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Prague Castle - Monitoring of stability of historical buildings

Pražský hrad - sledování stability historických objektů

Summary

Monitoring at the Prague Castle has been started in 1999 at the Royal Summer Palace and a year later at the St. Vitus Cathedral with the use of precise levelling. At the beginning of the levelling inside the nave of the cathedral, there were discovered vertical shifts of individual levelling points fixed in columns of the nave.

Available reference points for the precise levelling were too far for their efficient application in the monitoring system. High resolution of the future monitoring system was required due to expected small and long-term deformation changes. It resulted in the design of a new local system of reference points with the use of high precision geotechnical monitoring.

Selection of the geotechnical monitoring equipment, the design of a new type of reference points for the local geodetic network, high accuracy link of the geotechnical and the geodetic monitoring are presented in the first part of the lecture.

The foundation of the local network with the use of 3D line-wise monitoring in instrumented boreholes is described and discussed in the second part of the lecture together with presentation of selected results of monitoring. The next development from the point of view of measuring technique and the next use of gathered monitoring results are indicated in the last part of the lecture.

Souhrn

Na Pražském hradě bylo v roce 1999 zahájeno kontrolní sledování Královského letohrádku pomocí přesné nivelace, v katedrále Sv. Víta o rok později. Při nivelaci měřicích bodů ve sloupech vnitřní lodi katedrály byly zjištěny jejich svislé posuny.

Vztažné body pro přesnou nivelaci byly příliš vzdálené na to, aby mohly být přijatelně využívány. Vzhledem k očekávanému pomalému vývoj deformací byla požadována vysoká rozlišovací schopnost budoucího systému sledování. Proto byl navržen nový místní systém vztažných bodů na základě velmi přesného geotechnického monitoringu.

Prvá část přednášky je zaměřena na výběr vybavení pro geotechnický monitoring a návrh nového typu vztažných bodů pro místní geodetickou síť včetně velmi přesného propojení geotechnického a geodetického monitoringu.

Ve druhé části přednášky je popsáno zřízení místního systému vztažných bodů založených na geotechnickém sledování 3D deformací ve vystrojených vrtech. V závěru jsou uvedeny a hodnoceny příklady výstupů a je naznačen vývoj z hlediska měřicí techniky i dalšího využití výstupů sledování.

Klíčová slova:
Pražský hrad, monitoring, podloží, sedání, liniová měření, deformace, klouzavý mikrometr, Fiber Bragg Gratings

Key words:
Prague Castle, monitoring, subsoil, settlement, linewise measurement, deformation, sliding micrometer, Fiber Bragg Gratings

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1 Introduction

Monitoring of historical buildings in the Prague Castle area has been started in 1999 by Procházka, J. and Vobořilová, P. at the Royal Summer Palace with the use of precise levelling, [1]. St. Vitus Cathedral was monitored since 2000. At the beginning of the levelling inside the nave of the cathedral, there were discovered vertical shifts of individual levelling points fixed in columns of the nave. During two and a half of year settlement about 0,5mm of the “new part” of the cathedral was determined in relation to the old part constructed in the fourteenths century (built by Matthias of Arras and Petr Parléř).

A system of reference points was needed due to development of vertical displacements. Available reference points for precise levelling were too far for efficient application (about 900m along narrow streets). Monitoring was expected to be extended on selected buildings of the Prague Castle in the near future.

Complicated plan view of the Prague Castle and required high resolution of the future monitoring system resulted in design of a new local system of reference points taking into account the role of subsoil and masonry of foundations. A new research & development project “System of monitoring of engineering conditions and predictions of their development for historical buildings and its application for the Prague Castle Area” was successfully submitted to the Czech Science Fund, Záleský, J. et al, [2].

Selection of monitoring equipment, design of a new type of reference points for the local geodetic network, high accuracy link of geotechnical and geodetic monitoring together with set of gathered results are presented and discussed in the lecture.

Title of the lecture is related to the last research & development project “Stability of historical buildings” and my work was focused on high precision geotechnical monitoring executed at the Prague Castle together with completion of a local geodetic network and geotechnical support of our research team, [3].

2 Reasons for line-wise geotechnical deformation monitoring

Geodetic instrumentations produce a feedback on possible movements from geometric point of view (position and level domain) and operate from outside while geotechnical sensors are inside structures or below the ground level giving information about the subsoil mass behaviour.

There were four major reasons for application of measurements in instrumented boreholes:

- investigation of actual site conditions and determination of the foundation level of selected buildings,
- monitoring of deformation of the foundations and the subsoil in reference to the base rock,
- foundation of a reference base for geodetic monitoring of position and precise levelling of the system of measuring points on selected buildings and
- piles applied for robust reference points construction were avoided.

Line-wise monitoring in boreholes offers detailed description of deformation development in vertical and/or horizontal directions along the axis of the measuring casing. Measuring in the casing fitted to the foundation masonry and to the subsoil sequence can provide data describing deformation development meter by meter with the reference to the fixed toe in the rock.

If the geotechnical monitoring is well connected with the geodetic one, the local geodetic network for long term deformation monitoring can be founded.

Idea of boreholes carried out through the foundation masonry towards the sound rock with the direct link to geodetic monitoring was accepted by the Prague Castle Administration Office. Sketch of the deployment of the combined measuring casing for 3D deformation monitoring is in the Figure 1.

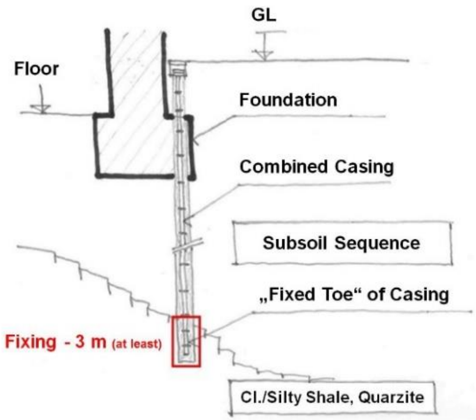

Fig. 1 Application of line-wise measurement for high accuracy deformation monitoring

The Prague Castle is located on a ridge in approximately W-E direction. The ridge is made mostly of Prague shales covered by sequences of made-up ground accumulated during the history of the Prague Castle, Fig. 2.

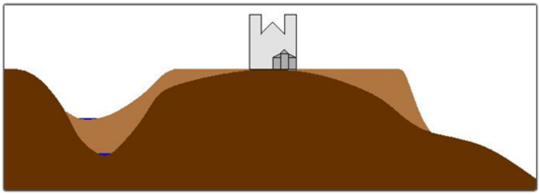

Fig.2 Schematic section through the made-up ground and the rock with the St. Vitus Cathedral in N-S direction, [4]

2.1 Selection of the measuring equipment

Development of settlement of a new constructed building is based on initial compression of the subsoil sequence followed by primary and secondary consolidation, Fig. 3.

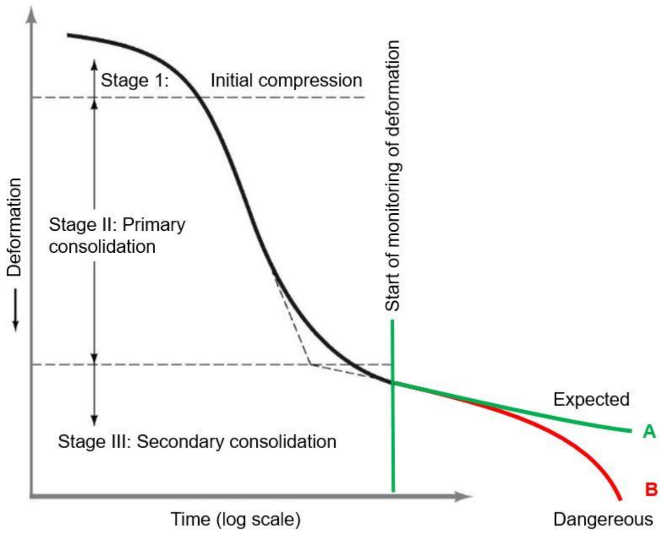

Fig. 3 Schematic view of stages of consolidation and next deformation trends, acc. to [5]

The secondary consolidation (curve A in the Fig. 3) and deterioration processes of footing masonry and bedrock (curve B - interaction of both ones), produce settlement. Time rate of the settlement development is expected to be very low, usually. Thus all the methods applied for monitoring of deformation shall be very sensitive and long-term serviceable. The settlement is suspicious to be differential due to non-uniform subsoil condition and actions in the area of interest.

The Sliding Micrometer of Solexperts, AG, Mönchaltorf, Switzerland, was selected due to high measuring accuracy and mechanical concept of the telescopic measuring casing with ball and cone seating principle, Fig. 4. The measuring base is 1m, the probe has resolution of ±1μm/m, system accuracy ±3μm/m, [6].

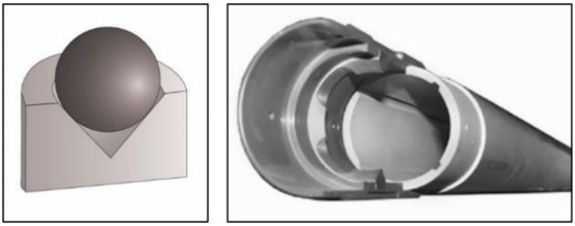

Fig. 4 Ball - cone seating principle and the measuring casing with four grooves, acc. to [7]

The Sliding Micrometer probe with accessories without guide rods is presented in the Fig. 5. The measuring system contains a cable winch which is during the measurement fixed to the top of the measuring casing, a Solexperts Data Controller (SDC in the Fig. 5) and a palmtop or a field computer with special software for measurement control and data acquisition.

Measurements are taken on way down and up to control accuracy and to avoid any accidental and not correct mechanical contact in the casing. Standard measuring range is ±10mm/m.

The Micrometer can be applied in any direction due to guide rods fitted to the top of the Micrometer probe. The guide rods are used to rotate the probe in the casing between measuring / sliding position and they can be used to push the probe in horizontal or upward directions.

The measuring casing can be equipped with four guide grooves for modified inclinometer probe, which can be included in the measuring system for measurement of displacements in X, Y (the inclinometer) and Z directions in one casing. The measuring base of the probe is 1m and the position of the probe is fixed to each measuring mark above it step by step during measurements.

Standard inclinometers are not so sensitive as the Sliding Micrometer. Standard resolution of the inclinometer is 0,1mm/m, usually. According to our tests, if the casing guide grooves are of high quality, the sensitivity of modified inclinometer can be higher.

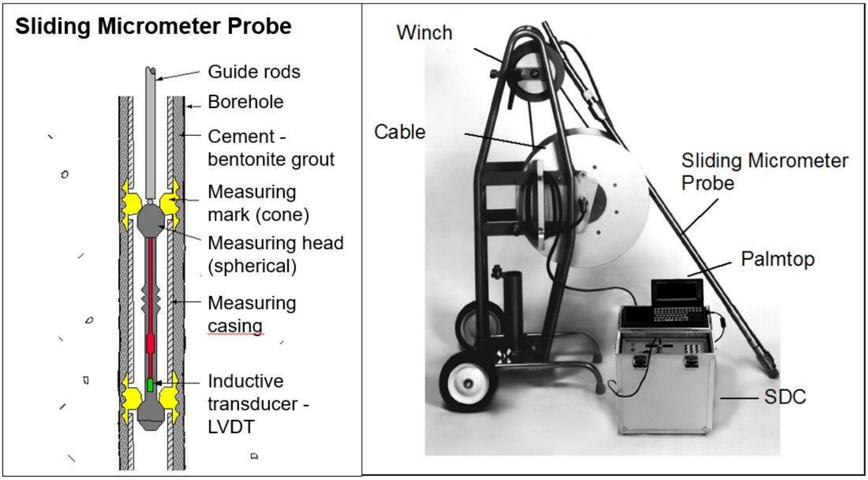

Fig. 5 Sliding Micrometer Probe and accessories (guide rods not presented), acc. to [8]

The second reason for higher resolution is more accurate and well repeatable positioning of the inclinometer probe connected to the measuring marks of the casing and not only to the cable. In the case of the modified inclinometer by Solexperts, AG, it was possible to increase sensitivity up to 0,02mm/m. The change in the measuring software (in Solexperts Data Controller) was made by Solexperts on our request with respect to the facts mentioned before. The standard range of the probe is ±30° to vertical and in the case of the higher sensitivity the measurement range is reduced to about ±20°.

There exists even more sensitive probe called Trivec (3D deformation monitoring) with the sensitivity of 1 μm/m for both, the Micrometer and the inclinometer, built in. But the range of its application is up to ±10° to vertical and the Trivec probe has larger diameter than the Micrometer. According to the Fig. 1, the vertical borehole with the use of the Trivec probe is the most accurate option.

The use of combination of Sliding Micrometer and modified inclinometer due to larger measurement range of inclination was selected. This was in relation to lack of knowledge about foundation conditions of historical buildings. If not, inclined borehole shall be used to pass through the wall to fix the casing in the footing and to give information about footing level and subsoil. The inclination shall be more than 10° with respect to drilling technology. Application of the Trivec probe is limited due to its inclination measurement range in these cases.

2.2 Evaluation of accuracy of vertical shifts of the top of the casing

The accuracy of measurement of the vertical shift of the top of the casing is based on line-wise extensometer measurements composed of measured couples of values with the same accuracy. The measurement is provided between each pair of measuring marks on the way down in the casing and followed by the measurements on the way up. The measuring software Trivec compares recorded pairs of values and indicates differences measured at the same level in the casing. In the case of modified inclinometer, the readings are taken twice on the way up with the probe in origin orientation and turned through 180°. Pair of values is measured at each level of the probe positioning, [8].

At each measuring level of the casing a couple of measured values (readings) l_1' and l_1'' is gathered (change of axial distance or inclination according to the probe used for the measurement). The n pairs of readings are recorded, where the n is the number of measuring positions in the instrumented borehole.

Using set of pairs $$l_1', \; l_1''\,; \ldots ; \; l_n', \; l_n'', \quad (1)$$

arithmetic mean is calculated as the most probable value for each pair of values:

$$x_1 = (l_1' + l_1'')/2 \; ; \ldots ; x_n = (l_n' + l_n'')/2, \quad (2)$$

followed by calculation of differences of readings („Check Sums“ in Trical data evaluation software):

$$d_1 = l_1' - l_1'' \; ; \ldots ; d_1 = l_n' - l_n''. \quad (3)$$

These differences are assumed to be real ones because of errorless value of both differences of readings is $d_i = 0$.

The mean value of (whichever) one reading determined with use of set of n pairs is

$$m = \sqrt{[dd] / 2n}, \quad (4)$$

where $[dd]$ is Gaussian script of expression $\Sigma(d_i^2)$, $2n$ is total number of readings, according to [10].

The mean error of arithmetic average $\underline{x_i}$ of whichever pair in case of $n \rightarrow \infty$

$$m_x = m/\sqrt{2} \quad (5)$$

$$m_x = (1/2) \sqrt{[dd] / n}. \quad (6)$$

In the case of small set of pairs of readings the mean selection error s and s_x is calculated with the use of relationships for mean errors. The number of measured pairs in the set shall be indicated, [9].

The mean error of each (whichever) pair of readings is determined, now. The components of the displacement vector of the top of the casing are sums of the most probable values of (mean averages) of pairs of readings. Hence indirect measurements are used to determine the components of the displacement vector of the shift and an estimate of their accuracy shall be calculated with the use of the law transmission medium errors, which implies next statement:

The mean error of the sum or the difference of measured values is calculated as the square root of sum of their mean errors, [9]:

$$\boldsymbol{m_y = \sqrt{(m_1^2 + m_2^2 + ... + m_n^2)} = \sqrt{[m^2]}}. \tag{7}$$

If the accuracy of measured values is equal $m_1 + m_2 = ... = m_n = m$, the mean error:

$$\boldsymbol{m_y = m\sqrt{n}}. \tag{8}$$

The next mean error calculation is based on the mean error of individual reading indicated by the producer of the Sliding Micrometer probe is ± 3μm/m.

An example of an assessment of accuracy of a vertical borehole with 19 measuring positions was made assuming the indicated mean error of reading equal to resulted in (vertical direction) medium selection error:

$$\boldsymbol{s_{y,z1} = \pm 0{,}003 * \sqrt{19}\ [mm]}$$

$$\boldsymbol{s_{y,z1} = \pm 0{,}01308\ mm \cong \pm 0{,}013\ mm}$$

If the measured actual differences were applied in the calculation, the medium selection error was:

$$\boldsymbol{s_{y,z2} = \pm 0{,}00574 mm \cong \pm 0{,}006\ mm}$$

(The measurements used for above indicated example were taken at the Rabenov site in the borehole VB01, which was used there as a reference point of the local geodetic network, [10]. This type of the measuring casing was used at the Prague Castle, too.) This indicates the medium selection error of the reference points shall be at the maximum equal to the one which has been based on the value of ±3μm/m.

The value seems to be a conservative one, because careful measurement with the Sliding Micrometer results in differences within up and down measurements at the maximum equal to the value ±3μm/m indicated by the producer.

2.3 Design of a reference point of the local geodetic network

Precise link of geotechnical monitoring to geodetic one was designed in the frame of the research & project [3]. Any topmost measuring mark of the casing enables precise and repeatable connection between geotechnical and geodetic monitoring (later G+G). An insert tool for the measuring casing is of our own design. It is based on a ball-cone seating principle, Fig. 4, and an axisymmetric flange on the top of the measuring casing, Fig. 6. The measuring mark has two identical cones with specular symmetry (mark made of bras and of plastic are similar inside).

The tool inserted into the casing with the spherical shaped head is in contact with the upper cone of the topmost measuring mark of the casing. The sliding cone lowered to the plastic flange centralises the tool at the level of the flange. The top of the central rod is ball shaped with a small neck representing a reference point of the measuring casing for the precise levelling and enables optic centralising of the total station on a tripod above, Fig. 6. The top of the central rod of the tool is covered by a protective cap - scheme on the left of the Figure.

The sliding cone of the insert tool was later modified to be heavier and thereby more stable in inclined measuring casings, photo in the Fig. 6.

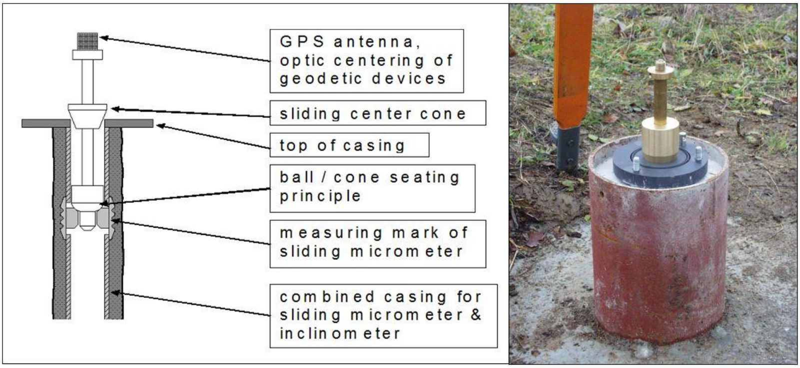

Fig. 6 Insert tool for high accuracy link of geotechnical to geodetic measurements, [11]

The reference point for precise levelling is constructed according to the Fig. 6, scheme on the left side. Measurements taken by the Sliding Micrometer are extended above the ground level with the use of the insert tool. The tool is directly connected to the Sliding Micrometer measurement through the contact on the topmost measuring mark, which is used from both sides, now. The reference points at the Prague Castle are located mostly in shallow shafts with covers made of cast iron.

3 Foundation of the geodetic network

The network foundation was funded by the project GA 103/01/1045 “System of monitoring of engineering conditions and predictions of their development for historical buildings and its application for the Prague Castle Area", started in 2000, [2], and completed in 2008 in the frame of the project GA 103/07/1522 "Stability of historical buildings", [3].

In relation to concerns about instabilities in the area located on the hill and composed of overburden supported by Prague shale's there were not directly discovered instabilities yet, but more signs of differential settlement. This was a reason for application of not only geodetic measurements but also geotechnical 3D displacement monitoring in instrumented boreholes. There is used a special combined casing for high accuracy measurements using the Sliding Micrometer and the modified inclinometer, there.

3.1 Morphology of the area of interest

The Prague Castle is located on a flat elevation about 250m above sea level at Hradčanské Place slightly sloping down to the East. The area is divided in two parts by Brusnice brook forming the Stag Moat about 20 to 30m deep with relative steep side slopes and a central ridge, where the Prague Castle complex is located. On the South of the ridge dips about 50m to the Lesser Town, Fig. 7.

Fig 7: View of the Prague Castle from the East: Greeting card "Hradschin" by Vincenc Morstadt, about 1830. St. Vitus Cathedral in the centre on the central ridge, on the right, Stag Moat and the Royal Summer Palace above; on the left, a slope to the Lesser Town, [10]

3.2 Design of positioning of the reference points in the network

The first part of the network was founded between 2001 and 2003. The part consisted of instrumented boreholes MPD01 through the foundation of the St. Vitus Cathedral in Vikářská Street and MPD02 at the Mathey buttress on the North Wing of the Castle, Fig. 8.

The borehole VB 011 is located in the western part of the area and is situated on a flat part of the central ridge. It is used as a reference point only. The final structure of the network was designed in two close polygons to cover the whole area of the Prague Castle providing a short access as possible for surveying of selected buildings in all parts of the Prague Castle area, Fig. 8.

The polygons with common part following W-E axis of the ridge with the St. Vitus Cathedral and the Jiřská Street were designed. On the South the polygon was guided through the Southern gardens of the Castle to the Hradčanské place. On the North the polygon started at the Hradčanské place, guided through Garden on the Bastion to the Powder Bridge, across the Bridge and through the Royal Garden to the Royal Summer Palace, crossing back the Stag Moat towards the Jiřská Street.

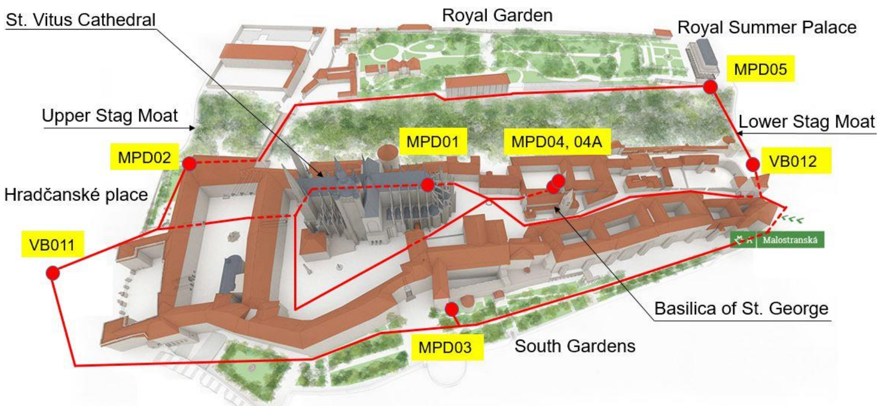

Fig. 8 Completed local geodetic network, acc. to [12], base view [13].

Local geodetic network is stabilised by seven geotechnical boreholes which are embedded in stable rock. Instrumented boreholes MPD 01 - 05 are drilled through footings of structures to monitor their vertical and horizontal displacements as well as to determine effect of the subsoil in development of local structural displacements.

The instrumented boreholes have been used in four ways:

- Extraction of samples of footing masonry, determination of technical state of the footing, footing depth, assessment of the contact of the footing with the subsoil and description of the borehole log, subsoil / rock quality.
- High accuracy monitoring provides the data for differential and integrated plots of 3-Dimensional displacements along instrumented lines with respect to depth and time.
- Connection to local geodetic network contributes to increase reliability and accuracy of measurements, [11].
- Potential confirmation of assumed stability of the toe of geotechnical boreholes.

This is a good reason for cross-comparing of results between geodetic and geotechnical measurements for confirmation of the assumption of the fixed toe of the each instrumented borehole. It is used in the consequence of concerns of instabilities of the Prague Castle area.

Note: The last reference point VB012 was made by re-instrumentation of an old existing borehole in eastern part of the Prague Castle area at the beginning of 2008.

Parallel to geodetic and geotechnical measurements contact thermometer, air temperature and humidity sensors are used for determination of actual temperature distribution and gradients on selected structural elements inside and outside of the buildings. Temperatures of inaccessible parts of masonry of the structure were measured by laser contactless thermometer.

4 Examples of results of geotechnical activities at the Prague Castle

4.1 Determination of the foundation level and the subsoil conditions

Drilling through the footing masonry of the St. Vitus Cathedral in the Vikářská Street was carried out with the use of water flush diamond core drilling, Fig. 9. The diamond drill bit was used to provide careful drilling through the sequence of historical foundation masonry of the St. Vitus Cathedral and to extract a complete set of samples of it. With the use of the samples, there were demonstrated almost no weathering effects in the masonry. The foundation level of the old part of the Cathedral was determined for the first time. It is located at 5,4m below the level of the present pavement of the Vikářská Street. The whole set of core samples of the foundation masonry is stored in the archive of the Prague Castle.

When the drilling resistance dropped down, the water flush was immediately stopped to obtain a core sample as much as possible not disturbed by the flushing water. The strongly weathered shale layer presented in the Fig. 9 is 2m thick. The weathered silty shale alternates to silty-sandy shale or sandstone and beds of quartzite. At 7,5m depth the rock becomes slightly weathered. No water was found in the borehole 10,6m deep. The borehole was instrumented with the combined measuring casing immediately after completion of drilling and cleaning the borehole.

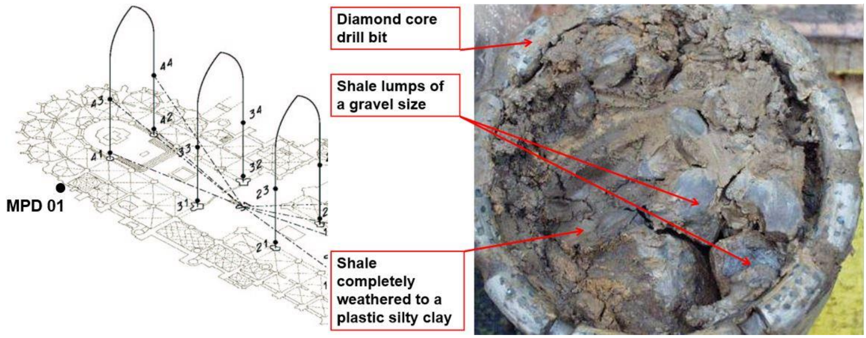

Fig. 9 Location of borehole MPD01 at the St. Vitus Cathedral plan view and core sample extracted from the footing level, [11], [14].

Although the toe of the borehole MPD1 is embedded in the weathered shale below the foundation, the axial deformation measurements show only seasonal changes related mostly to the temperature of the foundation masonry. No settlement of the subsoil sequence was observed. The northern tower of the Basilica of St. George was investigated with respect to historical inclination development and due to remedial action in the sixties of the last century. The inclined borehole MPD04 from inner quadrangle of the Basilica was not successful in discovering the foundation level of the tower and not in contact with any masonry. The borehole MPD04A was drilled directly inside the tower and indicated the foundation level at 0,6m below the level of the floor. Underpinning by cast concrete in this part was found. The subsoil was almost dry and very stiff, Fig. 10. The figure is presented to compare differences between extracted disturbed core samples and the image of the borehole.

A borehole camera was used to inspect the borehole and subsoil structure before grouting it. Only disturbed samples were used for soil characterization, due to the use of a small drilling machine inside the tower. This instrumentation requires the drilling diameter at least equal to 112mm.

The axis deformation measurements in the borehole MPD04A approved variations of range of 0,3mm at the top of the casing. The other instrumentations in the tower were focused on monitoring of temperature and inclination changes of the tower providing support to numeric modelling. During the continuous monitoring of the inclination, the air and the masonry temperature a cyclic behaviour was determined. The tower inclination was affected by variable sunshine exposition and randomly by the wind.

Fig. 10 Core samples extracted from the MPD04A borehole and view to the borehole before deployment of the measuring casing and grouting (grouting tube on the left of the photo).

4.2 Coupled subsoil description and measured vertical deformations

Combination of the borehole log (detailed description of the soil stratification and classification) was used together with measured vertical deformation development during monitoring episodes. This offers very good characterisation of the subsoil behaviour related to the real site conditions.

A simplified example of presentation of combination of the results of vertical deformation monitoring with very brief subsoil description is shown in the Fig. 11.

Note: The worksheets for any instrumented borehole are not presented here because of too tiny details for the printed form.

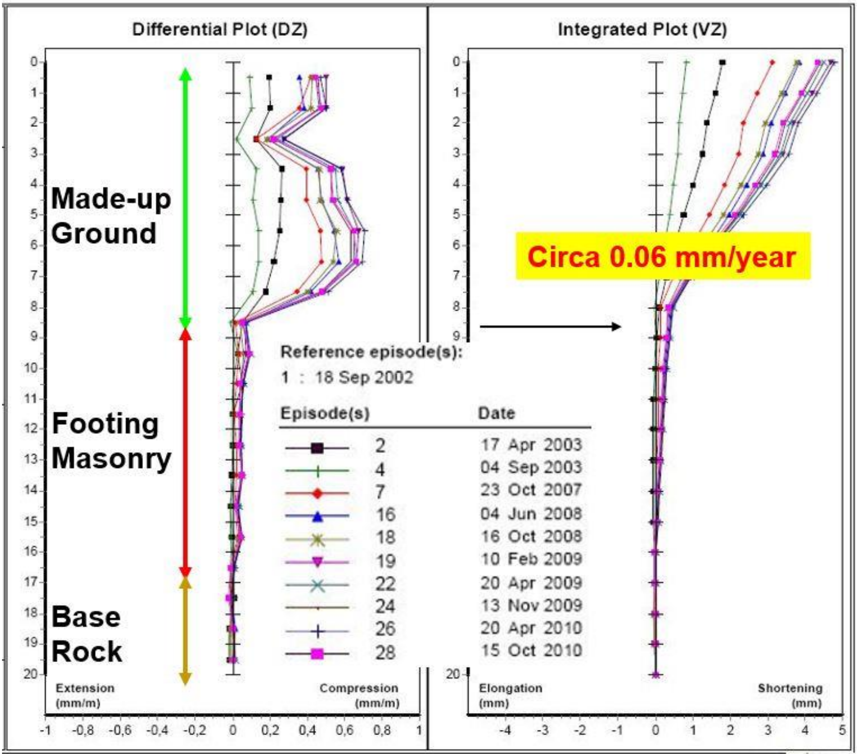

Fig. 11 Description of the sequence of soil-masonry-subsoil together with measured deformation indicates the compression of the foundation masonry, [16].

The annual compression of the footing masonry indicated in the Fig. 11 is small and in itself, not dangerous. With the respect to conservation of the historical buildings it can be important, especially in cases of differential development in the area of the building.

This fact proves the importance of the role of geotechnics together with surveying, particularly the well referenced precise levelling of historical buildings resulting in the control of deformation development within acceptable range.

5 Summary and outlook

Geotechnical activities at the Prague Castle have been started with the design and the foundation of a new type of the local geodetic network for precise levelling and positioning of historical buildings at the Prague Castle. The network is composed of the set of boreholes deployed with combined measuring casings for the high accuracy 3D line-wise deformation monitoring of the subsoil and the foundations of selected historical buildings.

The measurements provided periodically determine shifts of coordinates ***X***, ***Y*** and ***Z*** of the reference points and they are transferred to geodetic monitoring with the use of the casing insert tools of our own construction.

The shifts are taken into account in evaluation of the geodetic network arranged in the two closed polygons covering the area of interest. This brings the detailed information about not only deformation of building structures, but the deformation of the foundation masonry and the subsoil with respect to settlement and / or horizontal displacements potentially caused by made-up ground on the inclined shale base rock.

The results of geotechnical and geodetic monitoring were applied in modelling of behaviour of selected structures with respect to the Prague Castle actual site conditions by the team of the Department of Structural Mechanics, [15].

Very small differences of attitude (3,3mm) between the western and eastern edge of the local geodetic network were discovered during the period of the last three years of monitoring. A new robust analysis of precise levelling was executed, [18]. We expect to apply it, now, for evaluation of stability of the set of reference points connected to the rock base by series of the Sliding Micrometer measurements already made at the Prague Castle. This will contribute to selection of the area with no measurable deformations and these with indication of development trend of small and long-term attitude change, which is suspicious to be caused by geological structure of the area otherwise not possible to determine.

System of high accuracy referencing for the precise levelling, developed for the Prague Castle, is applied for the Broumov group of churches in the recent research & development project DG16P02R049 of the Ministry of Culture of the Czech Republic [17], now. New development in deformation sensing for boreholes and crack monitoring using Fibre Bragg Gratings based on before project [19] is under execution due to support of the project [17]. It resulted in design of a new robust customized system of fibre optic deformation sensors for continuous axial borehole deformation monitoring. The system is in operation at the Heřmánkovice Church of the All Saints and it has a remote access via mobile data transfer.

6 Acknowledgements

The research of applications of line-wise deformation monitoring in geotechnics connected to the Prague Castle has been supported by the Czech Science fund in the frame of the project GA 103/01/1045 System of monitoring of engineering conditions and predictions of their development for historical buildings and its application for the Prague Castle Area and the project GA 103/07/1522 Stability of historical buildings. The recent progress in development of fibre optics applied for geotechnical deformation monitoring is supported by the project Evaluation of stability and technical conditions of the Broumov group of churches and proposal of remediation of this unique Europe culture heritage. Project DG16P02R049 of the Czech Ministry of Culture.

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7 References

[1] Procházka, J., Vobořilová, P.: Complex of technical reports to measurement of shifts and deformation of buildings of the Prague Castle. In Czech. Czech Technical University in Prague, 1999-2003.

[2] Záleský, J. et al: System of monitoring of engineering conditions and predictions of their development for historical buildings and its application for the Prague Castle Area. Research & development project GA 103/01/1045, 2001-2003.

[3] Procházka, J. et al: Stability of historical buildings. Research & development project GA 103/07/1522, 2007-2010.

[4] http://web.asu.cas.cz/~slechta/phrad/phrad.html.

[5] Soil Mechanics: Consolidation, Fundamentals of Consolidation. University of Massachusetts Lowell. 14.3302013consolidation.pdf, file available at http://faculty.uml.edu/ehajduk/teaching/14.330/documents/14.3302013consolidation.pdf.

[6] Trivec · Sliding Micrometer · Sliding Deformeter. Linewise measurement of displacement and deformation profiles in geotechnical engineering. Issue date: 19/12/2014, en_01_geo_linewise_measur_v8.pdf, Solexperts, AG, Mönchaltorf, Switzerland.

[7] Záleský, J., Procházka, J., Pruška, J.: Geodetic and Geotechnical Long-Term Monitoring Applied for the Prague Castle Area. In: Geodesy for Geotechnical and Structural Engineering II. Wien: Institut of Geodesy and Geophysics, 2002, p. 382-391. ISBN 3-9501492-1-X.

[8] Záleský, M.: Application of line-wise measurements for monitoring of slope deformations. Diploma thesis, in Czech. Czech Technical University in Prague, Faculty of Civil Engineering, Prague 2004, 96p.
[9] Hánek, P., Švec, M.: Engineering geodesy. Script, Faculty of Civil Engineering, in Czech. Technical University in Prague, 1996.
[10] Záleský, J., Vobořilová, P., Pruška, J., Procházka, J.: Monitoring of Displacement of Vide Range Focused on Historical Buildings and Slopes. In: Proceedings 11th International Symposium on Deformation Measurements. Patras: Geodesy and Geodetic Applications Laboratory, Dept. of Civ. Eng., Patras University, 2003/05/25-26, p. 411-418.
[11] Záleský, J., Procházka, J., Jiřikovský, T., Salák, J.: Stability of Historical Buildings. In: Measuring the Changes. 13th FIG symposium on Deformation Measurement and Analysis, 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering. Papers on CD ROM. Lisbon: Laboratorio Nacional de Engenharia Civil, 2008, May 12-15, 10p.
[12] https://www.hrad.cz/en/prague-castle-for-visitors/castle-map.
[13] Procházka, J., Záleský, J., Jiřikovský, T., Salák, J.: Long-term Stability Monitoring in the Prague Castle Area. In: Acta Geodynamica et Geomaterialia. 2010, vol. 7, no. 4, p. 411-429. ISSN 1214-9705.
[14] Záleský, J.: 135FOU2_Intro_2016-a.pdf. Introductory lecture of the subject Foundations 2 for MSc. students.
[15] Procházka, J., Jiřikovský, T., Záleský, J., Salák, J., Máca, J. et al.: Stability of historical buildings. In Czech. Issue 1. Published by the Czech Technical University in Prague, 2011. ISBN 978-80-01-04776-7, 229 p.
[16] Záleský, J.: Broumov Group of churches affected by water table variation. Lecture at the CRRB - 14th International Conf. on the Rehabilitation and Reconstruction of Buildings. Technical University in Brno 06-07/11/2012.
[17] Kuklík, P., Záleský, J., Sněhota, M, Vogel, T.: Evaluation of stability and technical conditions of the Broumov group of churches and proposal of remediation of this unique Europe culture heritage. Research & development project DG16P02R049 of the Czech Ministry of Culture, 2016-20120.
[18] Štroner, M., Urban, R., Rys, P. and Balek, J.: Prague Castle Area Local Stability Determination Assessment by the Robust Transformation Method. Acta Geodynamica et Geomaterialia, Vol. 11 No. 4 (176), Prague 2014, ISSN 1214-9705 (Print), ISSN 2336-4351 (Online).
[19] Záleský, M., Záleský, J., Šašek, L.: Project TA01011650 Research and development of applications of dielectric strain sensors in geotechnics. Technology Agency of the Czech Republic, 2011-2013.

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Education

1974	C.E. Civil Engineer, (Ing.) Faculty of Civil Engineering, Czech Technical University in Prague, Study programme: Structures and Transport Constructions
1988	Ph.D. (former CSc.) Faculty of Civil Engineering, Czech Technical University in Prague, Study programme: Mechanics of Rigid and Ductile Bodies and Environments

Employment & Professional experience

1975-1982	assistant at the Department of Geotechnics, Faculty of Civil Engineering, Czech Technical University in Prague,
1982-present	assistant professor at the Department of Geotechnics, Faculty of Civil Engineering, Czech Technical University in Prague
1988	Soil and Rock Mechanics Laboratory, Centre of Field Testing, Stavební Geologie Comp., Prague
1989	Technical University in Ljubljana, Department of Geotechnics, Ljubljana,Slovenia, studies on problems of soft soils and foundations
1992-1994	Cooperation on the project: Czech Republic - North Bohemia Brown Coal Mining & Reclamation Study, Norwest Mine Services. Canadian government to Canadian Commercial Corporation and Ministry of Environment of the Czech Republic
1992-present	lecturer on Soil Mechanics, Foundation of Structures and Geotechnical Monitoring, Faculty of Civil Engineering, Czech Technical University in Prague, Department of Geotechnics; lectures delivered mostly in English
1996-1997	ETH Zürich, Institut für Geotechnik, Zürich, Switzerland: 4 months of studies and assistance in lecturing on Construction of landfills, mineral liners and monitoring

Recent research activities

Experimental research on geotechnical monitoring and field testing, research & development of methods of line-wise 3D deformation monitoring of soil/rock mass, development of measuring tools, static analyses of geotechnical constructions and stability assessment.

2016-2020 *key investigator*, DG16P02R049 - Evaluation of stability and technical conditions of the Broumov group of churches and proposal of remediation of this unique Europe culture heritage. Research & development project of the Ministry of Culture of the Czech Republic

2011-2013 *key investigator*, FR-TI3/609 - Research and development of detection and monitoring of critical areas of geotechnical constructions mainly in underground structures, mining industry and other engineering constructions. Ministry of Industry and Trade of the Czech Republic

2011-2013 *key investigator*, TA01011650 - Research and development of applications of dielectric strain sensors in geotechnics. Technology Agency of the Czech Republic (TA ČR)

2009-2011 *cooperating investigator*, GA103/09/1600 - Research of the monitoring methods of micro-deformations of underground (metro) structures, linked to Underground M3, Cambridge University, G. Britain, NCR v Bologna, Italy, UPC Barcelona, Spain. Cooperation on development of MEMS crackmeter, responsible for pilot instrumentation of MEMS in the Prague metro tunnel, foundation of comparison bench test. Czech Science Fund - GA of the Czech Republic

2007-2009 *key investigator*, GA103/07/0246 - Monitoring of slope deformation and slope stability numeric modelling in real time. Czech Science Fund - GA of the Czech Republic

2001-2005 *key investigator*, MSM6840770005 - Sustainable Construction, WP4 Natural Hazards (optimization of protection, interaction with structures). Ministry of Education Youth and Sports of the Czech Republic

2001-2003 *principal investigator*, GA103/01/1045 - System of monitoring of engineering conditions and prediction of their development for historical buildings and its application for the Prague Castle Area. Czech Science Fund - GA of the Czech Republic

Selected publications:

Ferri, M., Mancarella, F., Seshia, A., Ransley, J., Soga, K., Zalesky, J., Roncaglia, A.: Fabrication and packaging techniques for the application of MEMS strain sensors to wireless crack monitoring in ageing civil infrastructures. Smart Structures and Systems. 2010, vol. 2010 (6), no. 3, p. 225-238. ISSN 1738-1584.

Procházka, J., Záleský, J., Jiřikovský, T., Salák, J.: Long-term Stability Monitoring in the Prague Castle Area. Acta Geodynamica et Geomaterialia. 2010, vol. 7, no. 4, p. 411-429. ISSN 1214-9705.

Ferri, M., Mancarella, F., Belsito, L., Roncaglia, A., Yan, J., Seshia, A., Soga, K., Zalesky, J.: Strain sensing on steel surfaces using vacuum packaged MEMS resonators. Procedia Engineering [online]. 2010, vol. 5, no. 5, art. no. 352, p. 1426-1429. Internet: http://elsevier.com/locate/procedia. ISSN 1877-7058.

Vaníček, M., Záleský, J., Vaníček, I., Jirásko, D.: Monitoring and Wireless Data Collection and Transfer of Prague Metro. In Proceedings of the XIVth Danube-European Conference on Geotechnical Engineering: From Research to Design in European Practice. Bratislava: Slovak University of Technology in Bratislava, 2010, p. 243. ISBN 978-80-227-3279-6.

Ferri, M., Belsito, L., Mancarella, F., Masini, L., Roncaglia, A., Yan, J., Seshia, A., Zalesky, J., Soga, K.: Fabrication and testing of a high resolution extensometer based on resonant MEMS strain sensors. In SOLID-STATE SENSORS, ACTUATORS AND MICROSYSTEMS CONFERENCE. INTERNATIONAL. 16TH 2011. (TRANS-DUCERS 2011). Beijing: IEEE, 2011, p. 1056-1059. ISBN 978-1-4577-0157-3.

Procházka, J., Jiřikovský, T., Záleský, J., Salák, J., Máca, J. et al.: Stability of historical buildings. In Czech. Issue 1. Published by the Czech Technical University in Prague, 2011. ISBN 978-80-01-04776-7, 229 p.

Záleský, J., Kos, J., Kozel, M., Záleský, M.: From site instrumentation to reversed stability analysis. In 8th International Symposium on Field Measurement in GeoMechanics. Braunschweig: Technical University of Braunschweig, 2011, vol. 1, 20p.

Záleský, J. - Pospíšil, J. - Čápová, K. - Koska, B. - Jon, J. - Záleský, M.- Demuth, J.: Landslide Mapping and Monitoring Concept. In 2nd Joint International Symposium on Deformation Monitoring (JISDM). Nottingham: University of Nottingham, 2013, http://www.nottingham.ac.uk/engineering/conference/jisdm/documents/abstracts-s05/submission-126.pdf.

Záleský, J., Záleský, M., Šašek, L., Čápová, K.: Fiber optics applied for slope movements monitoring. In: Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering 2015, Geotechnical Engineering for Infrastructure and Development. London: ICE Publishing, 2015, pp.1699-1704. ISBN 978-0-7277-6067-8.

Záleský, J.; Kovářová, K.: Impact of subsoil and foundation on technical conditions of historical buildings. In Czech. Geotechnika. 2016, 19(1), 41-48. ISSN 1211-913X.