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LONG-TERM STABILITY MONITORING IN THE PRAGUE CASTLE AREA

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ABSTRACT
The static analyses and assessment of the technical condition of historical buildings in the Prague Castle Area are based on observational methods to gather the basic information about the behaviour of structures. The monitoring involves a combination of different methods of surveying, crack, inclination and temperature measurements together with the monitoring of dynamic effects of traffic and nearby tunnelling activities. These methods were enhanced by line-wise measurements using a high-precision sliding micrometer and inclinometer to assess the role of subsoil and to discover potential very slow slope movements in inclined parts of the area. The problems connected with long-term stability of historical buildings are further studied with the use of static analyses and numerical models of selected buildings in the area.

KEYWORDS: monitoring, surveying, precise levelling, settlement, slope movement

1. INTRODUCTION

The monitoring of the technical condition and deterioration of historical buildings requires the determination of their long-term deformation development affected mostly by temperature, humidity changes and dynamic effects produced by traffic. This is further used for the characterization of the expected annual cyclic behaviour of the buildings and their structural elements. The development trends, which are potential danger for the structural health of buildings, can be discovered by analysing the monitored data in a long-term period. The combination of deformation monitoring in the subsoil with high accuracy surveying is effective if carried out in relation to the reference system. The combination offers data for the assessment of overall stability of the whole area of interest. The monitoring of buildings of cultural heritage is extremely difficult due to a long-term incidence of different internal and external factors and registration of very small changes in the majority of cases.

Another set of problems is connected with the analysis part of structural behaviour and is related to so-called limits of standard structure behaviour. The values of relative and "absolute" (global) spatial shifts of measuring points are supposed to range up to millimetres, potentially and seldom to centimetres. The accuracy of selected geodetic and geotechnical methods of data acquisition has to correspond with the above values. The methods shall have a very high sensitivity to provide for prospective development trends and, in positive cases, to discover them early after the monitoring system completion.

Historical buildings had been rebuilt or reconstructed several times during the long time of their existence. Only few records describing structural changes are available. The monitoring is usually designed ad-hoc according to the occurrence of particular faults. In order to determine the causes of structural defects the monitoring system can further be extended. Different monitoring methods followed by static or numeric analyses are used in parallel in order to get feedback. This contributes to the development of a reliable monitoring and modelling system for the structural health assessment (Záleský et al., 2002) provided by a team-work of experts in surveying, geotechnics, structural mechanics and conservation of historical buildings.

Because of our previous activities in the Prague Castle Area and cooperation with the Prague Castle Administration Office, there were historical buildings selected for the assessment of their technical condition and structural health monitoring. A systematic approach was used in the former research project funded by the Czech Science Foundation GA 103/01/1045"System of monitoring of engineering conditions and prediction of their development for historical buildings and its application for the Prague

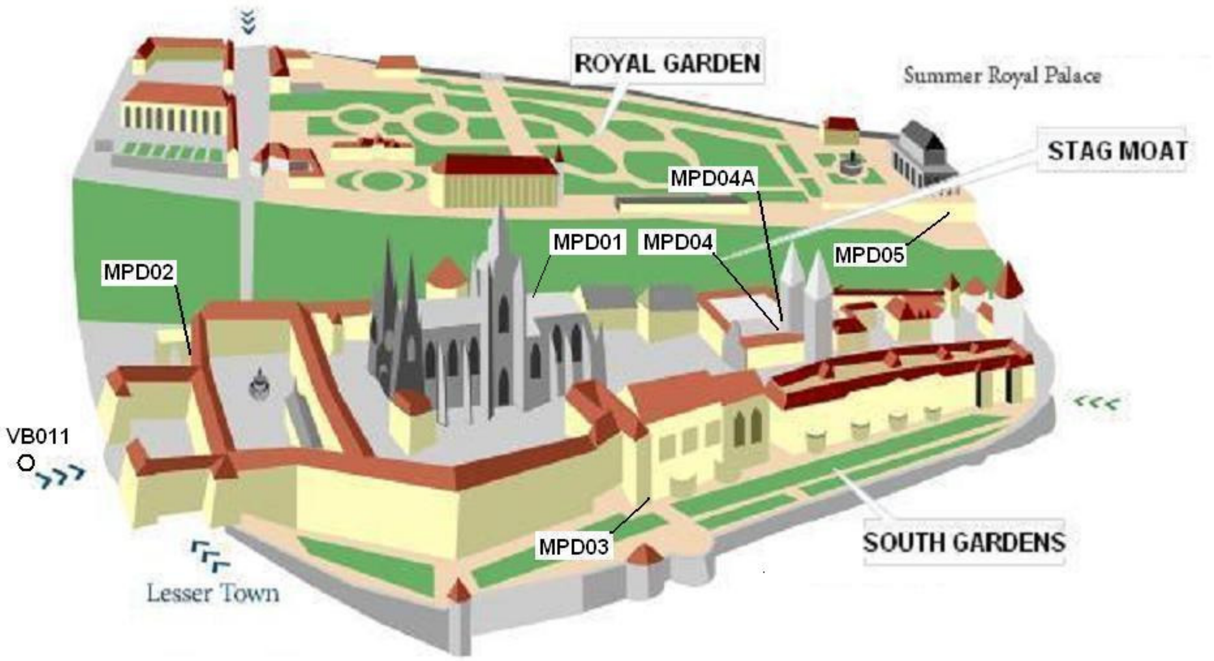

Fig. 1 Area of the Prague Castle with instrumented boreholes (based on www.hrad.cz).

Castle Area“, which is now extended in the project GA 103/07/1522 "Monitoring of stability of historical buildings".

2. DESIGN OF MONITORING SYSTEM

2.1. *GEOLOGICAL CONDITIONS*

The relations in the area of interest are not so complex on their own, but have become more complicated by anthropogenic activity during centuries. Construction activities were started in the Prague Castle Area in the tenth century, as far as known.

The host rock of the Prague Castle Area is made of Ordovic rocks of the late-Palaeozoic system. There is a folded and tectonically disrupted complex of the Letná formation, where intercalations of alleuritic and greywacke shales are alternated with beds of sandstone and quartzite. There are compact, sheet-like layered homogeneous rocks with remarkably irregular sheeting planes. The general direction of the layer inclination in the Prague Castle Area is on average 50° to the south or south-east. The whole series of rocks forms a morphologically remarkable point, which is sharply bounded in the east – west direction.

The site has been intensively reformed by a long lasting expansion of the Castle structures since the Middle Ages. A recent view of the Prague Castle Area is presented in Figure 1. The main part of the Castle is located on the shale ridge in the W-E direction separated from the Royal Garden by the deep Stag Moat.

According to the archive search and former investigations, the rock mass rises up to the ground or to a 2 m depth only in the central part of the Castle. Surface deposits are comprised mainly of material of made-up grounds, which were excavated during former construction activities to form the upland, which has achieved a thickness of 5 to10 m in the area of interest. There is loam and/or clay to sandy loam with debris and detritus, somewhere even sandstone. Their range of thickness is in the order of meters.

2.2. *MONITORING REQUIREMENTS*

Slope movements in the area of Prague Castle have been discussed by many experts for a long time. The development of displacements is evident on both sides of the Prague Castle hill. The extent of the impact on historical buildings in the area has not been objectively stated (the observation of movements and prediction of their development have not been hitherto performed).

On the west side of the North Wing of Prague Castle, a reinforcement system at each floor level was installed because of a long-term development of faults. This was done at the beginning of the nineties followed by a half-year crack monitoring. The western part of the North Wing is close to the Stag Moat side slope, and it was necessary to provide not only surveying but 3D deformation measurements in the subsoil to obtain an objective evaluation of the function of the supporting structure and the assessment of a possible impact of the slope and pier foundation movements.

In the case of St. Vitus Cathedral, it was expected that the cathedral had been founded on the rock and not on made-up ground. The role of potential shale weathering and the deterioration of masonry of the footings have not been determined yet. The cathedral is ranked in the first class of cultural heritage, thus the technical passport of the structure and surveying have been started there to describe the expected seasonal changes acting on the structure.

The next monitoring phase includes:

- South Wing of the Castle located in the South Gardens constructed on a steep slope to the Lesser Town,
- Basilica of St. George due to a significant inclination of the northern tower and
- Summer Royal Palace located on the edge of the Stag Moat south slope.

The monitoring of displacements of historical buildings brings ultimate requirements for long-life instruments with extremely high sensitivity and accuracy because of the almost completed subsoil consolidation and processes mostly driven by the deterioration of masonry, subsoil and rock together with the above-mentioned external factors.

2.3. DESIGN OF LONG-TERM MONITORING SYSTEM

The overall objectives of the monitoring were connected with the above stated problems and doubts resulting in the monitoring of superstructures with respect to a local network of reference points and instrumentation for 3D displacements of footings and subsoil measurement. The determination of the recent state of subsoil conditions of selected buildings was the basic step in the deployment of instrumentations.

The necessity of high sensitivity resulted in line-wise measurements using a sliding micrometer and a modified inclinometer to monitor 3-D displacements with respect to the depth and time. Six instrumented boreholes were drilled through the footings of structures to monitor their horizontal and vertical displacements as well as to determine the effects of subsoil on the development of local structural displacements. The majority of instrumented boreholes were inclined to pass through the footings of monitored buildings. The principle of line-wise measurement has been presented several times e.g. in (Záleský et al., 2003a). Instrumented borings equipped with combined casings embedded in stable rock base have been used in four ways:

- extraction of samples of footing masonry, determination of technical condition of the footing, the footing depth, assessment of the footing contact with the subsoil and borehole log description focused on the casing embedment conditions,
- high accuracy monitoring providing data for differential and integrated plots of 3-D displacements with respect to the depth and time,
- reference points of a local geodetic network with determined 3-D shifts of the top of the casing with respect to a fixed casing toe in solid rock and
- to confirm assumed stability of each toe of the measuring casing together with offering a possibility of judgement of the whole Prague Castle Area stability.

3. FOUNDATION OF REFERENCE POINTS NETWORK

The most problematic part of the superstructure monitoring was a set of reference points at one-kilometre distances. In terms of the required high accuracy of shift determination (tenths of millimetre) it was necessary to found a system of reference points near the objects of interest.

The stability of reference points is usually affected by annual climate changes and sometimes by the observed objects. These were the reasons why we have decided to use high-accuracy geotechnical 3-D displacement monitoring for the foundation of a local geodetic network, as well.

This network consists of points with known 3-D shifts which are taken into account in the displacement calculation. The shifts of the top of the casing in x, y z directions are calculated with special Trical software (SOLEXPERTS, AG, Switzerland). The calculation is based on the assumption of a fixed toe of the combined measuring casing located in stable rock.

A special insert tool for a high precision connection between geotechnical and geodetic measurements was constructed at the Czech Technical University (Záleský et al., 2003b). A section through a borehole with a sliding micrometer probe and an insert tool for linking geodetic and geotechnical measurements is presented in Figure 2.

The tool using the ball-cone seating principle is laid down on the uppermost measuring mark of the casing and a sliding cone extends above ground in the direction of the axis of the casing. The ball shaped head of the tool directly supports a bar coded staff in the case of precise levelling.

Periodic measurements of reference network points, performed in parallel by geotechnical and geodetic methods (modified inclinometer and sliding micrometer, GPS, polygonal and levelling lines) enables us to observe the stability of the whole area of Prague Castle. To achieve reliable results and high accuracy requires the sequence of geotechnical and geodetic measurements.

The local network of geodetic reference points is founded by seven geotechnical boreholes located in the area of Prague Castle. One of these, VB 011, placed in Hradcanske Square, is used as a reference point only. The site plan with geodetic and geotechnical instrumentation in the local network is presented in Figure 3. The network is used for both high accuracy levelling and for positional measurements. A reference point in a ca 2 km distance in the area of the Czech Technical University is similarly equipped and offers a seat for the GPS base

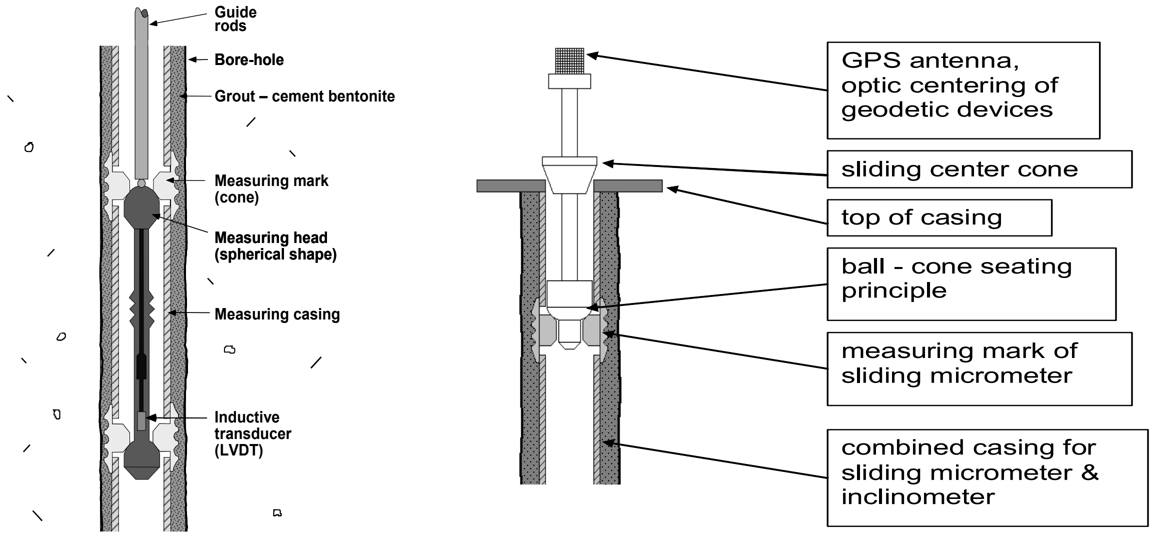

Fig. 2 Sliding micrometer probe in the casing (SOLEXPERTTS, AG) and insert tool (CTU in Prague) to extend geotechnical measurements to geodetic with high accuracy.

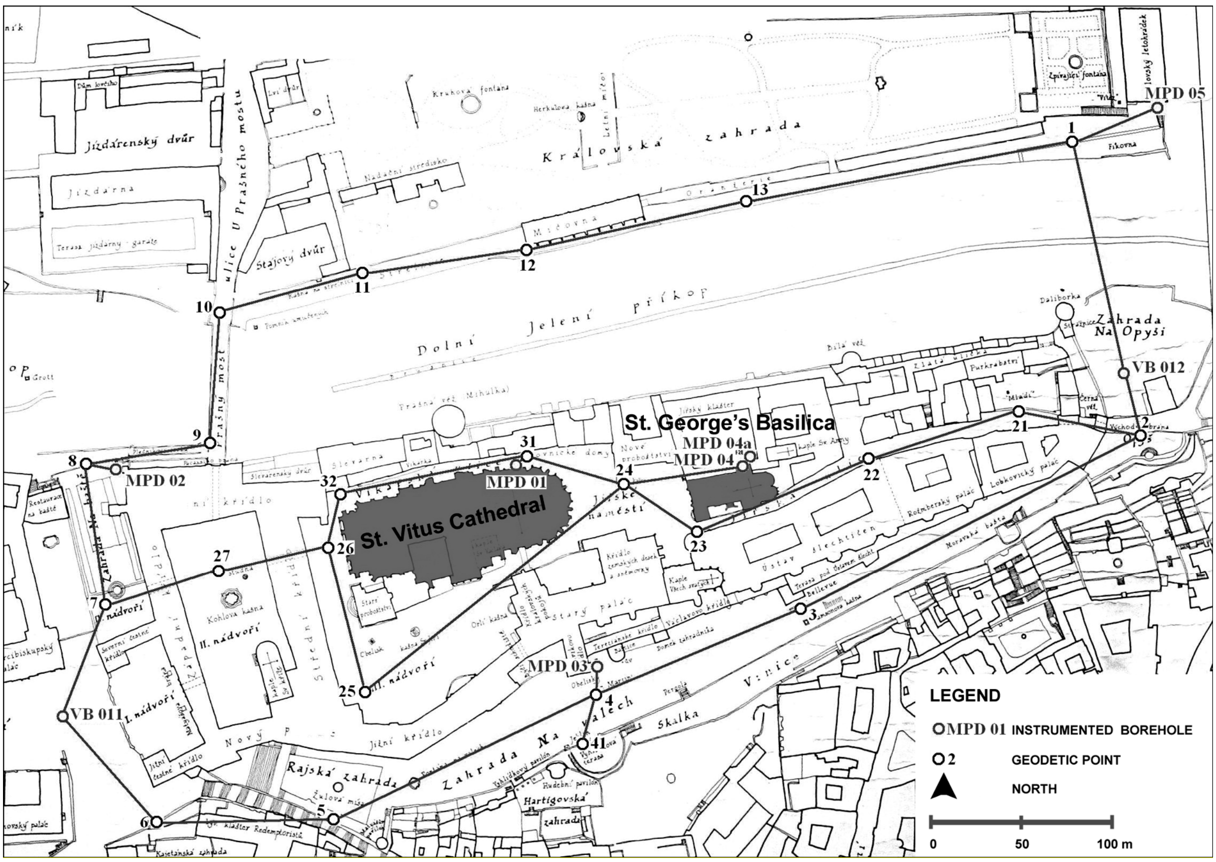

Fig. 3 Site plan of instrumented area of Prague Castle.

station. The rover station is applied in the Prague Castle Area.

Borehole VB 011 is located in the western part of the area and is situated on a flat part of the hill. A new reference point, VB 012, was made by re-instrumentation of an existing borehole in the eastern part of the Prague Castle Area at the beginning of 2008.

The local network was completed and consists of three parts now:

- Central part situated on the crest of the hill, surrounding St. Vitus Cathedral,
- Northern part crossing the Lower Stag Moat located on the north side of it and
- Southern gardens of the Castle.

The determination of the coordinates and altitudes of the points of the local network is provided by parallel measurements in cooperation of geodetic and geotechnical groups. It is composed of line-wise measurements in boreholes with a sliding micrometer and a modified inclinometer (accuracy of displacement on the top of the casing in the order of 0.01 mm in the vertical and less than 0.5 mm in the horizontal direction), high accuracy levelling and accurate polygonometry (accuracy in the order of 0.1 up to 1.0 mm) and GPS measurements with the use of base and rover stations.

The life cycle (lifetime) of measurements can be kept for many years because of special instrumentation of the bore holes; the system allows evaluating the behaviour of subsoil objectively and estimating or eliminating slope motions as sources of strains which possibly affect the above mentioned buildings.

Periodic measurements of points of the reference network by both of the above methods enables us to monitor the stability of the whole Prague Castle Area in relation to the bedrock and to the distant reference point at the University (Záleský et al., 2008)

4. EXAMPLES OF LONG-TERM MONITORING RESULTS

4.1. MATHEY BUTTRESS

In the western part of the North wing of Prague Castle, a strong buttress had been built by the end of the 17th century. The buttress was named after the French architect Jean-Baptiste Mathey who had built the structure.

Remedial works of the North wing reinforcement were done in the nineties of the last century due to a long term development of cracks. No link to any short-time crack monitoring and surveying was available.

A new geodetic monitoring of tilt and vertical shifts has taken place since 2004 and 15 stages have been measured and evaluated up to now. Long-term results of the monitoring are supposed to be used in the analysis of failure causes of the North wing of Prague Castle which is the corner of the well known Spanish Hall.

Temperature effects causing cyclic changes in the position and height of the measuring points on the observed buttress and irreversible changes are evaluated separately. To provide an objective evaluation of vertical shifts of the buttress, the shifts are related to later geotechnical measurements.

4.1.1. MEASUREMENT OF VERTICAL SHIFTS WITH SLIDING MICROMETER

In 2002, an instrumented borehole marked MPD02 was completed to monitor 3-D displacements of the buttress footing and the subsoil. The measuring casing MPD02 is instrumented through made up ground and the footing of the buttress to the rock base (Fig. 4). The footing is 9.4 m thick and is directly supported by the rock base. The weathering residue of the shale at the footing depth is about 0.2 m only.

The relation between the stable casing toe embedded in slightly weathered shale and the upper most measuring mark of the casing is determined by very accurate measurement using a sliding micrometer (Fig. 5), and each measured change is further transferred into surveying by means of a special tool (Fig. 2). The borehole log corresponds very well with the measured data.

The differential plot in Figure 5 represents local changes related to a 1.00 m measuring base length of the sliding micrometer. The integrated plot describes the evolution of the vertical displacement – compression of the whole soil and rock sequence. The compression of the backfill was expected, but the slight and long term development of the footing body compression (about 0.5 mm in 6 years) shall be further monitored.

The embedment depth of the casing is 5 m in the rock base below the footing. It was not possible to drill deeper because of the shale quality and the capacity of the boring machine. The capacity of the machine was limited by the difficult transport to the place of instrumentation (Fig. 6).

This is another reason for a parallel application of GPS besides surveying and geotechnical line-wise measurements. The location of the instrumented borehole MPD 02 is presented in the Figure 6 together with the measuring point for surveying.

4.1.2. SURVEYING OF HORIZONTAL SHIFTS OF THE BUTTRESS

In the case of temperature changes ranging from 3 °C to 27 °C the horizontal shifts measured in five years are about 2 mm. The accuracy of the horizontal shift characterized by the standard deviation σ_p is expected to be approximately 0.2 mm, i.e. the shift can be taken as proven for values higher than approx. 0.4 mm. The course of horizontal shifts is illustrated in Figure 6.

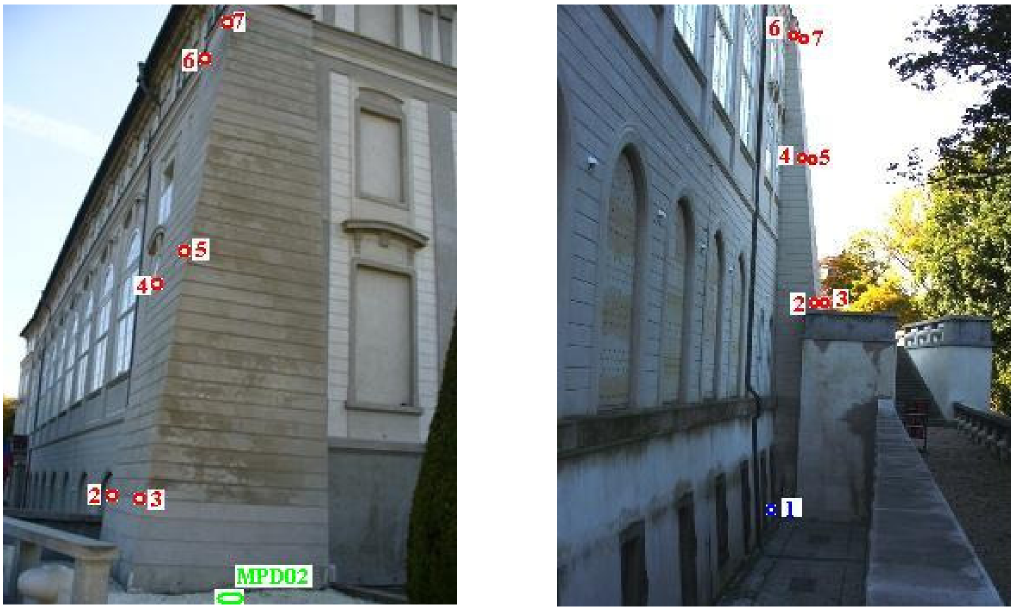

Fig. 6 Front view of Mathey buttress (in eastern direction) and side view (in western direction).

Figure 6 illustrates horizontal shifts of observed points nos. 6 and 7 towards reference point no.1, which is placed approximately 8 m under the level of the upper terrace on the north side of the building and it is therefore exposed much less to temperature changes. Horizontal shifts measured in individual stages are plotted with respect to increasing temperature. The shifts of point no. 6 are illustrated with a blue zigzag line and no. 7 with a green one. There is an obvious proportionality of the size of shifts with temperature. Horizontal shifts of observed points nos. 4 and 5 (in the middle of the overground part of the buttress) and observed points nos. 2 and 3 (just above ground – Fig. 10) are, however, very similar. They are therefore not caused by the tilt of the structure, but rather by thermal expansion of the buttress masonry above the level of the terrace.

The results presented in Figure 7 seem to confirm the reasoning about the expansion of the buttress masonry above the upper terrace. This is proved by the locations of fitted lines, which are close to be parallel to the horizontal axis. This was observed within 5 years and in a temperature range of 24 °C. We suppose it is possible to state that the tilt change of Mathey buttress has not been determined during about 5 years of the monitored period.

4.1.3. MEASUREMENT OF VERTICAL SHIFTS OF THE BUTTRESS

Vertical shifts of the buttress are related to the upper most measuring mark of the MPD02 combined casing (Table1) using a special insert tool, Figure 2.

As the difference in the results displayed in Tables1 and 2 shows, the pillar can be assumed as stable when relating vertical shifts to the rock base using sliding micrometer measurements in the MPD02 casing, Figure 9.

The condition of the fixed bottom of the casing is confirmed by almost no deformation in the embedded part of the casing below the buttress footing, Figure 5. The courses of transformations of long-term geodetic monitored values of shifts confirm the above assumption, too. We assume that the embedment of the MPD02 casing into the system of stabilized points of the local geodetic network is justified.

Based on the analysis of the results of geotechnical and geodetic measurements it is possible to state that neither tilt nor vertical shifts of Mathey buttress were proved during the five-year period of monitoring.

4.2. ST. VITUS CATHEDRAL

The tilts and vertical shifts of the pillars of the longitudinal body (in selected 4 transverse sections) and of the transverse body (in two transverse cuts) of St. Vitus Cathedral have been geodetically measured and evaluated for a period of 8 years (Zalesky et al., 2008).

4.2.1. MEASUREMENT OF TILTS OF PILLARS OF ST. VITUS CATHEDRAL

The dependence of horizontal shifts of the upper observed points placed in the pillars in the triforium level of St. Vitus Cathedral (circa 15 m above the floor - Fig. 11) towards the lower observed points (about 2 m above the floor of the cathedral – Fig. 11) on temperature changes and with respect to time is illustrated in Figure 10. Tilts are determined with the marginal deviation $\delta_{Mp} = u_p.\sigma_p = 2.5.\ 0.2 = 0.5$ mm.

Table 1 Vertical shifts of observed points related to the top of MPD02 casing.

Point	t [°C]	MPD02 [mm]	8 [mm]	9 [mm]	10 [mm]
0.stage	14	0. 0			
1.stage	11	0. 0	0. 2	- 0. 4	- 0. 2
2.stage	3	0. 0	0. 2	0. 2	0. 1
3.stage	21	0. 0	0. 5	0. 1	0. 2
4.stage	20	0. 0	0. 1	- 0. 1	- 0. 1
5.stage	15	0. 0	0. 3	0. 2	0. 2
6.stage	10	0. 0	1. 4	1. 3	1. 3
7.stage	25	0. 0	1. 3	1. 2	1. 2
8.stage	14	0. 0	1. 2	1. 2	1. 1
9.stage	12	0. 0	1. 5	1. 4	1. 5
10.stage	5	0. 0	1. 5	1. 4	1. 8
12.stage	9	0. 0	1. 8	1. 9	1. 9
13.stage	9	0. 0	2. 7	2. 3	2. 3
14.stage	15.5	0. 0	2. 4	2. 4	2. 3
15.stage	14.5	0. 0	3. 0	2. 5	2. 5

Table 2 Vertical shifts of observed points related to the rock base using sliding micrometer in MPD02 casing.

Point	t [°C]	MPD02 [mm]	8 [mm]	9 [mm]	10 [mm]
0.stage	14	0. 0			
1.stage	11	0. 0	0. 2	- 0. 4	- 0. 2
2.stage	3	- 0. 2	0. 0	0. 0	- 0. 1
3.stage	21	- 0. 4	0. 1	- 0. 3	- 0. 2
4.stage	20	- 0. 5	- 0. 4	- 0. 6	- 0. 6
5.stage	15	- 0. 7	- 0. 4	- 0. 5	- 0. 5
6.stage	10	- 1. 0	0. 4	0. 3	0. 3
7.stage	25	- 1. 1	0. 2	0. 1	0. 1
8.stage	14	- 1. 2	0. 0	0. 0	- 0. 1
9.stage	12	- 1. 3	0. 2	0. 1	0. 2
10.stage	5	- 1. 6	- 0. 1	- 0. 2	0. 2
12.stage	9	- 1. 9	- 0. 1	0. 0	0. 0
13.stage	9	- 2. 3	0. 4	0. 0	0. 0
14.stage	15.5	- 2. 6	- 0. 2	- 0. 2	- 0. 3
15.stage	14.5	- 3. 3	- 0. 3	- 0. 8	- 0. 8

The graph shows an indirect dependence of average tilts of the pillars of the longitudinal body of the cathedral on temperature changes. The use of geodetic measurement results for numerical modelling enables evaluation and prediction of the distribution of deformation and stresses in the bearing and supporting structures of the cathedral (Beran et al., 2008), e.g. Figure 11.

4.2.2. MEASUREMENT OF VERTICAL SHIFTS OF PILLARS OF ST. VITUS CATHEDRAL

Vertical shifts are first evaluated in a "relative" way related to one of the observed points (transformation of the supporting structure) and then "absolute" with respect a reference point outside the cathedral. For the purposes of measuring total vertical shifts of the observed points on the observed objects, it is necessary to ensure simultaneous measurements of the boreholes by geotechnical methods and geodetic determination of shifts.

Figure 12 illustrates the course of relative vertical shifts of observed point no. 45 on the north pillar of the 4th transverse section through St. Vitus Cathedral (in the altar location), related to observed point no.15 on the north pillar of the 1st section near the main cathedral entrance.

Figure 13 represents the course of vertical shifts with respect to reference point no. 100, stabilized by a pivot benchmark on the object opposite the main cathedral entrance. The stability of the benchmark is

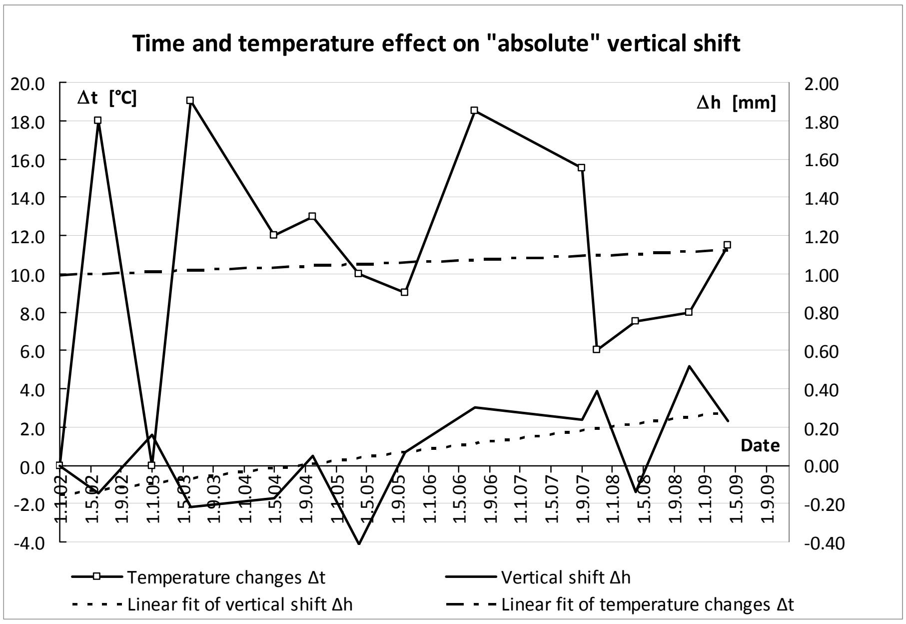

Fig. 13 Development of ”absolute“ vertical shifts with respect to time and temperature.

regularly verified by levelling on reference point MPD01 (inclined casing through the footing of the cathedral located in Vikarska Alley), (Záleský and Salák, 2009).

The difference in temperature changes and shifts is influenced by temperature differences in the basic stages (for “relative” shifts it was +20 °C in June 2000, for “absolute“ shifts. For objective reasons, the measurement was started later in January 2002 at + 4 °C). In the case of relative shifts, it is not possible to determine whether they result in heave or settlement in general, e.g. lifting of observed point no. 45 by ca 0.8 mm or, on the contrary, subsidence of point no. 15, to which the shifts are related.

For ”absolute“ shifts, a lifting of observed point no. 45 by + 0.5 mm is proven for almost 6 years, even with respect to the fact that the verification of measurements was not possible due to the instability of reference point no. 100.

A small lifting is confirmed even by independent geotechnical measurement using the MPD01 casing in Vikarska Alley. The casing is located in the extension of the 4th transverse section (observed points nos. 45 and 46) through the cathedral.

4.3. MEASUREMENT OF TILTS IN ST. GEORGE'S BASILICA

The measurement of deflections of the south wall of the northern tower of St. George's Basilica from the vertical was made with a laser beam of the Ammann Lasertechnik AS 125L. In December 2008, the laser was placed on a tripod and the vertical beam was guided to the highest part of the tower through small floor windows for a former plumb line used in the sixties of the last century. The measured deviations are presented in Figure 14 representing a schematic section through the northern tower. Unfortunately, old data and the former plumb line were not available.

The deviation of the south wall of the northern tower of the basilica from the vertical of 0.260 m towards the north was measured at a height distance of circa 15 m. The tower is 26 m high, which corresponds to a deflection of about 0.45 m!

The deflections of the north and south walls of the basilica (Fig. 15) were further experimentally measured in accessible places upon the structural engineer's request. It is possible to review the tilt of the northern tower with respect to the walls of the basilica (no significant fissures signalizing a separate tilt of the tower were discovered).

As the figure and the measured values show, the walls of the basilica gape open upwards to the ceiling and deviate from the inside outwards from the vertical.

In the end, we measured non-verticality of the walls of the corridor in St. George's Cloister, adjoining the north wall of the basilica and leading under its north tower, in places not only directly under the tower, but also in more distant parts of the mentioned corridor. The walls of the corridor are also deflected from the vertical towards the north (into the courtyard of the cloister), which explains the absence of bigger fissures in the walls.

The measurements of deflections of longitudinal walls of Saint George's Basilica (the north and the south wall) from the vertical were carried out in April 2009. The measurements were provided in 5 vertical sections according to the choice of the structural engineer, Figure 16. The locations of individual points

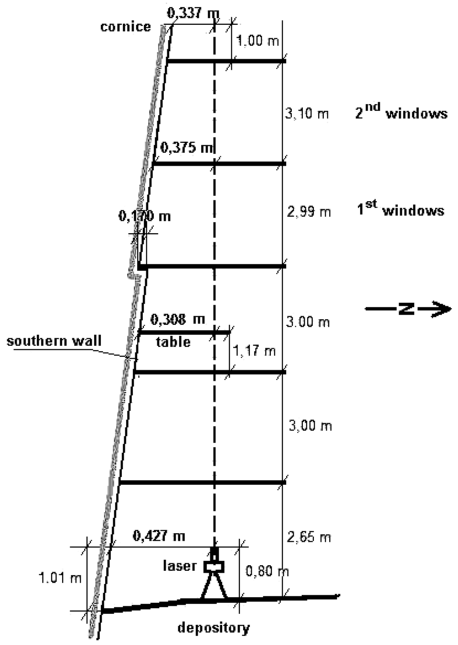

Fig. 14 Section through the northern tower of St. George's Basilica, with measured deviations from the vertical.

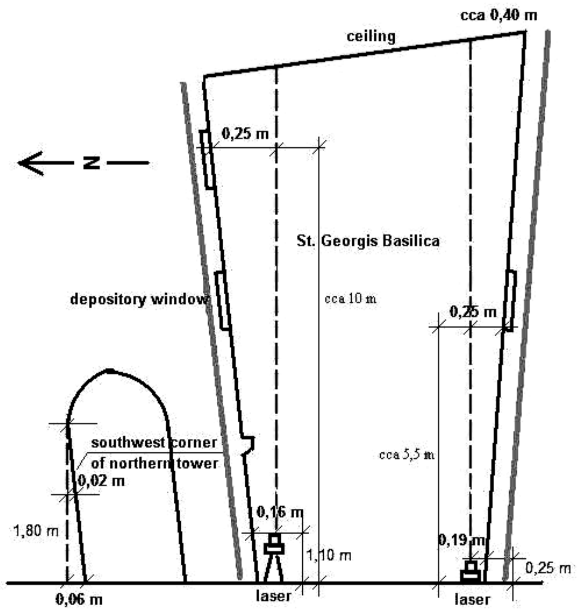

Fig. 15 Section through St. George's Basilica, with measured deviations from the vertical.

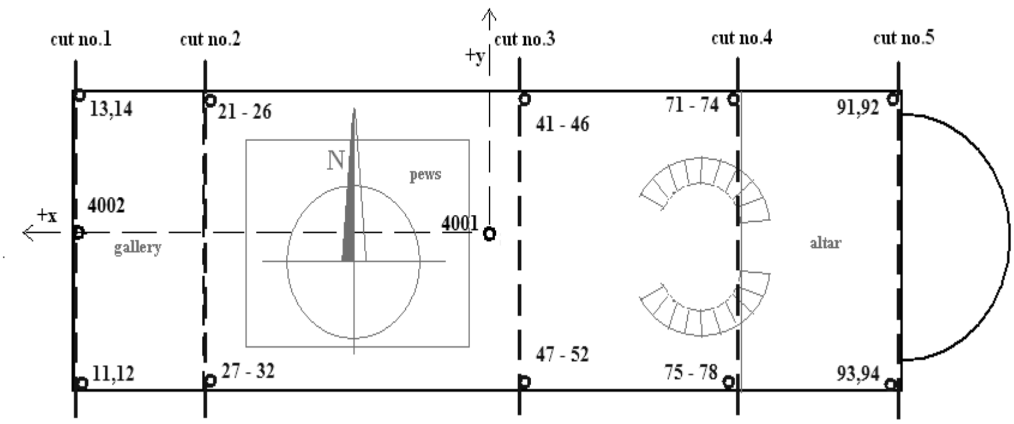

Fig. 16 Layout of cross-sections in St. George's Basilica.

were determined by the space polar method with the use of the Trimble S6 Robotic total station equipped with an electronic distance meter with passive reflection.

With respect to the purpose of the measurement, the standpoint of the instrument (point 4001) was chosen approximately in the middle of the basilica and the orientation was set approximately in the longitudinal axis of the basilica (to the top of the gothic window in the middle of the west wall – point 4002). The direction of the +x axis of the local system of coordinates was parallel to the longitudinal axis of the basilica, (Fig. 16). The measured deflections of two basilica towers and the walls of the nave are presented in a simplified N-S section and layout, Figure 17. The observed points of cross-sections nos. 4 and 5 are presented in Figure 18.

On the basis of the results of geodetic and geotechnical measurements, the structural mechanics group evaluates the causes of deflections of the observed tower from the vertical. By means of numerical models the developments of periodic and permanent changes are characterised (Beran et al., 2009), but the models need calibration and verification, as well.

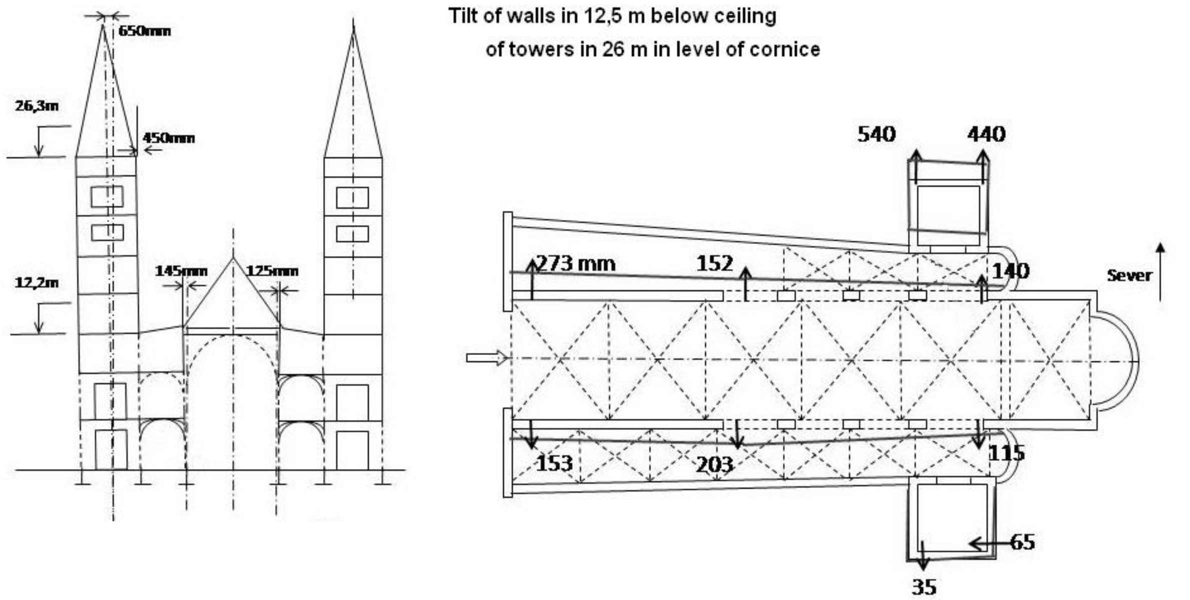

Fig. 17 Simplified vertical section with the layout of the basilica and deflections.

The northern tower of the basilica was selected for enhanced instrumentation. Two boreholes underneath the tower were instrumented with combined casings. One, inside the tower (MPD04A), passed through a very shallow footing of the northern tower and weathered rock to solid one. The measurements in MPD04A have indicated very small changes of axial deformation of up to 0.1 mm on the top of the casing up to now.

In the level of the cornice (at about 26 m above ground inside the tower) four tilt plates in each direction were placed together with tilt and temperature sensors and dataloggers. The time sequence in Figure 19 demonstrates the relationship of the inclination and temperature. The temperature of the masonry is monitored in the centre of the southern tower wall below the cornice.

The aim of the records is to determine the annual range of inclination changes related mostly to temperature and to the other effects (e.g. wind) together with the identification of potential development trends. The knowledge of solar radiation effects and the magnitude of changes of inclination will be used for the calibration of numerical models and for the study of long-term ageing of the tower masonry affected by low frequency cyclic loading.

5. CONCLUSION AND RECOMMENDATIONS

The local geodetic network of the Prague Castle Area was completed in two closed loops composed of one reference levelling mark on a modified micropile and seven instrumented boreholes for high accuracy 3D displacement monitoring. The seven boreholes equipped by combined measuring casings together with developed insert tools offer reference points with high accuracy determined shifts in *x, y* and *z* directions. The geodetic monitoring of buildings has reached a higher level of accuracy due to analyses on the local network based on coupled geotechnical and geodetic measurements.

The results of the analyses made on the network have indicated the stability of the whole ridge-and-valley area of the Prague Castle Area so far.

The differentiation of cyclic changes or long-term alterations and development trends due to temperature and humidity changes or traffic and construction activities induced effects or the deterioration of masonry and subsoil is provided by analysing periodical geodetic and geotechnical measurements. The settlement in the case Mathey buttress was determined in the backfill soil sequence and not in the subsoil. Excepting the compression of the huge Mathey buttress footing body, which has reached up to 0.5 mm within 8 years, there were no development trends of deformation determined.

The static analyses and numeric models were developed with the use of the monitoring results. The numerical models of St. Vitus Cathedral, St. George's Basilica and the vault of Vladislav's hall were calibrated and verified by the monitoring. The behaviour of the structures and the subsoil were assessed and successfuly incorporated into numerical models (Beran et al., 2010, Fajman et al, 2010).

The established monitoring systém enables a long-term monitoring of previously selected buildings and in connection to numerical modelling the assessment of the progress of deterioration of historical buildings. These activities will contribute to planning more sophisticated and careful remedial actions respecting the protected area of Prague Castle.

The execution of the project would not be effective without cooperation of all the involved groups of experts including the Prague castle administration office, when solving such a complicated problem as an objective evaluation of the stability of historic objects with respect to their protection.

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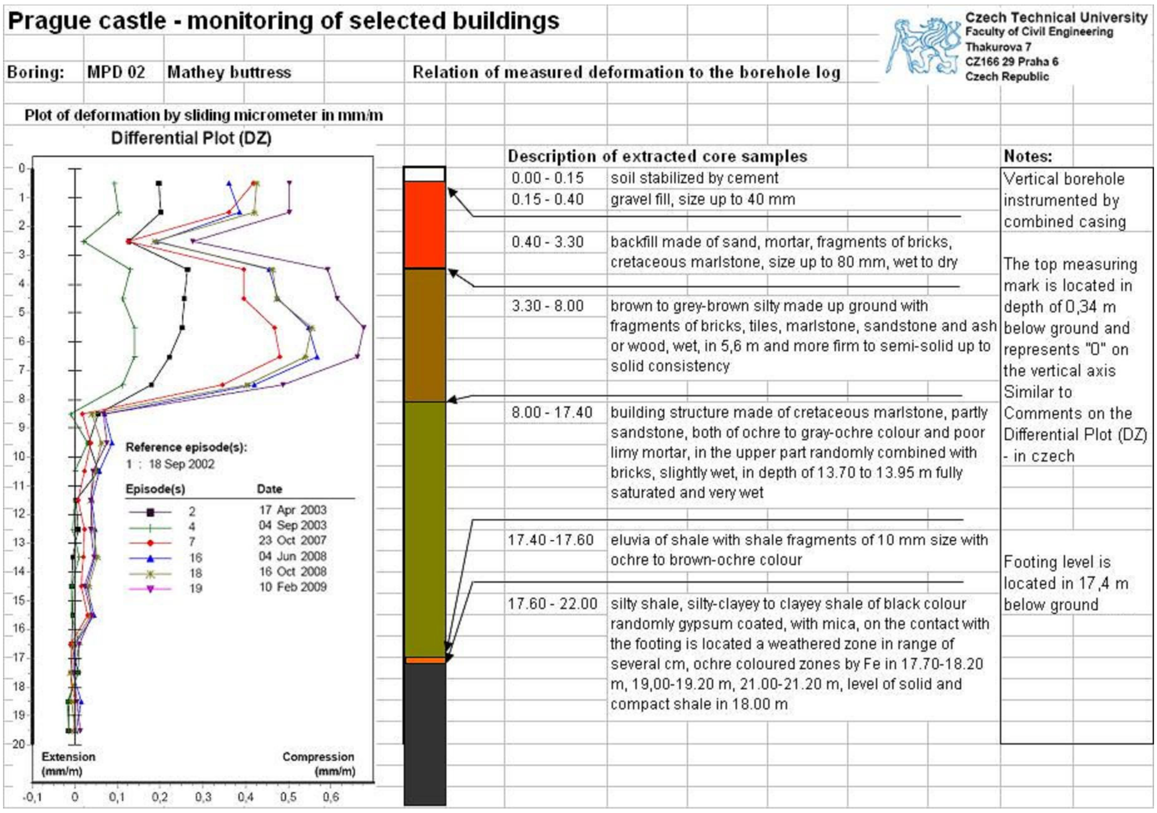

Fig. 4 Vertical deformation is presented in relation to the borehole log – Mathey buttress.

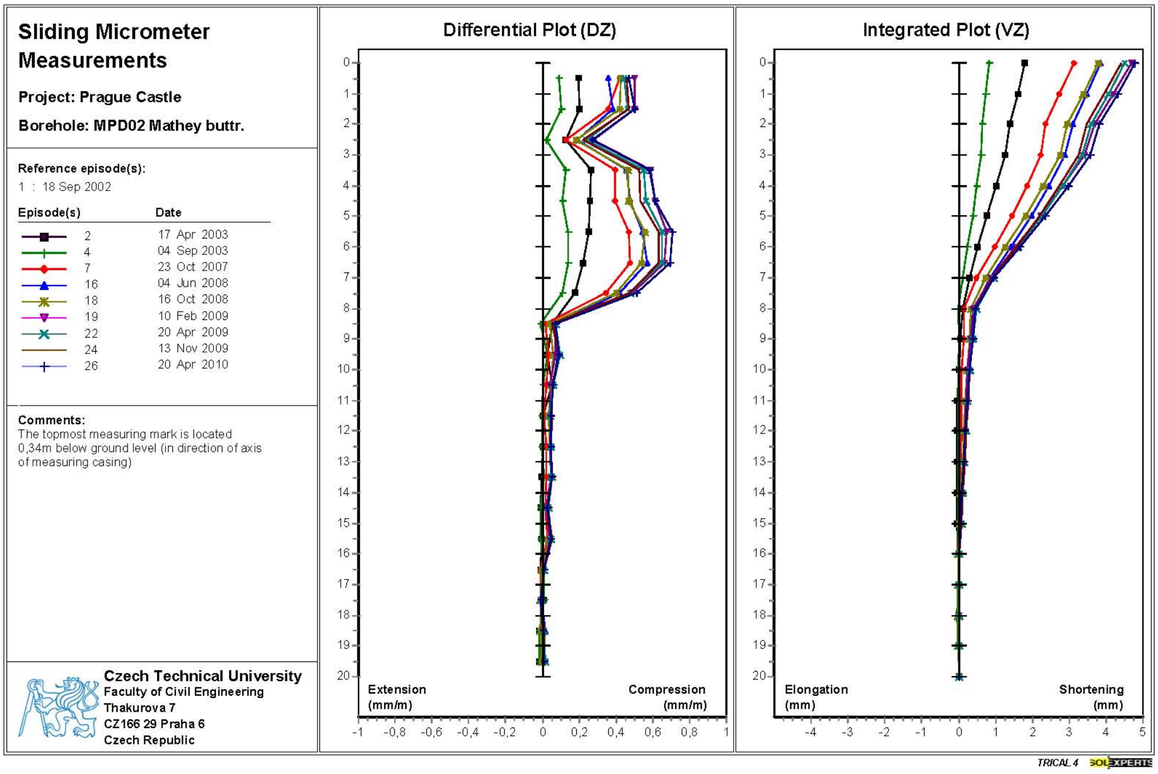

Fig. 5 Development of vertical displacements with use of sliding micrometer – Mathey buttress.

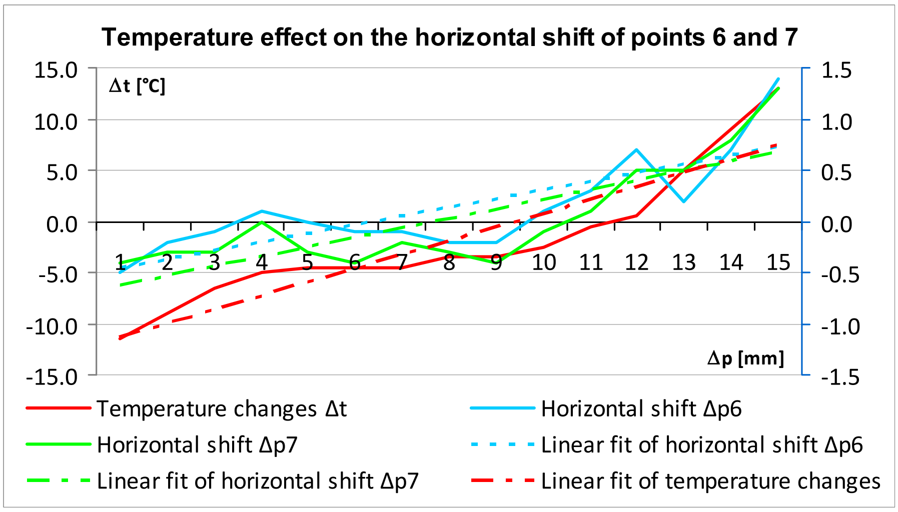

Fig. 7 Illustration of horizontal shifts of upper points of the buttress with respect to point no.1.

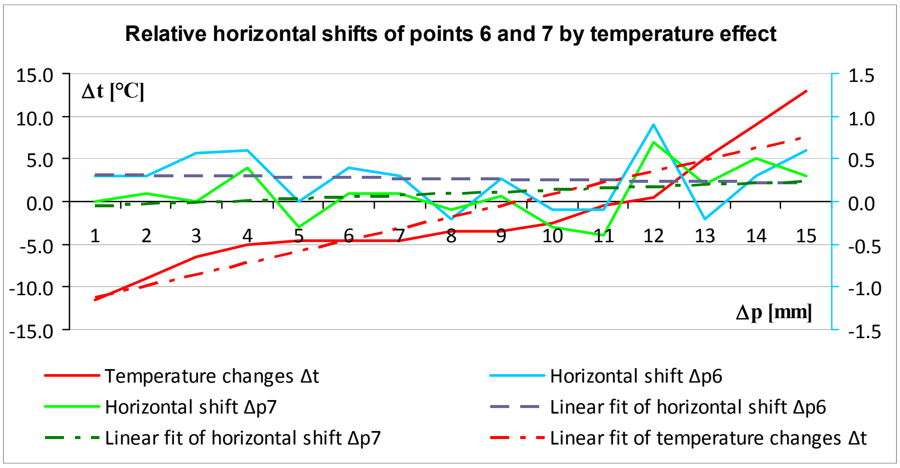

Fig. 8 Plot of relative horizontal shifts of upper points of the buttress related to points 2 and 3.

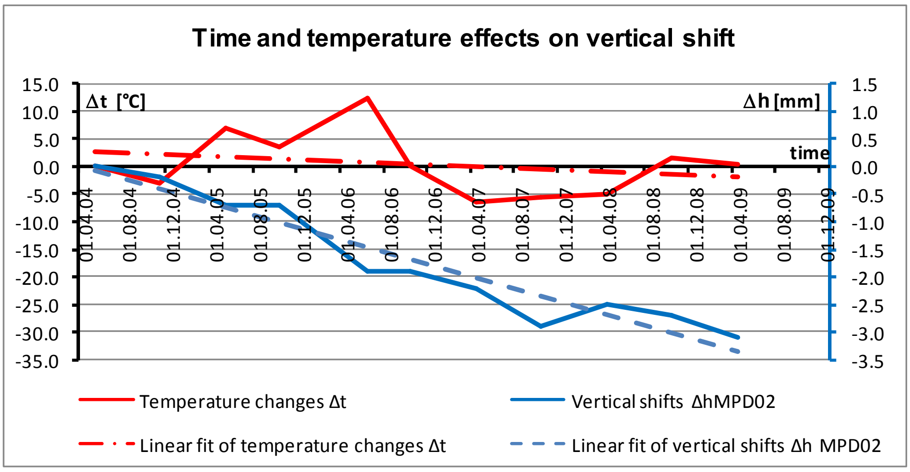

Fig. 9 Plot of settlement of the top of MPD02 casing measured with precise levelling.

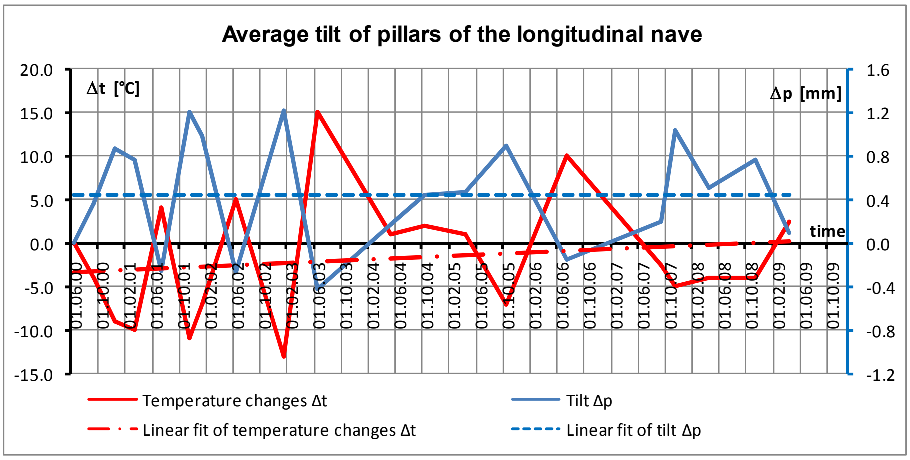

Fig. 10 Average tilt of pillars of the longitudinal nave related to time and temperature ganges.

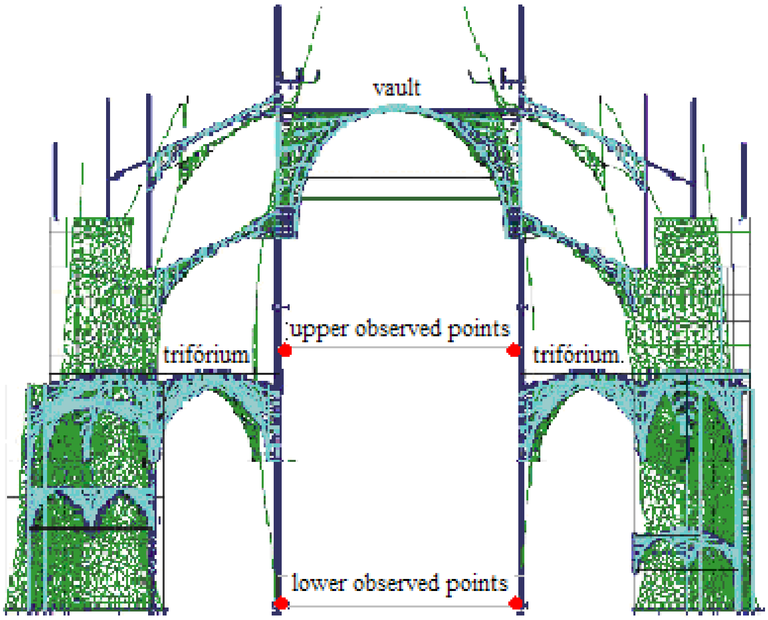

Fig. 11 Horizontal deformations of a typical section through St. Vitus Cathedral caused by temperature changes (Beran and Maca, 2008).

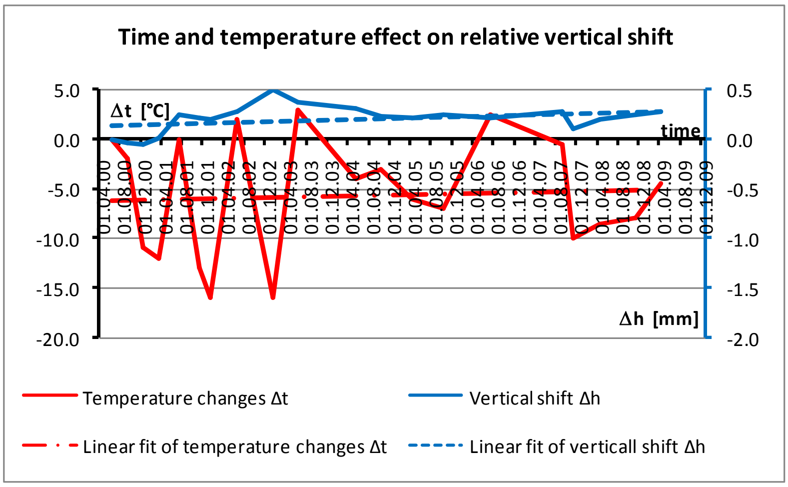

Fig. 12 Development of relative vertical shifts related to time and temperature.

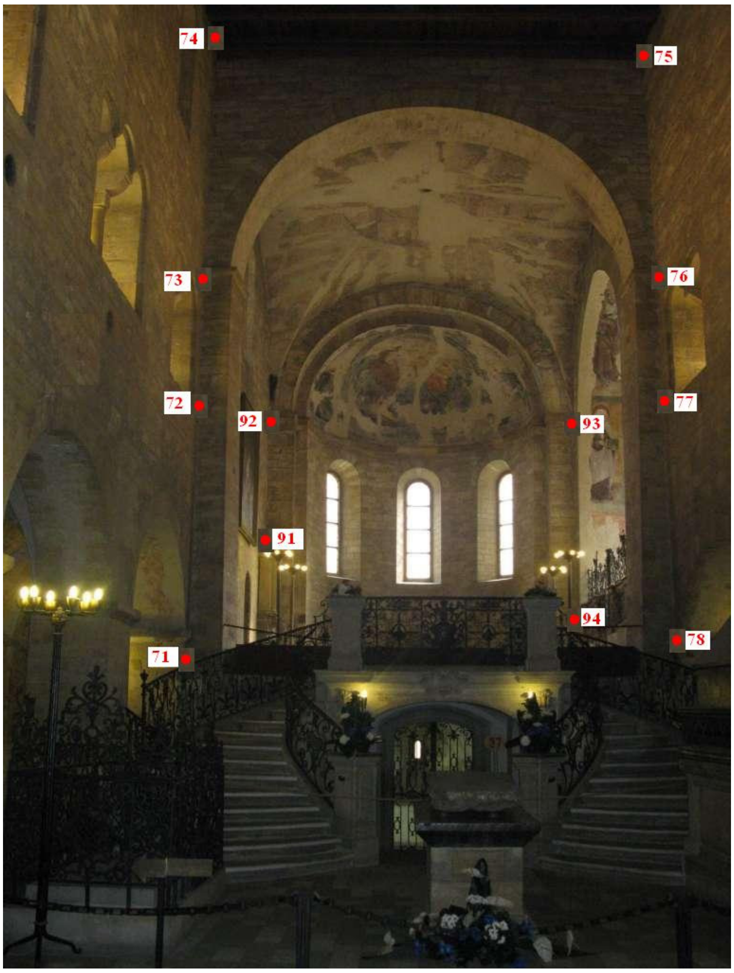

Fig. 18 Illustration of measured points in vertical sections nos. 4 and 5 – as seen from the west.

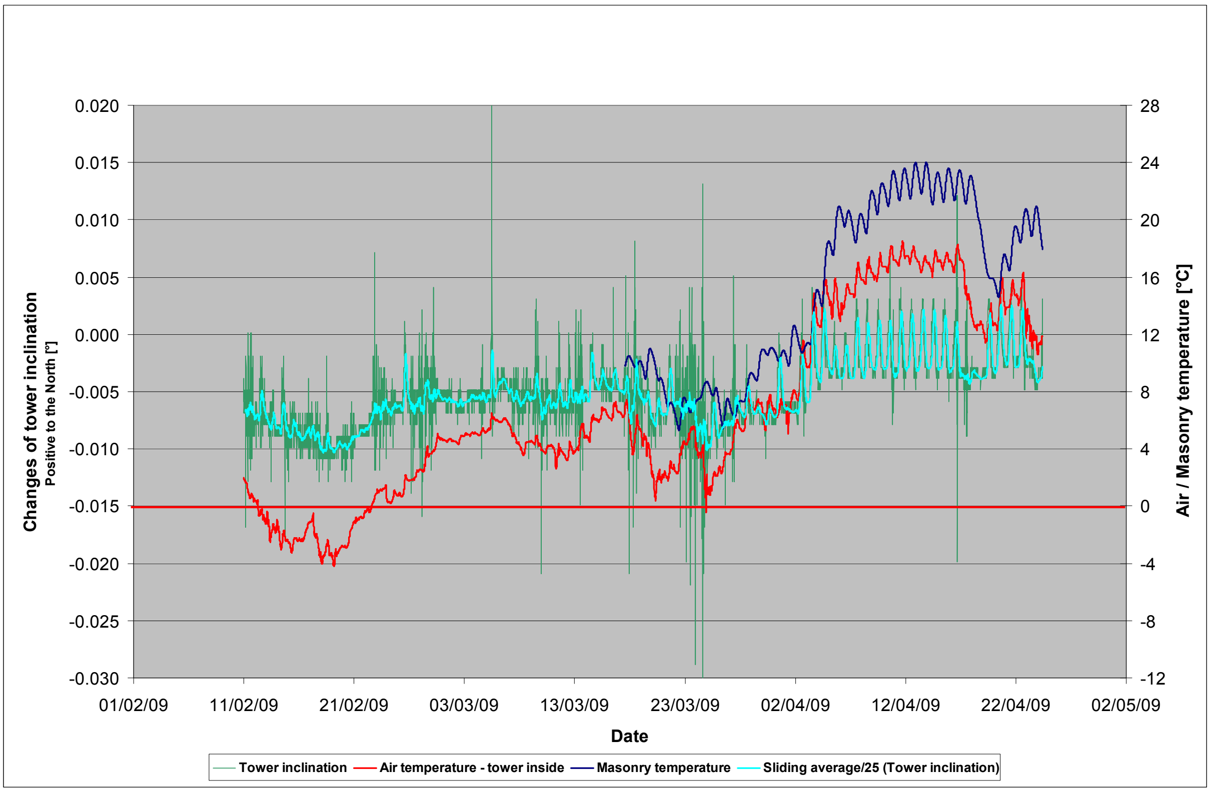

Fig. 19 Inclination and temperature changes of the northern tower of St. George Basilica.