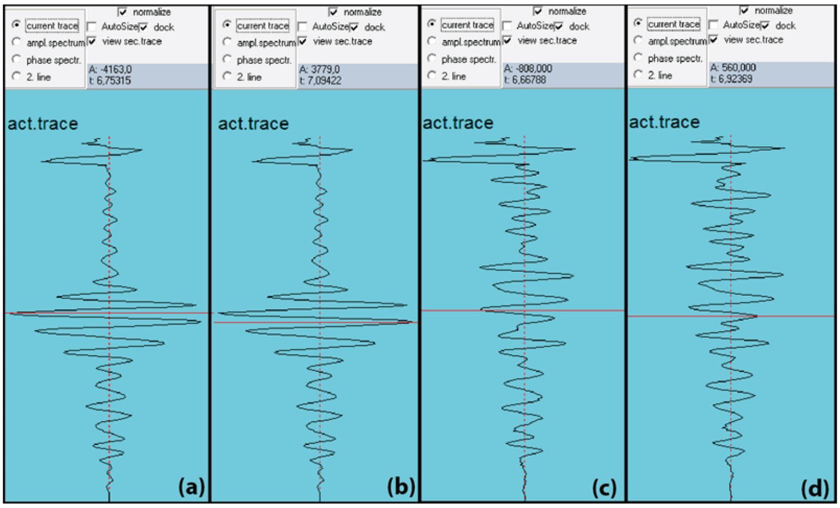

Figure 2. Amplitudes obtained from wall measurements. (a) Negative amplitude above the cavity, (b) positive amplitude above the cavity, (c) negative amplitude at the solid level and (d) positive amplitude at the solid level.

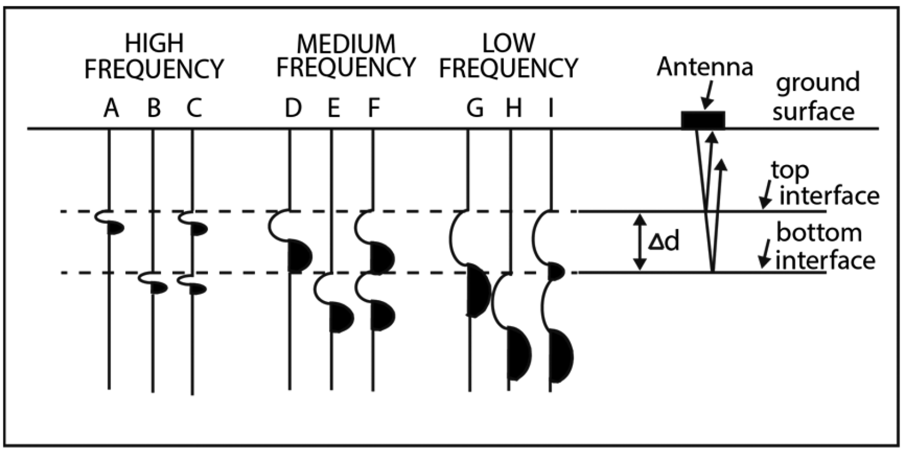

Figure 3. Schematic of GPR traces between layers (Conyers 2004).

by clear changes in wave speed and noticeable reflections in discontinuities. Resolution is essentially linked to the characteristics of the material and the wave frequency band (Annan 2003; Pérez-Gracia *et al.* 2008). Higher frequencies present high resolution but reduce penetration depth. As shown in figure 3, according to the energy of the transmitted frequency, the thickness between two layers (Δd) and vertical resolution are determined. High energy is sufficient to identify the upper and lower boundaries of (A) and (B) layers and obtain an image of the junction between the two (C). Moderate frequencies can only identify the upper boundary of the layer due to having longer wavelength (D, E and F). Though low frequencies pass through all layers, they do not provide very clear images due to the very wide wavelength (G, H and I) (Conyers 2004). Considering the structure researched (wall thickness 100–150 cm) and the detail desired for the results (cm scale) in this study, measurements were completed with a 1.6 GHz central frequency GPR antenna.

For field studies, the part of the fortification wall that may have experienced most damage (seaward side) was determined with the aid and recommendations of art historians and test measurements were performed on the wall (figure 4a). Before test measurements, a 140 × 140 cm chart was used (figure 4b). Measurements were completed at both horizontal and vertical intervals of 10 cm with 0.5 cm chosen as the point interval. The volumetric 3D presentation of GPR data results showed the cavity with an amplitude threshold between −2048 and 2048 (figure 5). With the aim of providing GPR results identifying cavity areas as a result of test measurements, the identified cavities were visually investigated with an endoscopic camera (figure 6). The cavity area confirmed by endoscopic imaging had injection procedures performed. After the injection procedures, the measurement times for control GPR processes was debated. Though the injection process used 8 bar pressure, it required a certain duration to reach functionality by converting from fluid to

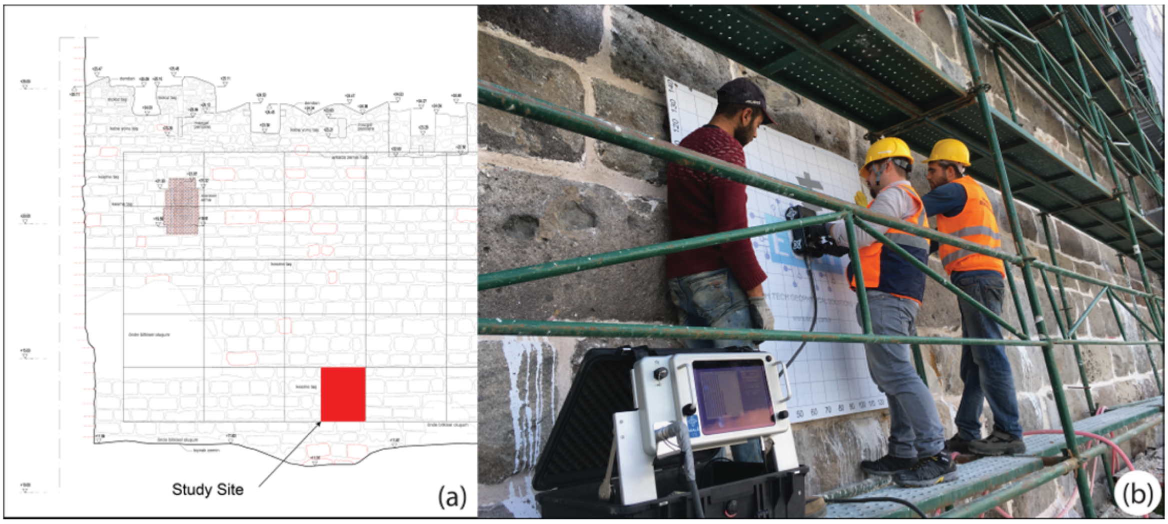

Figure 4. GPR studies: (a) measurement region on plan (area in red shows fortification wall in the study) and (b) GPR photograph during measurement.

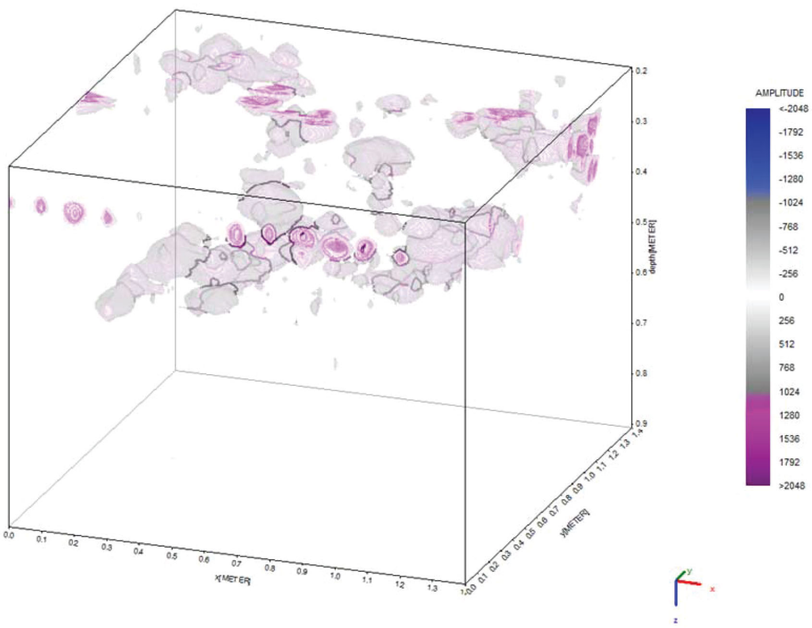

Figure 5. Volumetric 3D presentation of GPR data results before injection (cavity proportion 17.73%).

solid form and this duration varies according to environmental conditions (temperature, humidity etc.) from 7–14 days as confirmed by the experts applying the injections. With the aim of monitoring this interaction process, GPR measurements were first performed 7 days later, the second 15 days later and finally 21 days later (figure 7a–d). Care was taken that all measurements were performed with the device in the same area and format (battery status, temperature etc.). Additionally, parameters used for GPR measurements (Table 1) and data processing steps and parameters applied after measurements (Table 2) were applied with the same values every time.

3. Discussion and conclusions

The non-destructive method of GPR is a very effective method for research of historical structures with high value obtaining intense data and rapid measurements. Most of the fortification walls of Bodrum Castle comprise limestone, sandstone and low amounts of volcanic stones. In addition to the dielectric difference between the rock types, the GPR method provided a high-resolution result for identification of disintegration, cavities and missing material. Additionally, the low-density mortar used between the stones as filling material has a high air content. Over time, cavities and disintegration forming in the castle fortifications has negatively

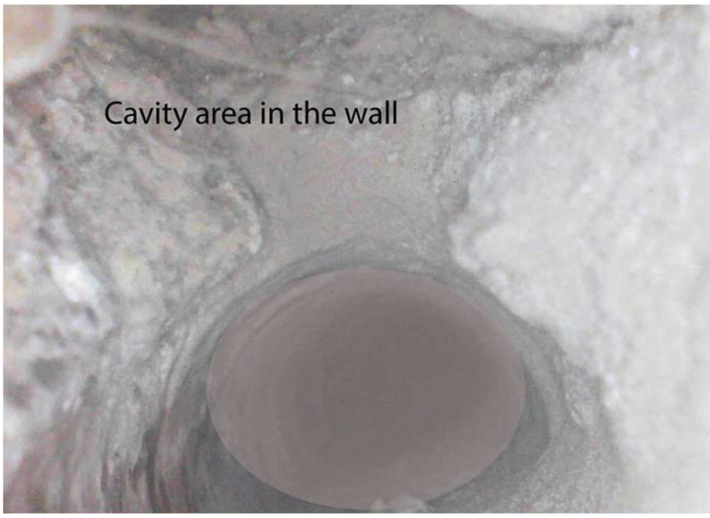

Figure 6. Endoscopic camera image.

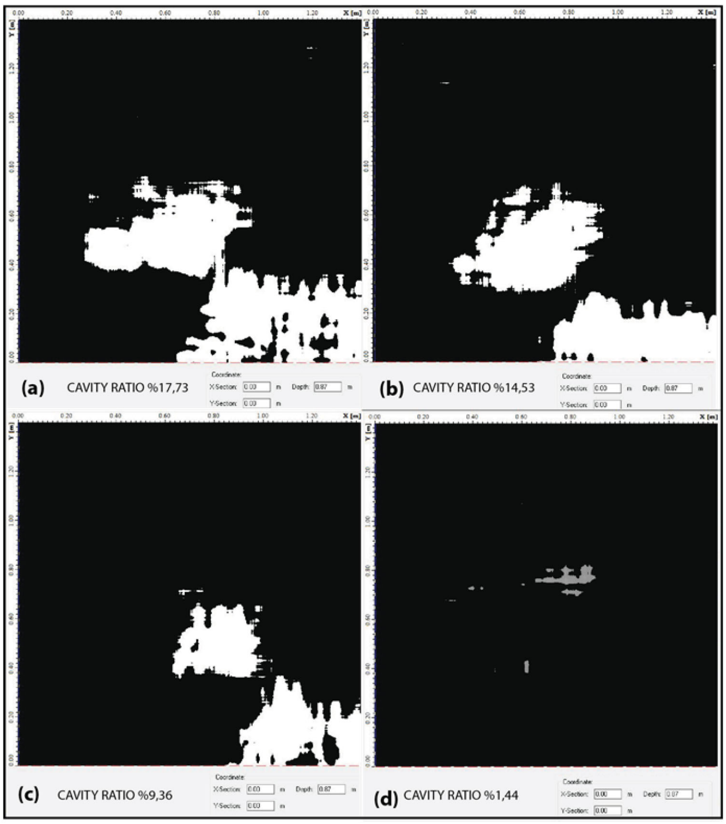

Figure 7. GPR depth sections obtained at an 87 cm depth in the measurement area: (a) measurement results before injection (cavity proportion 17.73%), (b) measurement results 7 days after injection (cavity proportion 14.53%), (c) measurement results 15 days after injection (cavity proportion 9.36%) and (d) measurement results 21 days after injection (cavity proportion 1.44%).

affected the carrying capacity of the wall. For injection processes performed with the aim of strengthening, identifying this type of cavity has great importance. Injection applications may cause more harm than benefit if performed when the structural state of the wall is not well-known and so should be very carefully applied to structures with historical importance. As a result, if there is disruption of the natural structure of the wall or if the injection is applied at high pressure, it may cause fracturing or static disruption of the wall. Similarly, applying insufficient injections to a wall with excess cavities or fractures will only place more load on the wall. Due to this type of method revealing the state of the wall

Table 1. GPR measurement parameters

Antenna frequency	1.6 GHz
Trace interval	0.005 m
Samples	312
Sampling frequency	19 000 MHz
Signal position	31.84210526
Raw signal position	47 385
Time window	16.421053 ns
Profile interval	0.1 m

Table 2. Filter processing steps and parameters of the GPR survey

Filter Name	Parameters
Antenna frequency	1.6 GHz
Time-zero correction	−1.35 ns
Subtract-mean (dewow)	0.6181
Band-pass filter	640/1280/1920/2560 MHz
Energy decay	0.512
Subtracting average	31 trace/0 to 11.6413 ns
Velocity analysis	0.13 m ns^{-1}
Diffraction stack migration	11 trace/0.13 m ns^{-1}/0 to 11.6413 ns/$\varepsilon r = 8.7$

nondestructively, the necessity for the injection is revealed in addition to ensuring the correct amount of injection is performed in accurately selected areas.

Data obtained from test measurements provided understandable visuals with the data processing stages. GPR data identified a cavity at depth (87 cm), which was transformed to a black and white image. Using code prepared in the MATLAB program, white areas above a certain threshold were defined as cavity with the area of the cavity determined as a percentage of the whole area (figure 7). As can be clearly seen from black and white depth sections obtained from all measurements and assessed with the same threshold value and digital data, the observed reduction in cavity proportion (figure 8) shows the success of the injection process. Additionally, it is understood the hardening time for the injection to gain functionality is longer than 14 days (14–21 days). Measurements of the whole of the tested wall clearly show the reduction in identified cavities on measurement results after the injection on figure 7 (cavity proportion 17.73% to 1.44%).

Before structural strengthening studies, GPR identification of cavities and disintegrations formed a foundation for the injection process and similarly measurements after injection revealed the efficacy of the injection results and the state of the fortification wall. Before injection-style restoration of cultural heritage structures with large scale and historical importance like Bodrum Castle, it is very important to clearly reveal the state of the walls. Otherwise, there is no return after making a mistake and irreparable damage may be made to the historical heritage. While identifying the approximate volume of cavities within the wall determined the amount of the injection needed, the control measurements afterward reveal the success of this process and show the final state of the wall. In the future, this type of study can be performed on walls with different material and structural elements in different climatic conditions and will contribute to the preservation of many historical and archeological artifacts from the past to the future. Considering the sensitivity and cost of the injection process, the importance of non-destructive imaging processes is obvious in terms of time and cost. This study shows GPR-based non-destructive geophysical methods can be used rapidly, reliably and productively for research of cultural heritage structures.

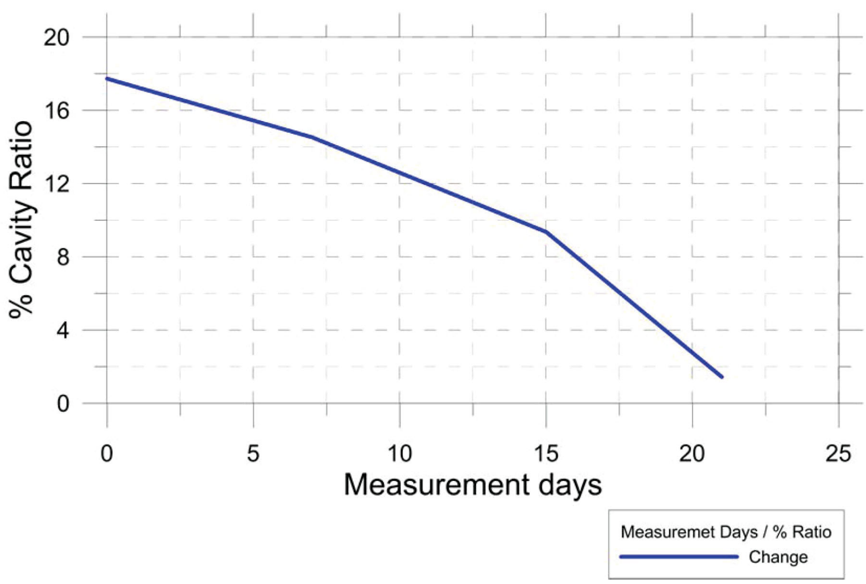

Figure 8. Variation graph in percent according to measurement days.

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Conflict of interest statement. None declared.

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