# Issues in the Identification and Monitoring of Historical Structures – Monuments

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**ABSTRACT**

This paper aims to introduce a general methodology for the structural identification and monitoring of historical monuments. The identification and monitoring procedure was discussed within four main frameworks: (1) visual inspection, (2) finite element modeling, analysis, updating, validation and simulation, (3) short term measurements, and (4) long term monitoring. The defined approach targets to determine the current state (material data, structural behavior, and existence/extend of damage) of structure as well as monitor changes and extrapolate them over time or event basis (e.g. environmental deterioration and earthquakes). The mentioned steps were presented in the form of a detailed and hierarchical schema regarding both methodology and instrumentation. The methods proposed for the structural identification and material characterization of monuments were mainly non-destructive. In addition, the eminent monuments of the Mount Nemrud in Adıyaman, Turkey were chosen as a case study, briefly explaining the preparation studies carried out so far.

**KEYWORDS**

Structural monitoring, Historical structures, Non-destructive methods, Finite element modeling and analysis, Structural identification

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## 1 INTRODUCTION

The identification, monitoring, and evaluation of historical structures / monuments have some additional difficulties in comparison with that of modern structures. These difficulties were mentioned before by many scholars [i.e. Lourenço 2002 and Binda & Anzani 1997]. The most important of them can be briefly listed as follows:

1. There are no standards applicable for monitoring and system identification (St-Id) of historical structures,
2. The physical, mechanical, chemical, and compositional characterization of materials are difficult, expensive and sometimes too destructive to be accepted in the case of historical structures,
3. Masonry walls are generally composite structures. While the material properties of each individual building material (e.g., brick, mortar, stone etc.) can be successfully obtained, it is still a problem to determine the overall effective material properties of composite masonry walls,
4. Masonry is a heterogeneous material both in terms of constitution (rubble stone masonry, multi-leaf walls, or those having inclusions and/or voids) and material properties (historical brick and mortars not produced according to some common standards and therefore having different characteristics throughout the structure). Therefore, it is difficult to obtain meaningful representative values by considering just a few reference locations; however, taking many samples from a historical structure is not preferred due to nondestructivity principle,
5. The damage to a historical structure by taking material samples may be minimized by taking micro samples; but, samples taken under these circumstances are not in standard test size and shapes,
6. Structure's inner and outer walls are normally covered with plaster and like, so it is not possible to see the masonry surface to evaluate the external texture parameters such as mortar joint thickness, distribution and size of building blocks, etc.,
7. Since the original material properties of a historical structure are not well known, it is usually not possible to evaluate the material damage caused by environmental conditions over time, except for the original material can be found from nearby quarries or other resources,
8. The experimental data to be used for calibration of analytical models are usually not available or not adequate,
9. History of structural modifications (e.g. removing load carrying walls, opening windows, adding floors etc.), functional modifications (house, library, museum), structural damages (e.g. seismic), repairs, or restoration works on the monument may not always be available.

Facing up to these matters necessitates unique approaches for each case to collect needed data, processing, evaluation, and management of them. For these purposes, the authors developed a hierarchical schema regarding both methodology and instrumentation, which is described in the following section.

## 2 A GENERAL METHODOLOGY FOR THE STRUCTURAL MONITORING

Structural monitoring is more than arbitrarily attaching a few sensors and collecting data for a selected period of time. The general approach to structural monitoring may be considered to be a three dimensional matrix where the width can be defined as (1) visual inspection, (2) finite element analysis, (3) short term measurements, and (4) long term monitoring. The depth can be defined as different parameters to be monitored/evaluated and methods used for this purpose. The height of the defined three dimensional methodology matrix is formed by the type, number, and location information; however, these parameters show great variation and are highly case dependent. Therefore, the methodology matrix developed in this study was limited to only two dimensions, which are the width and depth. It is important to note that this study was aimed to present a general framework for the structural monitoring and evaluation of the historical structures; however, each individual case may have specific requirements and conditions. Each individual item of the presented matrix is described under each heading below.

## 2.1 Visual Inspection

Visual inspection step is the most direct and economical step of the condition assessment and structural monitoring of historical structures. The qualitative evaluation of the state of conservation is mainly based on visual inspection which can detect:

- Structural anomalies (structural cracks, deformations, tilted columns and walls, sagged slabs etc.) which gives idea on load transfer mechanisms and possible foundation problems,
- Mechanisms of material deterioration, degradation, and decohesion (visible in the form of efflorescence, biodeterioration, color changes, non-structural cracks, flaking, detachments etc.), their potential causes (unhealthy drainage, large temperature changes, wetting-drying cycles, damping problems, freeze and thaw, previous restorative interventions performed with incompatible material such as concrete), level of deterioration (in a relative manner), and their distribution in the structure,
- Some basic features of structure in terms of construction materials, structural technology (different construction materials and techniques used, mural and structural typology etc.), possible plan or elevation irregularities in geometry,
- Perceptible structural changes and adaptations performed throughout the life of a structure (an added bell tower, a divided room etc.) and the traces of previous repairs and restorations.

Visual inspection method obviously cannot be performed to detect invisible features or to obtain quantitative data and yet it is a very basic part of structural investigation of a historical structure / monument. As a matter of fact, visual inspection methods are frequently referred during short and long term measurements for structural monitoring, as a strong complementary support.

Visual inspection can be additionally used for on-site environmental survey, to evaluate close range water sources, topographical features such as slopes, soil conditions (clay, sand, rock), potential construction material resources, similar structures in the vicinity (from structural, material, and exposed conditions' points of view). Thereby, a regional catalogue of mural morphology can also be developed using open cross sections.

## 2.2 Finite Element Analysis

Finite element analysis is defined to have five stages: modeling, analysis, updating, validation, and simulation. Modeling stage would include preliminary, original, and calibrated analytical models. The preliminary model approximately reflects the geometrical and material characteristics of the structure, and used to give an idea about the structural system and behavior. The original model uses basic dimensions taken during on-site measurements or from available plans. The calibrated model would form the last modeling step and mostly uses short-term test results; the static loading and dynamic measurement results (mode shapes, modal frequencies) are tried to be replicated by the analytical model and the structural parameters (such as effective elastic modulus, poisons ratio, density, support-boundary conditions) are iteratively modified until the simulated and measured responses are closely matching. The calibrated analytical model would closely reflect the actual structural behavior/response and be used for structural identification (St-Id). The calibrated models are especially important in the case of historical structures, since there are many uncertainties associated with the material, boundary, and geometrical features.

The field tests conducted for calibration of analytical models and related structural identification studies need to be in the linear range to prevent any damage to the structure. The constructed model is analyzed under certain loading cases defining the normal service conditions as well as those thought to be critical. Response of historical structures should often times be evaluated for extreme loading cases such as earthquakes, where demand on the structure is in the non-linear range and material and geometric nonlinearities should be considered. Therefore, the choice of the analysis type to perform is a function of the level of loading and forms another crucial point [Lourenço 2002].

The available modeling types, such as smeared (macro) modeling or micro modeling, would also play an important role for the simulation studies. The overall modeling of a structure would usually be not feasible using micro modeling, since large number of members and related degrees of freedom would require extensive amount of computer time. The global behavior of a structure in the linear range may be well simulated using elements that would reflect the average properties of composite structural members; on the other hand, non-linear range modeling and simulation using smeared (macro) modeling may only give a rough idea. Although exact nonlinear behavior of a historical structure can never be fully modeled, modeling carefully each detail of composite geometry and material characteristics of the whole structure (micro modeling on a global scale) would give the closest results to actual response.

**2.3 Short Term Measurements**

Short term measurements may include parameters related to structural morphology such as
- geometrical features (member size and dimensions, type and distribution of load carrying members, crack width, differential settlement, tilt, section loss, georadar, etc. measurements)
- technological characteristics of structural members defining the material type and distribution (material variation across the thickness of a masonry multi-leaf wall, physical, chemical, mechanical, and compositional characterization of building materials, connection of members, ultrasonic pulse velocity, elasticity etc. measurements)

Furthermore, dynamic and static test results constitute the products of form and structure of a system and would also be collected during short term measurements. The static tests generally include loading the structure with a known magnitude of force which would remain in the linear range of the system. Dynamic tests are conducted using either ambient vibration or forced vibration excitation. The structural parameters are obtained in the form of structural stiffness-flexibility and mode shapes, frequencies, damping ratios. All these parameters should be evaluated and used to update the original finite element model.

**2.4 Long Term Monitoring**

At the long term monitoring step, the parameters exhibiting change over time are investigated; these parameters would include environmental factors like temperature, humidity, wind and rain, and other factors related to structural changes over time such as crack width variation, dynamic characteristic changes etc. Long term measurements might as well include short term static and/or dynamic measurements which are repetitively conducted over time (mostly with equal time intervals such as once every three months). Long term static measurements mostly consider measurements of temperature, humidity, change in crack width, strain, tilt etc. and these are repeated with frequent intervals in a quasi-continuous manner (such as one measurement at every 30 minutes). On the other hand, the continuous measurement of dynamic characteristics of a structure generates large size data packets which are not possible to store as raw data. Therefore, all dynamic data are not recorded; instead, the data are processed online and only relevant dynamic characteristics (such as periods) are stored. In the case of repetitive loading – such as vehicles passing over a historical bridge – statistical methods are utilized to generate histograms.

As seen, the four steps mentioned above are interrelated. The correct management of the collected data requires a multi-level comprehension. In the given schema, the potential methods and instruments that

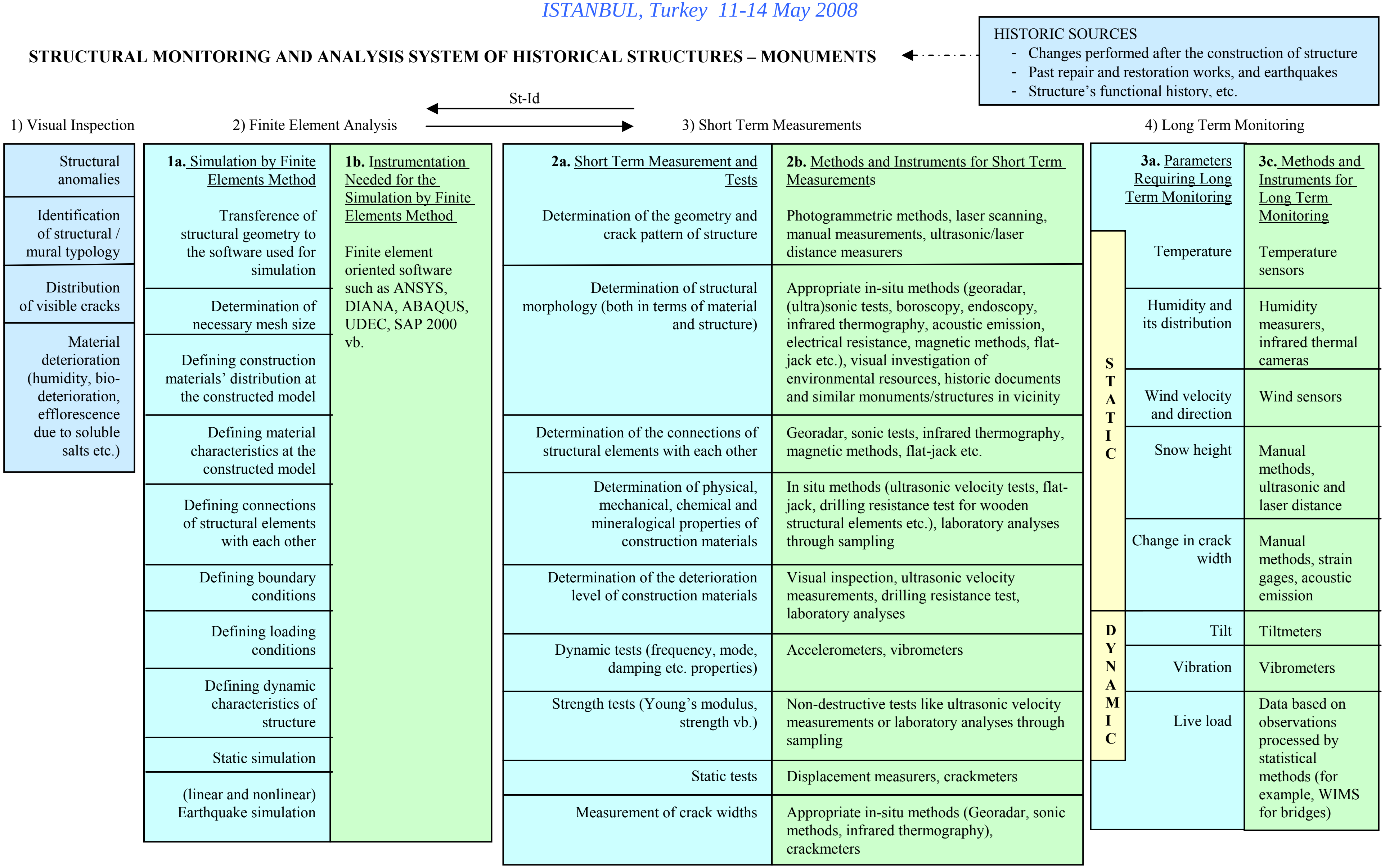


Figure 1: Schema for the structural monitoring of historical monuments

are related to measurements are also listed in the second column of Fig 1. The examples presented in Fig 1 are general; therefore, each unique application case should be evaluated individually for the method and instrument selection. The needed level of accuracy and information, available human resources, and budget also play an important role in the choice of instrument, which points out the significance of planning in such studies. In the case of historical structures, the selected methods are expected to be as non-destructive as possible. Since non-destructive methods give generally indirect results, one method should always be supported with one of its complementary methods (in the relevant literature, there are many studies on NDE and complementary techniques [i.e. Binda *et al.* 2004 and Binda *et al.* 2003]). It should also be noted that some indirect non-destructive investigation techniques on historical structures may be lacking calibration (e.g., ultrasonic pulse velocity, georadar) for different types of heterogeneous and aged materials used in historical structures. Similarly, standards may not be applicable for some specific NDT techniques (such as forced infrared thermography) applied on historical structures. The ongoing studies are promising for their reliability when each technique is used within its specific applicability limitations. Another problem of common NDE methods is that the raw data obtained are mostly difficult to evaluate, requires post-processing, and therefore depends on expertise causing possible increase of the evaluation costs.

In addition to all of these, historical sources may also be put to use if present. These historic sources can be inscriptions, visual and/or written archive documents, travel books, etc. The use of available documents can constitute a tool for anamnesis, informing us on the changes, adaptations, additions / cancellations performed on the structure, repair and restoration works carried out, the seismic and functional history of the structure.

## 3 NEMRUD MONUMENTS

Nemrud is an archaeological site in Adiyaman, in the eastern part of Turkey. The site, which was discovered in 1835, is famous with the big monumental statues (8 to 10 meters in height) more than two thousand years old, lined up in the form of two rows on two sides (east and west terraces) of a centered tumulus. The site belongs to an ancient kingdom called 'Commagene' and is located at the top of Mount Nemrut (2150 m). Each statue, except that of the king building the site, represents a Greek god / goddess corresponding at the same time to a Persian sacred figure, which is sitting on a throne. At the backsides of the thrones there are some inscriptions which render the site also valuable in terms of the presence of written documents [Cimok 1995].

The bodies of the statues are composed of big stone blocks. They are probably simply put on top of each other without any physical binder or mechanical connection like mortar or metal clamps. The heads are made of a single piece of stone. The statues are made of limestone which is a readily available material of the region. Moreover, the statues on the east and west terraces are almost identical. In spite of these similarities, those in the east terrace are in relatively good structural condition in comparison with those located on the west terrace. The west terrace statues were torn down towards west, while the statues on the east side have a better physical integrity and yet, all of the statue heads were detached from their bodies and fallen down. The site is located at a highly seismic zone; therefore, the detachments are thought to have happened during a previous strong earthquake or series of earthquakes. Furthermore, the difference between the two terraces in terms of physical integrity is thought to be caused by non homogeneous distribution and accumulation of snow load due to high winds. The accumulated snow might be pushing down the slope, slowly moving segments of stones over hundreds of years causing a progressive failure.

There are different material deterioration phenomena observed in Nemrud Monuments. Material is further abraded due to physical and mechanical inducements of environment such as wind, serious seasonal and daily temperature variations, precipitations, sun exposure etc. For all these reasons, an international Nemrud project was funded by the Turkish Ministry of Culture, World Monument Fund, and TUBITAK (104I011). The aim of the project is to execute a more structured and proper damage assessment and diagnosis of the monuments in a multi-disciplinary, integrated manner from structural and materialistic assessment, conservation, site presentation, restoration points of view. The preliminary site and material investigations have begun in 2006 within the framework of current project and some in-situ studies, such as ultrasonic velocity measurements and stone deterioration maps were obtained. Two temperature and humidity sensors as well as a sensor to meaure the direction and velocity of wind were installed on site which would continuously collect data and can be remotely connected via GSM modem (Fig 2). Meanwhile, the preliminary FEM of a typical Nemrud monument was constructed and a modal analysis was carried out to have an idea about the range of natural frequencies and mode shapes. The initially obtained mode shapes indicate that the heads may have fallen because of an earthquake (Fig 3-4). Moreover, dynamic tests were conducted to obtain the natural vibration frequencies of the standing statues.

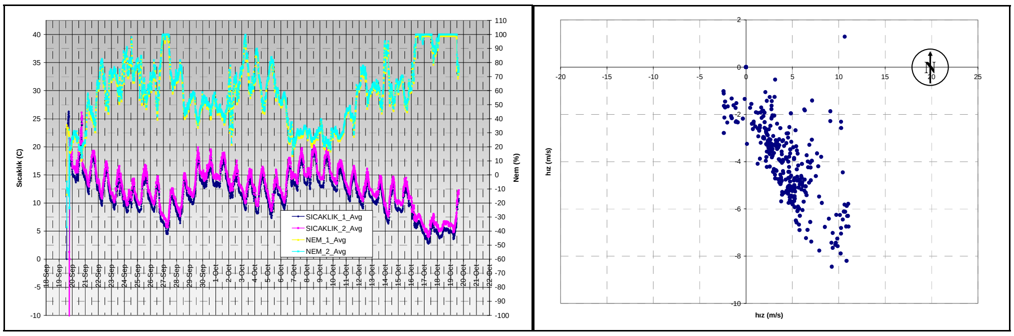


**Figure 2.** An example data reading obtained for temperature and humidity, and for wind velocity and direction, respectively.

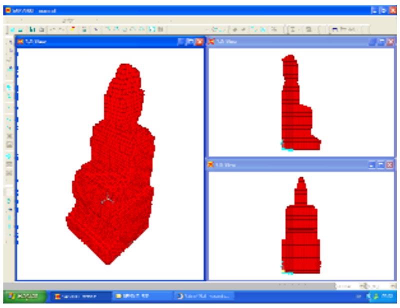

**Figure 3.** 3D FEM of a typical Nemrut monument

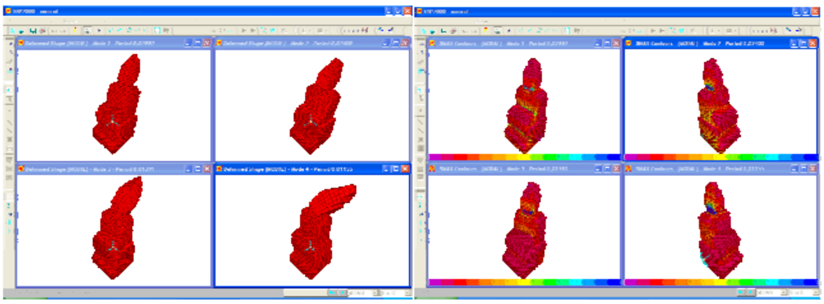

**Figure 4.** The obtained modal shapes and the corresponding maximum stress distributions

In 2007, the sensors to monitor the snow height will be installed. Moreover, the stone location map of collapsed statues will be obtained by photogrammetric methods. The structural investigations are planned to be continued with more detailed calibrated linear and non-linear FE models, synthetic and recorded earthquake simulations, and the formation of retrospective damage scenarios. The 3D-FE model will be updated using field measured dynamic data to conduct St-Id. The short term dynamic measurements and long term monitoring results will be combined to understand the behavior and deterioration mechanisms. The calibrated analytical model will be used to simulate possible earthquake loading and pertinent damage scenarios. These investigations will be fed by the data regarding the materials, obtained by more in-situ measurements and laboratory analyses. Finding sensors functioning at extremely harsh environmental conditions is another challenging task in the Nemrud project. In addition, the site is at the top of a mountain, far from settling areas, which brings in additional difficulties e.g. easy access, accommodation, lack of electricity, and security concerns.

## 3 CONCLUSIONS

- This paper aims to introduce a four-step framework for structural monitoring of historical / archaeological structures regarding both methodology and instrumentation. According to this framework, a structural monitoring study can be handled as (1) visual inspection, (2) finite element modelling, analysis, updating, validation and simulation, (3) short term measurements, and (4) long term monitoring. These four steps form the general approach of identification and monitoring of historical structures – monuments,

- The structural monitoring of historical / archaeological structures entails some extra difficulties in comparison with that of modern structures. These difficulties should be tackled within the constraints recognized for cultural heritage investigations (e.g., non-destructivity),

- As the Nemrud example indicates, each case of historical / archaeological structure / monument / site exhibits particular problems that should be specially considered. The information and accuracy needed, available human resources and budget etc. are other factors playing role in the constitution of monitoring approach. Therefore, each case is unique within itself.

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