Rock monuments and historical buildings

Authors: Prof. Dr. habil. Heinz Konietzky & Dr. Jörn Wichert
(TU Bergakademie Freiberg, Geotechnical Institute)

Editor: Prof. Dr.-Ing. habil. Heinz Konietzky Layout: Gunther Lüttschwager
TU Bergakademie Freiberg, Institut für Geotechnik, Gustav-Zeuner-Straße 1, 09599 Freiberg • sekr_fm@ifgt.tu-freiberg.de

1 Introduction

Within this document the term ‘Rock Monuments’ include rock monuments (e.g. memorials or tombstones like documented in TUBAF (2012)) as well as historical buildings like churches, cathedrals, castles, palaces, walls etc. made of natural stone. Such monuments are exposed to several environmental and man-made short- and long-term influences, which will lead to damage (degradation) of such monuments.

This documents gives an overview about:

- Typical processes of rock monument degradation
- Characterization and evaluation of monument degradation
- Conservation methods
- Stabilization of historical buildings

Monument degradation can be categorized as follows:

- Physical weathering
- Chemical weathering
- Biological weathering
- Natural or man-made produced damage due to fire or flooding

In last year’s most attention is paid to air pollution, salts, bio-deterioration and so-called differential stress, which means the following effects (Doehne & Price, 2010):

- Wet / dry cycles
- Clay swelling
- Differential hygric stress
- Differential thermal stress / strain

Weathering is a time-dependent process like documented in Fig. 1 by average weathering rates.

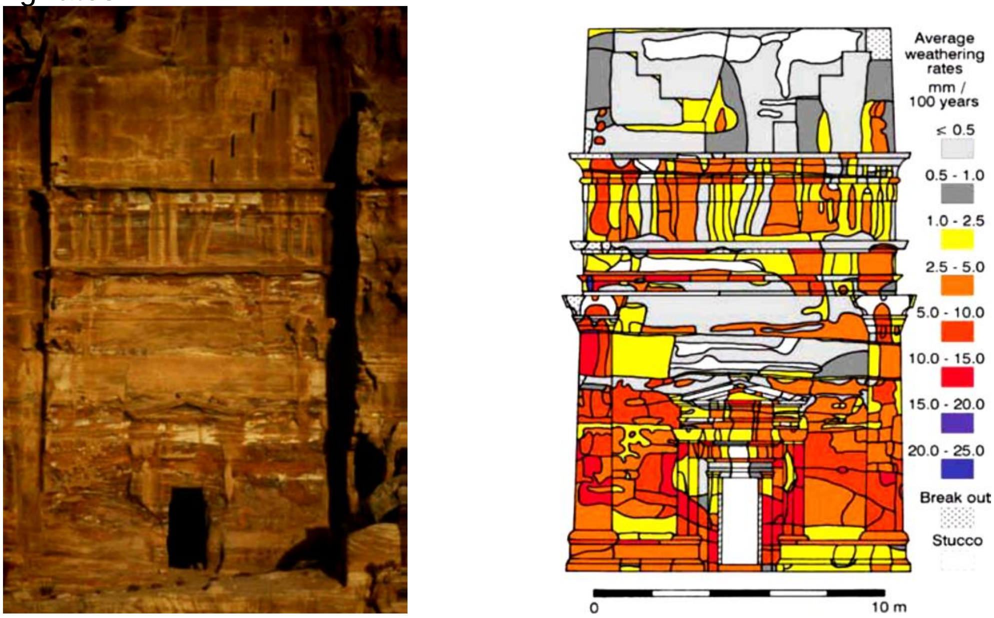


Fig. 1. Average weathering rates of Tomb 778 (Petra, Jordan) (Fitzner, 2004)

2 Degradation processes

Physical degradation means degradation due to mechanical forces which effect the rock structure, but not the chemical composition. Several types of physical degradation can be distinguished:

- Damage due to thermal impact (sunshine, shadow): thermal expansion of minerals (grains) or induced thermal stresses. Different minerals have different thermal expansion coefficients, which leads to local stresses at the micro-scale and consequently to microcracks. Also, strong thermal gradients within a monument will lead to increasing damage.
- Wedging or splitting: Existing microcracks or fractures expand due to inner forces (frost, crystallization, root growth etc.) until surface parts of the monuments are chipped.
- Abrasion occurs when parts of monuments rub together or strong winds transport sand particles which create abrasion.

Chemical degradation leads to a change of the chemical composition due to chemical reactions at the grain size level and below. The following processes can be distinguished:

- Oxidation (e.g. rust of iron-bearing rocks)
- Carbonation: carbonic acid is degrading the rock by creating openings, holes etc. (e.g. karst)
- Acid rainfall: sulphur and nitrogen compounds create acids, which attack (damage) the rocks. This is mainly caused by industrial pollution and especially dangerous for weak rocks like sulphate-rich rocks.
- Hydrolysis means absorption of water by the rock, which weakens the rock.

Biological degradation is based on microorganisms (fungi or bacteria), living in the pores or in the fractures of the rock. They contribute to the damage of the rocks by physiological activity, but also due to their by-products (produced acids, release of cations or anions, change of local pH etc.). Different types of microorganisms live under different environmental conditions like temperature and humidity.

Fire for instance created due to forest fires, bomb attacks or fire in buildings can create substantial damage, especially due to the high temperature (up to about 1000 °C), the high thermal loading rates and the cooling process (often under application of water). Thermal shocks are extremely dangerous due to the produced huge thermal stresses and strains.

Flooding of monuments can be caused by extreme weather conditions (heavy rainfall or floods by rivers) and leads to saturation or partial saturation of monuments. This in turn weakens the rock and offers improved conditions for mechanical, chemical and biological weathering.

3 Deterioration pattern

ICOMOS-ISCS (International Scientific Committee for Stone: ISCS) has introduced a common language to describe degradation pattern (tab. 1). Besides general terms like alteration, damage, decay, degradation, deterioration and weathering this document describes and illustrates the different types of cracks, deformations, detachments, features induced by material loss, discoloration, deposit and biological colonization (see ICOMOS 2008). Fig. 2 and 3 illustrate the procedure on the basis of a baroque tombstone.

Tab. 1: Categories to classify stone deterioration pattern according to ICOMOS (2008)

Main Category	**Sub Category**
crack and deformation	▪ fracture ▪ star crack ▪ micro-fissure ▪ craquelure ▪ deformation
detachment	▪ blistering ▪ bursting ▪ disintegration ▪ fragmentation ▪ peeling ▪ scaling
features induced by material loss	▪ alveolization ▪ erosion ▪ mechanical damage ▪ microkarst ▪ missing part ▪ perforation ▪ pitting
discoloration and deposit	▪ crust ▪ deposit ▪ discolouration ▪ efflorescence ▪ encrustation ▪ film ▪ glossy aspect ▪ graffiti ▪ patina ▪ soiling ▪ subflorescence
biological colonization	▪ biological colonization ▪ alga ▪ lichen ▪ moss ▪ mould ▪ plant

Fig. 2. Weathered baroque sandstone tombstone in Dresden [Wichert at al. 2018]

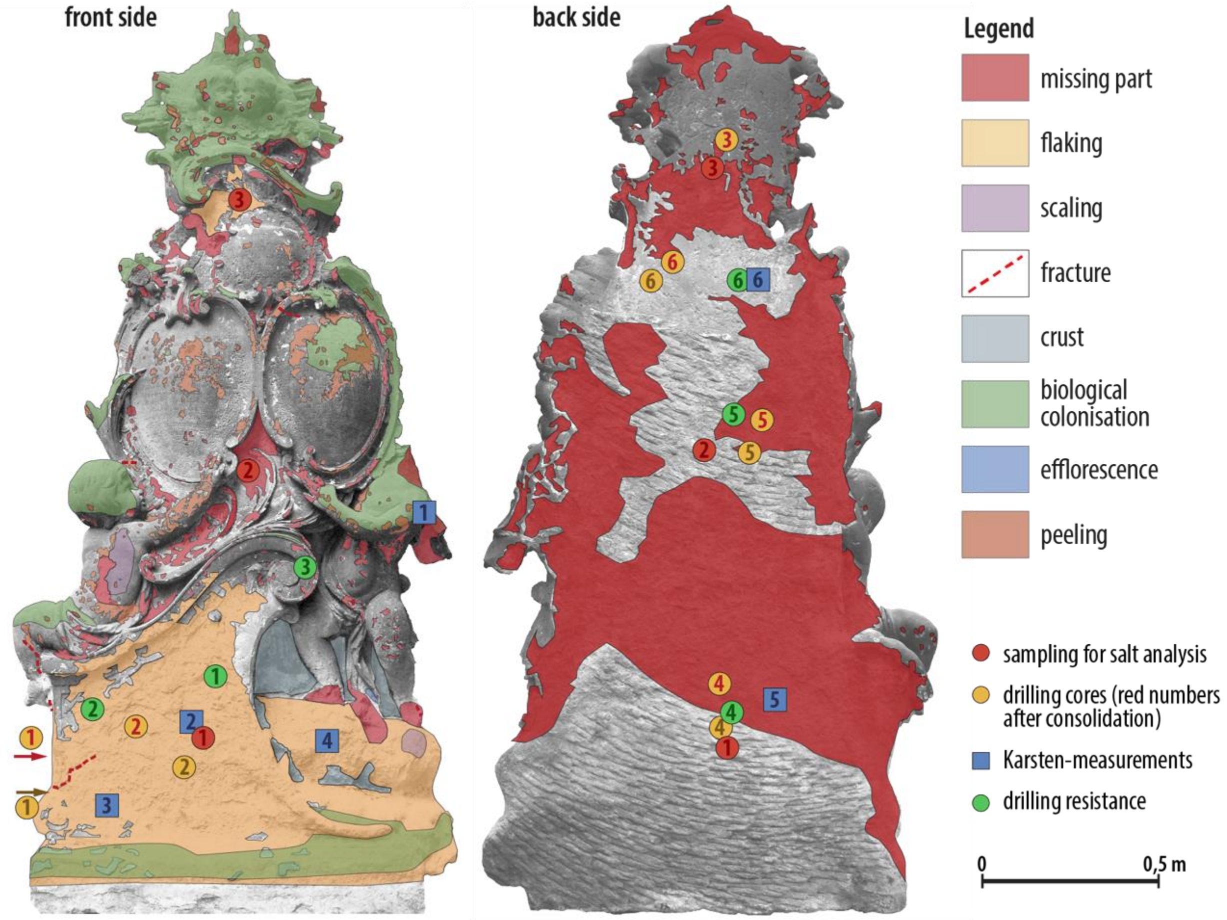


Fig. 3: Damage mapping of baroque tombstone according to the ICOMOS classification [Wichert et al. 2019]

4 Documentation

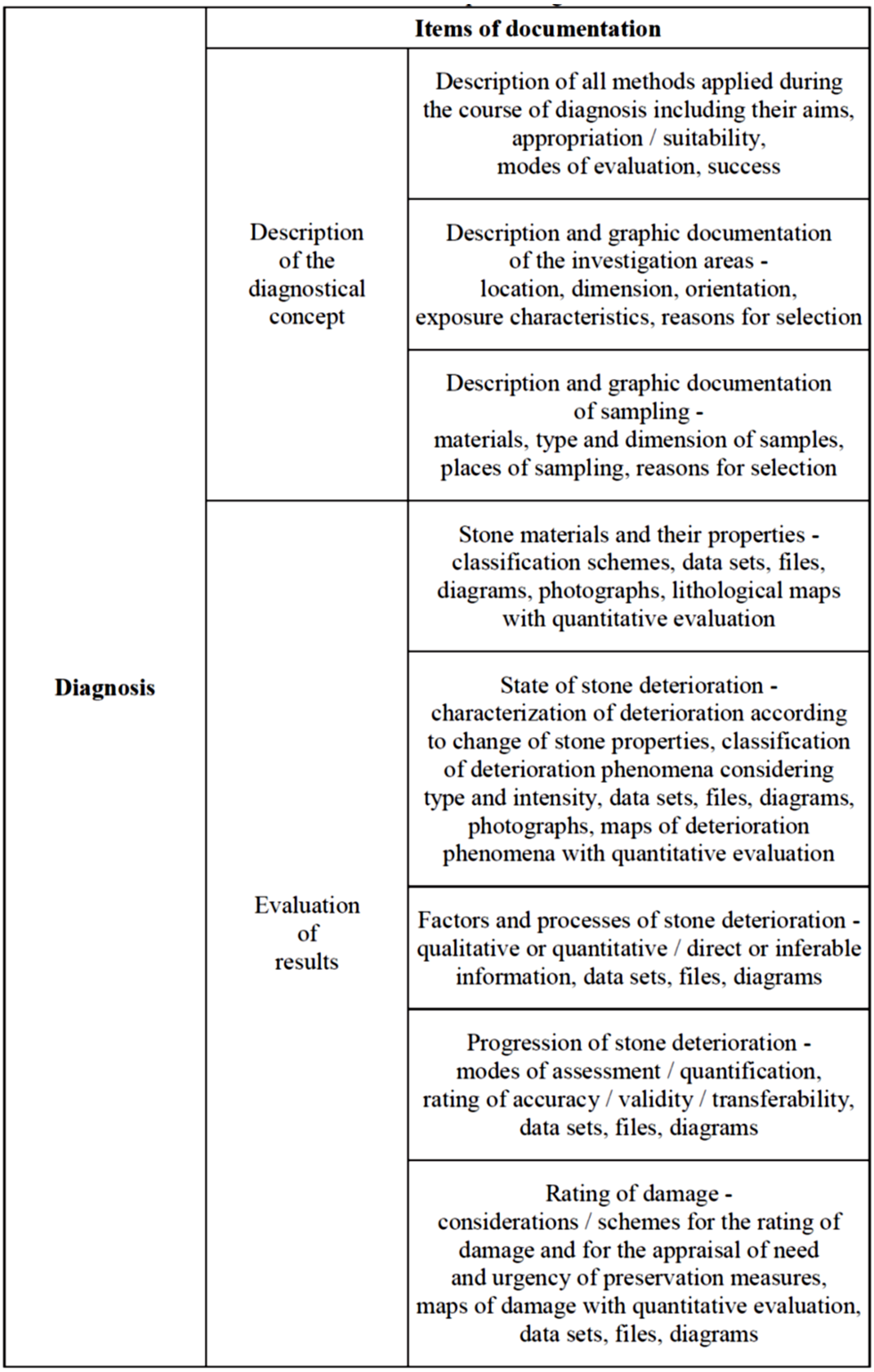
Besides the documentation of the deterioration pattern by visual inspection (see chapter 3) it is imperative to make a record of the actual stone. There are different methods / technique available (e.g. Doehne & Price, 2010; Lehrberger & von Plehwe-Leisen, 2015):

- Moulding or casting
- Drawings
- Photography
- Raking light photography
- Stereo-photography
- Holography
- 3D Laser-Scanning

Today high-resolution Laser-Scanning (resolution up to 0.01 mm) is available to generate Digital Elevation Models (DEM) like shown in Fig. 4.

Fig. 4: 3-dimensional DEM of a Chinese rock statue (company material: CG studio, 2016)

Tab. 2: Items of documentation for degraded rock monument (Fitzner, 2002b)



	Items of documentation	
Diagnosis	Description of the diagnostical concept	Description of all methods applied during the course of diagnosis including their aims, appropriation / suitability, modes of evaluation, success
		Description and graphic documentation of the investigation areas - location, dimension, orientation, exposure characteristics, reasons for selection
		Description and graphic documentation of sampling - materials, type and dimension of samples, places of sampling, reasons for selection
	Evaluation of results	Stone materials and their properties - classification schemes, data sets, files, diagrams, photographs, lithological maps with quantitative evaluation
		State of stone deterioration - characterization of deterioration according to change of stone properties, classification of deterioration phenomena considering type and intensity, data sets, files, diagrams, photographs, maps of deterioration phenomena with quantitative evaluation
		Factors and processes of stone deterioration - qualitative or quantitative / direct or inferable information, data sets, files, diagrams
		Progression of stone deterioration - modes of assessment / quantification, rating of accuracy / validity / transferability, data sets, files, diagrams
		Rating of damage - considerations / schemes for the rating of damage and for the appraisal of need and urgency of preservation measures, maps of damage with quantitative evaluation, data sets, files, diagrams

5 Quantitative characterization of damage

A quantitative characterisation of the degree of deterioration demands the use of non-destructive or minimal-invasive measuring techniques. The following techniques are common (e.g. Siegesmund et al. 2005; Lehrberger et al. 2015):

- Ultrasonic wave measurements (> 20 kHz)
    - Based on determination of wave speed and/or attenuation of waves
    - Serves to determine the degree of weathering, to estimate the actual strength and to detect fractures
- Ground penetrating radar techniques (MHz to GHz)
    - Based on electro-magnetic waves
    - Provides general and large-scale overview about the internal structure
    - Allows to locate wet and salty horizons
    - Localization of invisible wooden or metal parts
- Micro-seismic techniques (1- 20 kHz)
    - Determination of weathering degree
    - Detection of local anomalies
- Microwave measurements (1 - 300 GHz)
    - Based on electro-magnetic waves
    - Estimation of degree of humidity
- Radiographic image techniques
    - Based on gamma-rays or X-rays
    - Detection and localization of invisible wooden or metal parts
- Drilling resistance measurements
    - Estimation of degree of weathering
    - Estimation of strength of material
    - Extraction of sample material for lab investigations
    - Proof of effect of conservation measures
- Rebound hardness test
    - Estimation of degree of weathering and strength

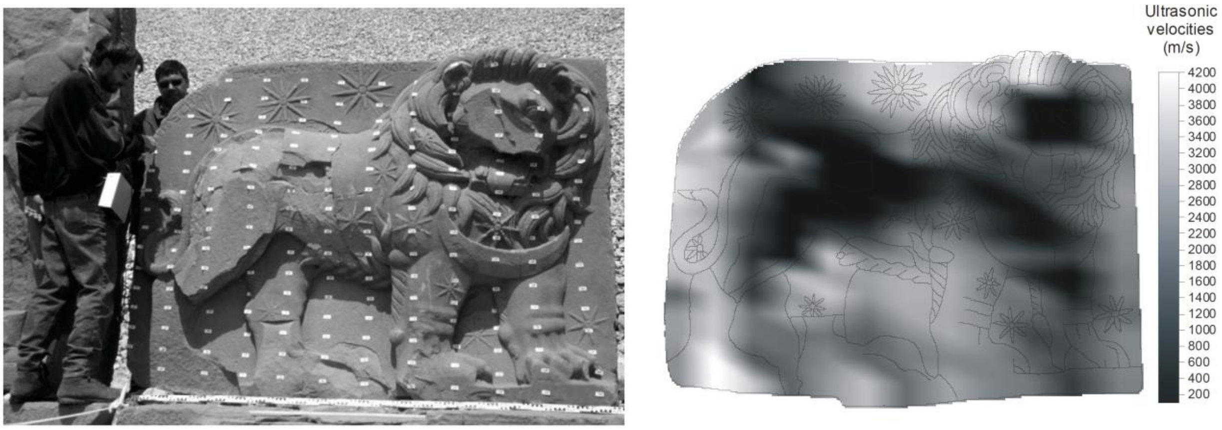


Fig. 5: Ultrasonic P-wave speed measurements (Fitzner, 2004b)

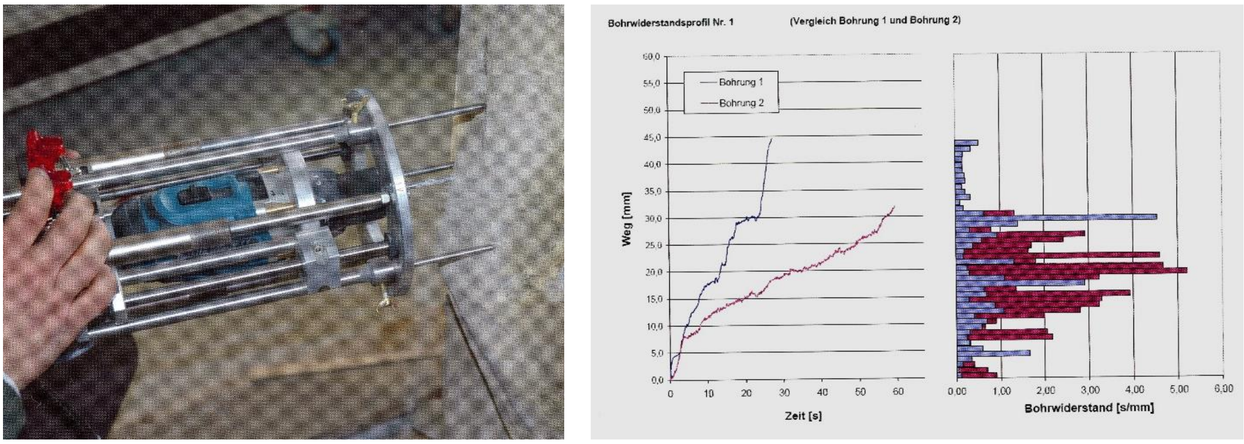


Fig. 6: Drilling resistance measurement (left side, Pummer, 2007). The diagram shows penetration depth (in mm) versus time (in s) for two different boreholes and penetration depth versus drilling resistance (in s/mm) (right side).

6 Preservation measures

Preservation measures can comprise the following actions (Fitzner, 2004):

- Safeguard measures (fixing of loose stone fragments, pre-consolidation)
- Cleaning (by washing, by laser cleaning, mechanical, chemical, biological)
- Desalination
- Stone repair (piecing-in of stone, repair with mortar, crack-filling)
- Stone replacement
- Surface protection
- Consolidation (with limewater, organic polymers, epoxy resins etc.)
- Hydrophobising coatings
- Treatment with reaction inhibitors
- Control of biological colonization
- Structural reinforcement (grouting, dowels etc.)
- Sheltering

7 Example

The following example documents the restauration of a baroque sandstone tomb. The complete procedure comprises several steps (Wichert et al. 2015, Wichert et al. 2019):

(1) Documentation of damage state according to ICOMOS standard
(2) Desalting and Consolidation using VCM (Vacuum Conservation Method)
(3) Accompanying measurements
(4) Numerical simulations

The considered baroque tombstone is shown in Fig. 2 and the damage state is characterized according to the ICOMOS classification (see Fig. 3). As Fig. 3 shows, the monument is heavily damaged.

The VCM was applied first for desalting (flushing the tomb with distilled water using underpressure for a few weeks) and later to consolidate the monument with a special injection material also using the vacuum technique. Fig. 7 illustrates the procedure.

In parallel some measurements were conducted to quantify the consolidation effect. Cores were drilled from the tombstone and sample cubes for the determination of the standard rock-mechanical parameters. Furthermore, specific methods in conservation science were applied like determination of the drilling resistance (Fig. 8-A), biaxial flexural strength and uniaxial compression tests as well as Brazilian tests on sample discs (Fig. 8-B, C). These tests deliver high resolution information about strength and stiffness. The drilling resistance measurements were carried out by the device DURABO (3 mm diameter driller) with constant rotation speed and constant contact pressure. The reciprocal velocity of penetration n (in s/mm) describes the drilling resistance. The higher the drilling resistance the harder the stone, resulting in a hardness profile which allows a general statement of the stone condition before and after the consolidation.

The determination of the biaxial flexural strength and the Young's modulus of discs allows to obtain a strength and stiffness profile from the surface to the inner part of an object. Normally, a core with a length of 10 cm and a diameter of 5 cm is drilled and cut into 5 mm thick discs. With a specific test equipment and corresponding evaluation formulas it is possible the measure the biaxial flexural strength as well as the Young's modulus as an expression of the deformability of the sample.

Fig. 7: Desalting measures of a tombstone; A: Protection of the surface by covering with non-woven fabric before covering with the foil; B: Equipment for desalting; C: Desalting of the foil covered tombstone with tubes for water supply; D: Cellulose compress on the wet tombstone shortly after removing the foil; E: Active drying to remove remaining moisture after natural drying (Wichert et al., 2019).

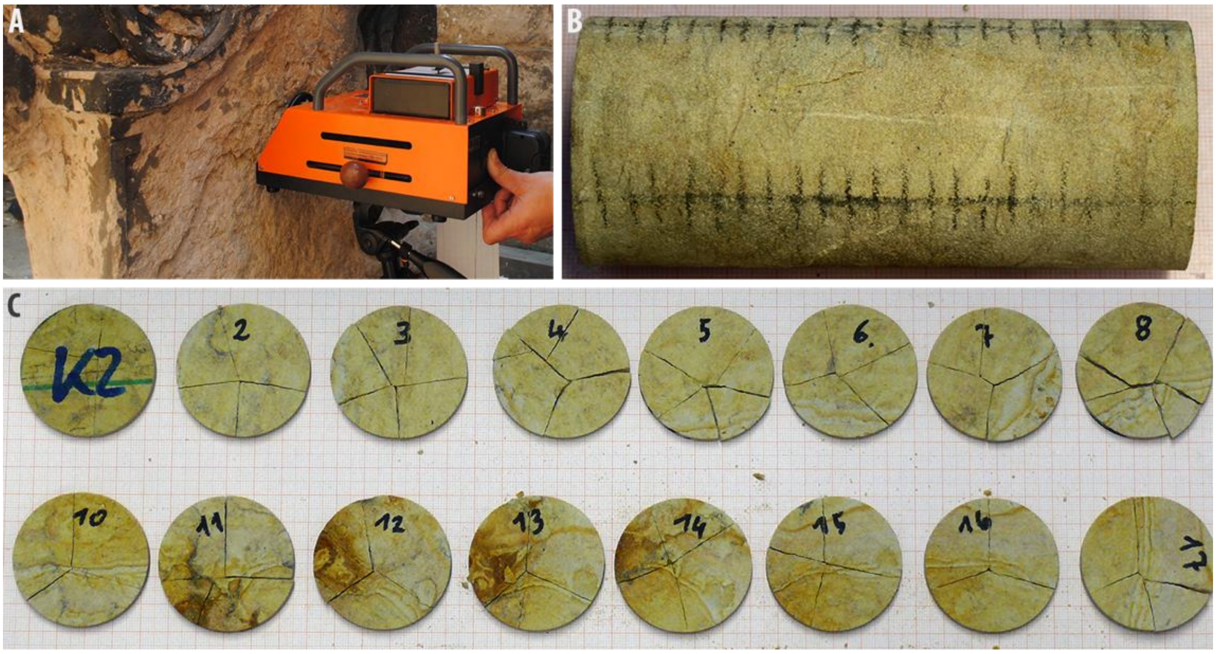
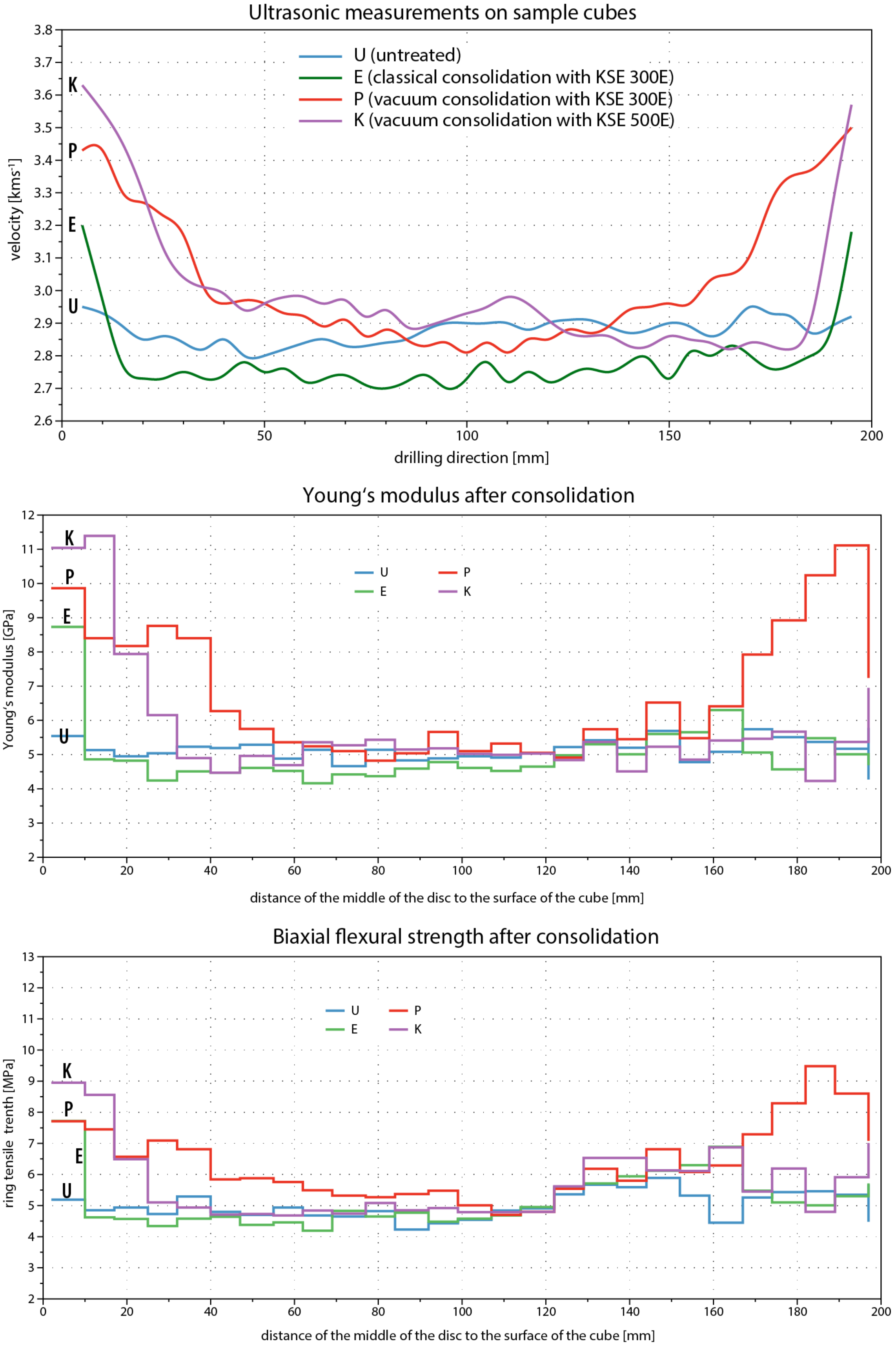


Fig. 8: A: Drilling resistance measurement; B: Core from tombstone with marks for cutting discs; C: Discs with a thickness of 5 mm for the fine scaled determination of the flexural tensile strength and Young‘s modulus (Wichert et al., 2019).

By determining the propagation speed of ultrasonic wave pulses of identical, but freshly broken rock material, the effect of different treatments and different consolidants are evaluated. Drill cores obtained from treated cubic samples are used to monitor p-wave-speed orthogonal to the drill core’s axis and hence set up a speed-profile in penetration direction of the consolidant (Fig. 9). Since this method is fully non-destructive the results can be compared and related to strength and stiffness profiles obtained by (destructive) biaxial flexural tensile tests on the same drill cores (Fig. 9). The blue line (U) corresponds to the untreated samples. All treatments lead to a strengthening up to a depth of 50 mm. Test results also reveal that there is no local over-strengthening. Vacuum consolidation using the consolidant KSE 300E shows rather smooth strength-depth curves. However, the use of other consolidants or application of the classical consolidation approach led to a more altered surface while rock volume at greater distance from the surface is not apparently strengthened.



Ultrasonic measurements on sample cubes

Young's modulus after consolidation

Biaxial flexural strength after consolidation

Fig. 9: Charts showing different rock parameters before (U, blue curve) and after different consolidations (E, P, K) of the cubic samples demonstrating the consolidation effect of different degree (Wichert et al., 2019).

In general, **numerical simulation** of rock monuments has the following tasks:

- Prediction of stress-strain behaviour under different initial and boundary conditions
- Prediction of damage evolution under different initial and boundary conditions
- Investigation of effects of consolidation
- Comparison between different consolidation procedures and products
- Prediction of the behaviour of consolidated objects
- Optimization, sensitivity and robustness analysis

Based on a simulation at the grain size level (see Li et al., 2017) the potential crack propagation due to heating is predicted. Thermal impact due to sunshine, day and night change in temperature or even stronger, by fire, can lead to dramatic damage. In respect to that the thermal expansion coefficient of the minerals and the consolidation material and their ratio to each other are important.

The performed simulations correspond to untreated, treated (consolidated) and untreated-consolidated configurations. The models are mechanically fixed at the lower edge. Afterwards, thermo-mechanical impact by temperature of 0°C, 40°C, 60°C and 80°C were simulated. For the untreated-consolidated state also temperatures of 100°C, 150°C, 200°C and 800°C were simulated. Note, this and even higher temperatures can be reached during fire. During the simulation the higher temperature is assigned on the left model side while 0°C is assigned to the right model side (Fig. 10). Furthermore, the left side corresponds to the consolidated part with a width of 3 cm assuming a total model length of 12 cm.

The thermo-mechanical simulations are carried out stepwise. Firstly, the temperature is increased. Aim is to simulate the stress development depending on the development of the temperature over time. By applying high temperatures cracks are induced, followed by the propagation and coalescence of cracks. Based on different parameters like stress and strain distribution as well as crack development proposals for possible conservation measures can be deduced. Microcracks occur in different quantities, size and distribution. First partial but not continuous cracks develop at a temperature of about 80 °C in all models. The partial crack propagation continues and first continuous cracks develop at a temperature of about 100 °C. Crack development proceeds up to about 200 °C and, as shown in Fig. 10, cracks propagate further into the rock with lower temperature of about 20 °C.

The simulation with maximum temperatures of 800 °C is carried out because fires can reach temperatures of over 1000 °C, although “common fires” reach only lower temperatures. In these simulations massive crack propagation develops already after a few seconds. Please note, that the special phenomena of α-β-transition of quartz is not considered.

During all simulations, no abrupt changes of principal stresses or displacements between the untreated and consolidated parts are observed.

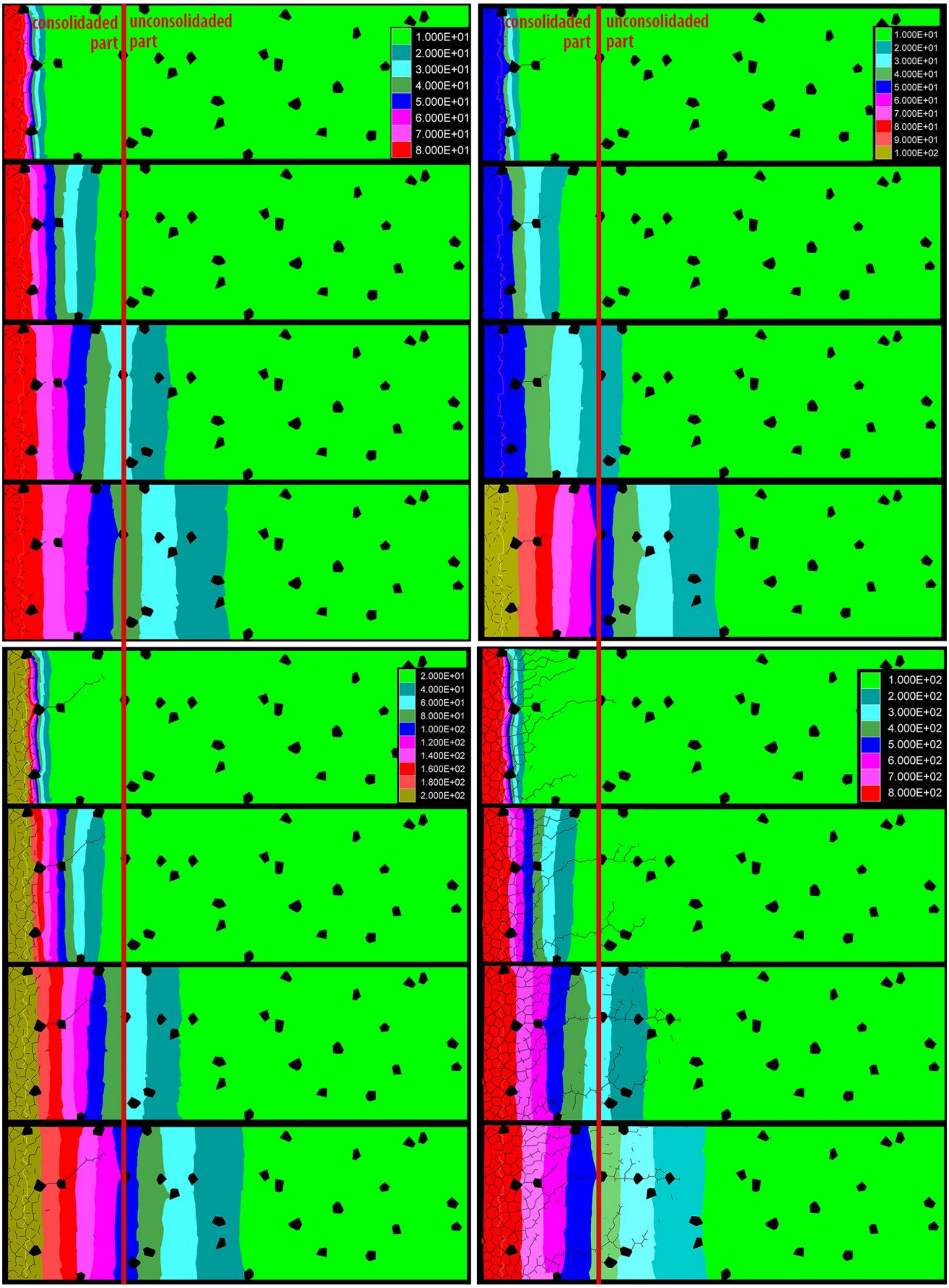


Fig. 10: Crack propagation due to thermal impact with 80 °C (upper left), 100 °C (upper right), 200 °C (lower left) and 800 °C (lower right). The size of the model corresponds to the sample size of 12 cm x 5 cm.

Some historical monuments or buildings do not only need renovation, but also stabilization in respect to the foundation. Instability of the foundation can have different reasons, for instance:

- Foundation was performed on weak ground without special treatment of the foundation
- Foundation material became weathered
- Natural underground solution processes lead to deformation at the surface
- Man-made underground activities like mining lead to surface movements
- Water level changes

Solutions to fix the foundation problem can be quite different and depend on size and value of the object as well as the cause of the foundation problem. The following techniques are most popular:

- Improvement of load bearing capacity of the ground by injections (grouting)
- Replacement of old foundation by a new one
- Enlargement of load transmission area
- Stabilization of the building / monument by retaining structures
- Insertion of structural elements like piles, micro-piles, frames, anchors etc.
- Drainage

The leaning tower of Bad Frankenhausen (Germany) is an interesting example, which shows the application of a special retaining structure to stabilize the tower (part of an old church). The inclination of the 56 m high tower is 4.7° (4.6 m away from the perpendicular). The inclination is caused by an ongoing underground solution processes due to the existence of salt-bearing rock layers in contact with groundwater (Fig. 11 and 12):

- 1920: 2,21 m
- 1960: 3,60 m
- 2001: 3,89 m
- 2007: 4,41 m
- 2013: 4,60 m

Fig. 11: Leaning tower of Bad Frankenhausen (Germany)

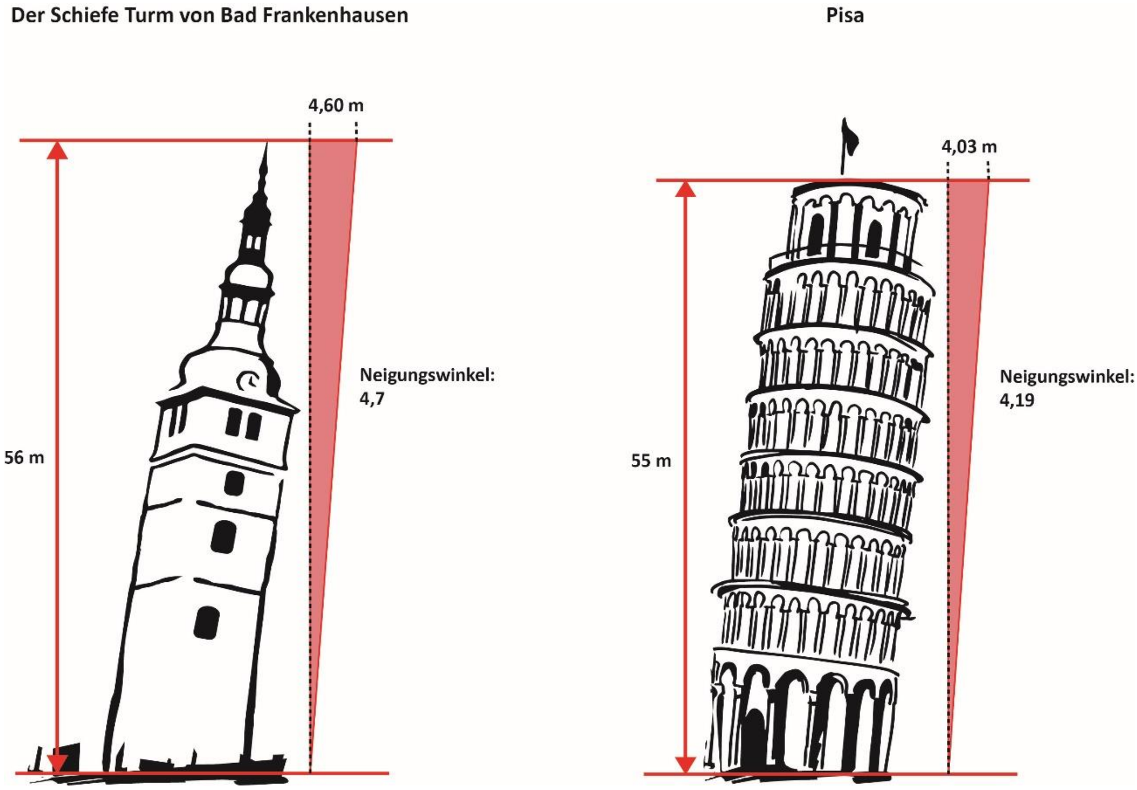


Fig. 12: Comparison between Leaning Tower of Bad Frankenhausen and Pisa (www.der-schiefe-turm.de)

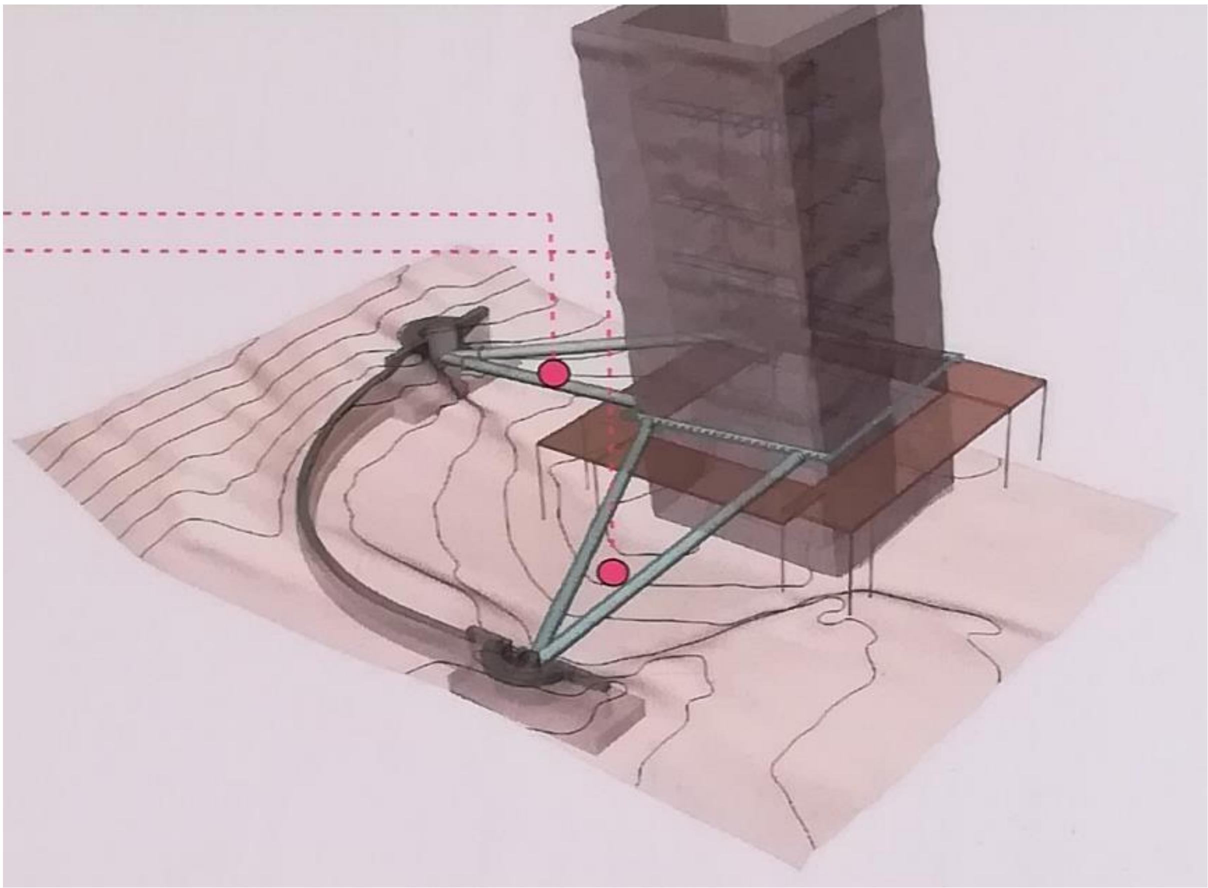


Fig. 13: Retaining structure to stabilize the leaning tower of Bad Frankenhausen

The whole stabilization consists of several elements: injections up to 8 m deep to improve load bearing capacity and a retaining structure with 14 and 16 m long steel struts connected with a retaining wall (see Fig. 13).

Another example is the well-known Leaning Tower of Pisa (Burland et al. 2009, 2015). The evolution of inclination is documented in Fig. 14. The geological profile of the foundation region is documented in Fig. 15. The inclination process of the tower is governed by rotation of the foundation inside the horizon A (see Fig. 15 and 16). It was recognized that fluctuating water level has strong influence on the ground movement. This would lead to a potential leaning instability of the tower if a certain inclination angle is reached. The following combined countermeasures were undertaken:

- The underexcavation technique (local removal of soil via an auger) was applied to reduce the inclination of the tower. The technique is illustrated in Fig. 17.
- The ancient concrete ring was connected with the masonry foundation by stainless steel reinforcement strengthened by circumferential post-tensioning (see Fig. 18)
- A drainage system was installed to lower and stabilize the water level.

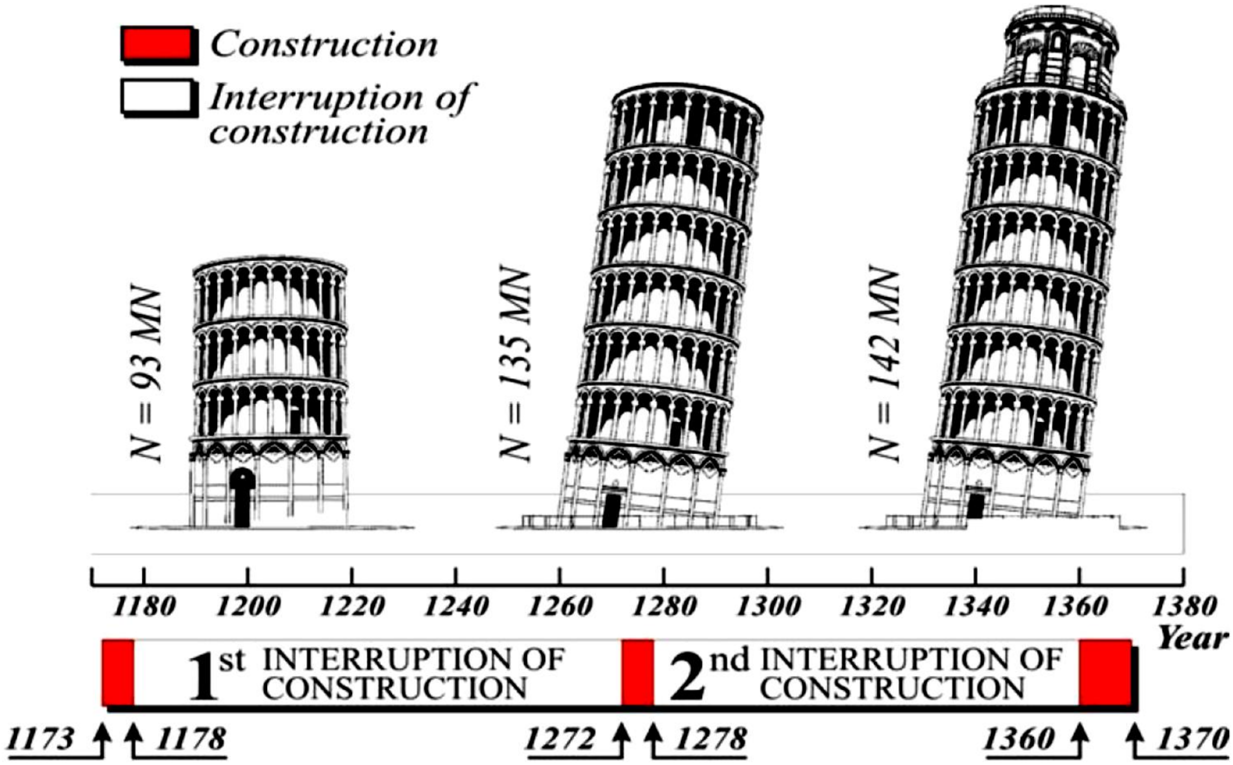


Fig. 14: Evolution of inclination in relation to construction stage and time (Burland et al. 2009)

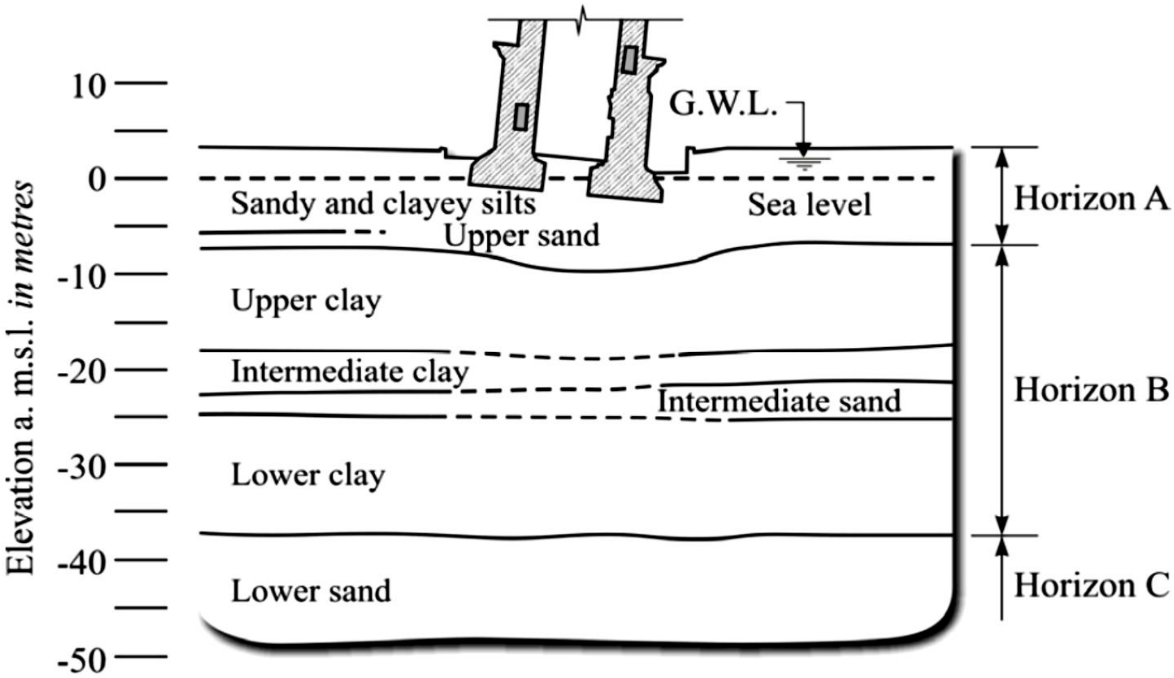


Fig. 15: Geological profile of underground and foundation area (Burland et al. 2009)

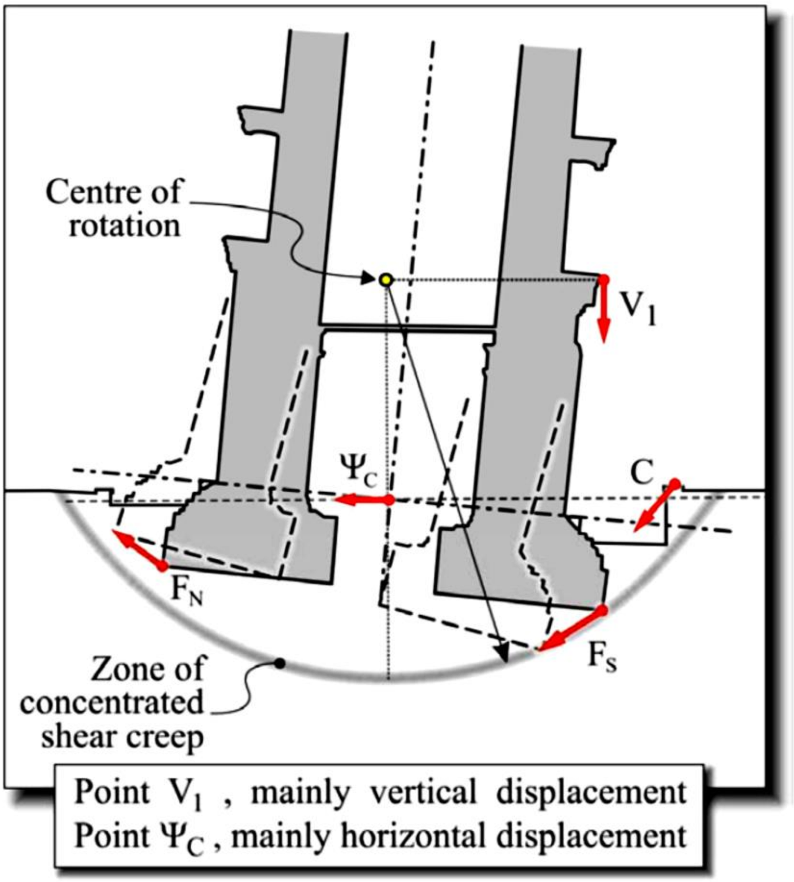


Fig. 16: Illustration of potential mechanism of ground movement (Burland et al. 2009)

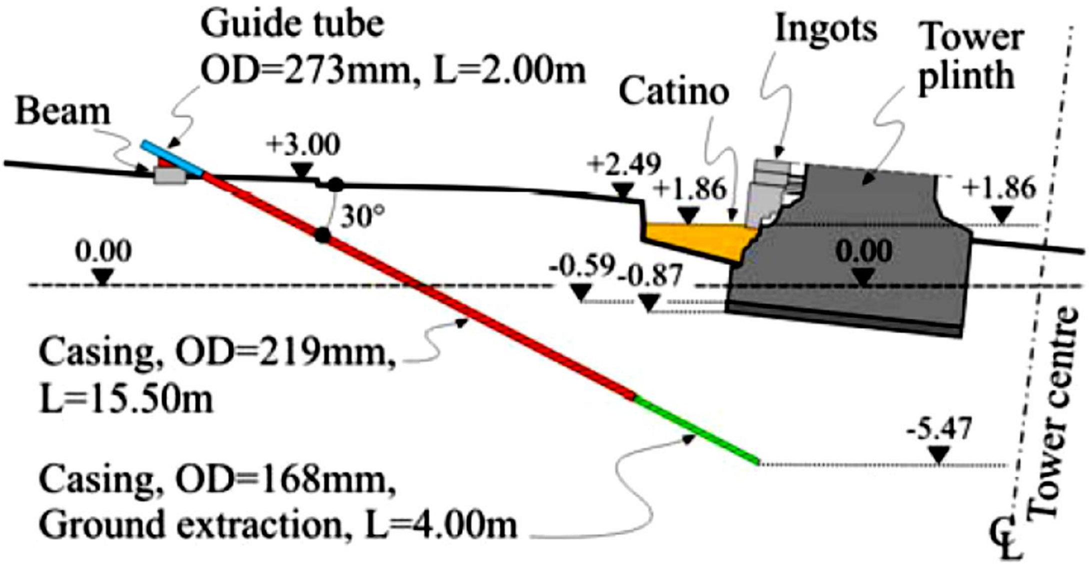


Fig. 17: Illustration of under-excavation technology (Burland et al. 2009)

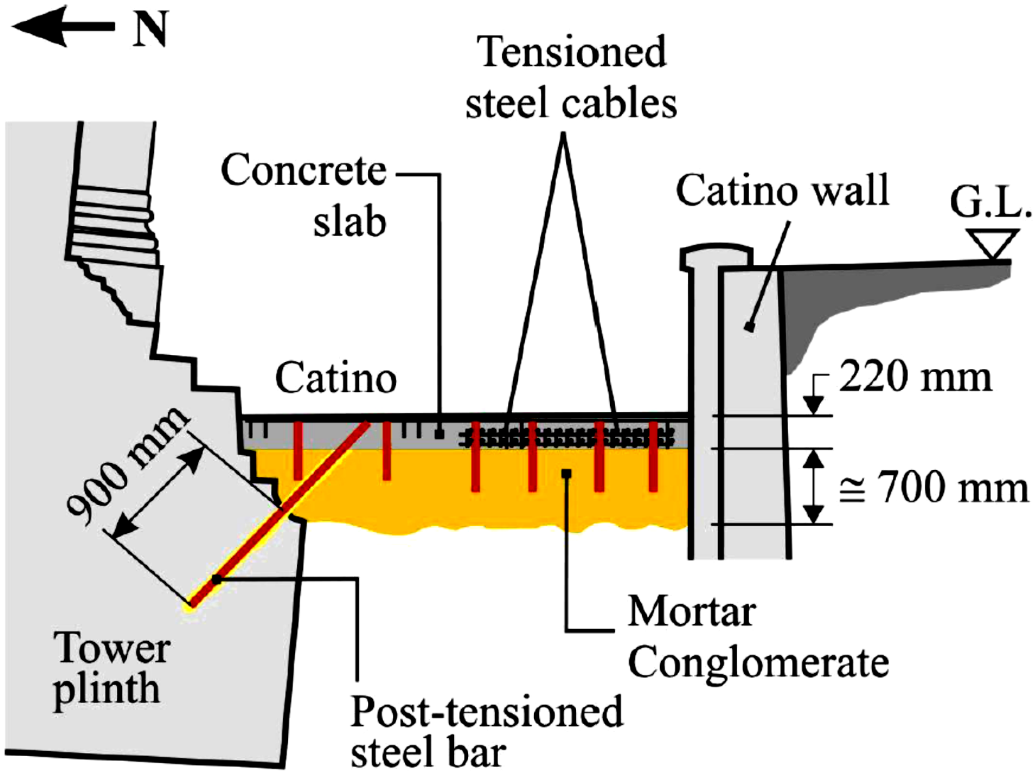


Fig. 18: Illustration of structural connection of concrete ring with tower foundation (Burland et al. 2009)

8 References

Burland, J.B. et al. (2009): Leaning tower of pisa: behaviour after stabilization operations, Int. J. of Geoengineering Case Histories, 1(3): 156-169

Burland, J.B. et al. (2015): Underexcavating the tower of pisa: back to future, Geotechn. Eng. J. of SEAGS & AGSSEA, 46(4): 126-135

Doehne, E. & Price, C. (2010): Stone conservation – an overview of current research, Getty Conservation Institute, 176 p.

Fitzner, B. (2004a): Diagnosis of weathering damage on stone monuments, Proc. Conferencia Diagnosis of Weathering Damage on Stone Monuments Bacteria, 21-28, http://www.ehu.eus/sem/macla_pdf/macla18/Macla18_021.pdf, last accessed: 04.01.2019

Fitzner, B. (2004b): Documentation and evaluation of stone damage on monuments, Proc. 10th Int. congress on deterioration and conservation of stone, Stockholm, Sweden, 2004, 677-690

Hirsch, P.; Eckhardt, F.E.W. & Palmer Jr., R.J. (1995): Methods for the study of rock-inhabiting microorganisms – A mini-review, *Journal of Microbiological Methods.*, 23(2): 143-167

ICOMOS (2008): Illustrated glossary on stone deterioration patterns, ICOMOS International Scientific Committee for Stone (ISCS), 86 p.

Lehrberger, G. & von Plehwe-Leisen, E. (Hrsg.) (2015): Barrois-Oolithe: Vorkommen, Verwendung, Verwitterung und Erhaltung, Münchner Geowissenschaftliche Abhandlungen, Reihe B, Nr. 22

Li, J., Konietzky, H. & Frühwirt, T. (2017): Voronoi-based DEM simulation approach for sandstone considering grain size structure and pore size, *Rock Mech. Rock Eng.*, 50(10): 2749-2761

Przewlocki, J. et al. (2005): Review of historical buildings‘ foundation, Geotechnique, 55(5): 363-372

Pummer, E. (2007): Die Kremser Dreifaltigkeitskirche: Forschung / Konservierung / Restaurierung, Atelier Erich Pummer GmbH, Wachau, Austria

Siegesmund, S.; Weiss, T. & Vollbrecht, A. (2002): Natural stone, weathering phenomena, conservation strategies and case studies: introduction, *Geological Society London Special Publications*, 205(1-7)

Siegesmund, S., Auras, M & Snethlage, R. (Hrsg.) (2005): Stein- Zerfall und Konservierung, Confererence Proceedings: "Umwelt - Naturstein - Denkmal"; 19.-20.4.2005 in Osnabrück, published in Leipzig, 310 p.

TUBAF (2012): Kleindenkmale im sächsisch-böhmischen Grenzgebiet, final report, EU-Ziel3-Projekt, TU Bergakademie Freiberg, Geotechnical Institute

Wichert, J. Konietzky, H., Siedel, H & Frühwirt, T. (2015): Innovatives Verfahren zur Festigung von schwer konservierbaren umweltgeschädigten Sandsteindenkmalen und numerische geomechanische Simulation der Risiken, final report, DBU-Projekt, TU Bergakademie Freiberg, Geotechnical Institute

Wichert, J., Konietzky, H. & Frühwirt, T. (2019): Restauration, Characterization and Simulation of damaged stone monuments, Proc. ICASGE’19,10 p.