13th FIG Symposium on Deformation Measurement and Analysis
4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering

LNEC, LISBON 2008 May 12-15

STABILITY OF HISTORICAL BUILDINGS

Jan ZALESKY[1], Jaromir PROCHAZKA[2], Tomas JIRIKOVSKY[3] and Jan SALAK[4]

Czech Technical University in Prague, Faculty of Civil Engineering,
Department of Geotechnics[1,4]
Department of Special Geodesy[2,3]

Abstract: The main objective of the project "Stability of historical buildings" supported by the Czech Science Fund is to develop a methodology of complex stability analysis of historical buildings. The analysis is based both on archive search started before the year 2000 and visual inspections. Different sets of long-term measurements as surveying, structural monitoring and geotechnical measurements are performed to gather input data for assessment of the technical state of buildings and their interaction with the subsoil. The project is executed in the Prague Castle area, because of different structures selected for application and verification of the developed methodology, as well as previous activities of the team members there. The project will be described in brief and the ways of instrumentation, monitoring and its results will be discussed. Combination of line-wise subsoil deformation measurement together with sensitive geodetic methods and GPS applications are used for assessment of long-term structural behaviour followed by numeric modelling of selected structures.

1. INTRODUCTION

Monitoring of technical state and deterioration of historical buildings requires determination of their long-term deformation development influenced mostly by temperature and humidity changes and or observations of their stability with respect to displacements in the whole area of interest in relation to the reference system. This can determine expected annual cyclic behaviour and in long-term period development trends which are potential danger for structural health of the buildings. Monitoring of buildings of cultural heritage is extremely difficult due to a long-term incidence of different internal and external factors and to registration of very small changes. Another set of problems is connected with the analysis part of structural behaviour and is related to so-called limits of standard structure behaviour. Values of relative and "absolute" spatial shifts are supposed to range from several millimetres up to centimetres. Accuracy of selected geodetic and geotechnical methods of data acquisition has to correspond with the expected values of displacements

Historical buildings were more times rebuilt or reconstructed during long time of their existence. Only few poor records describing structural changes are available. Monitoring is usually designed ad-hoc according to occurrence of particular faults. In order to determine the cause of structural defects the monitoring system can be further extended. Application of different monitoring methods followed by static / numeric analyses are used parallel in order to get feedback. This helps in development of reliable monitoring and calculation system for structural health assessment (Zalesky et al. 2003a). This approach was used in former research project by the Czech Science Fund GA 103/01/1045 „System of monitoring of engineering conditions and prediction of their development for historical buildings and its application for the Prague Castle Area“ and it is extended now in the project GA 103/07/1522 Monitoring of stability of historical buildings.

2. LOCAL NETWORK APPLIED FOR THE PRAGUE CASTLE AREA

The aim of the project is to enhance and to apply methodology for complex stability analysis of historical buildings in the area.

In relation to concerns about instabilities in the area located on the hill 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 sliding micrometer and modified inclinometer. Site plan with geodetic and geotechnical instrumentation in the local network is presented in Figure 1.

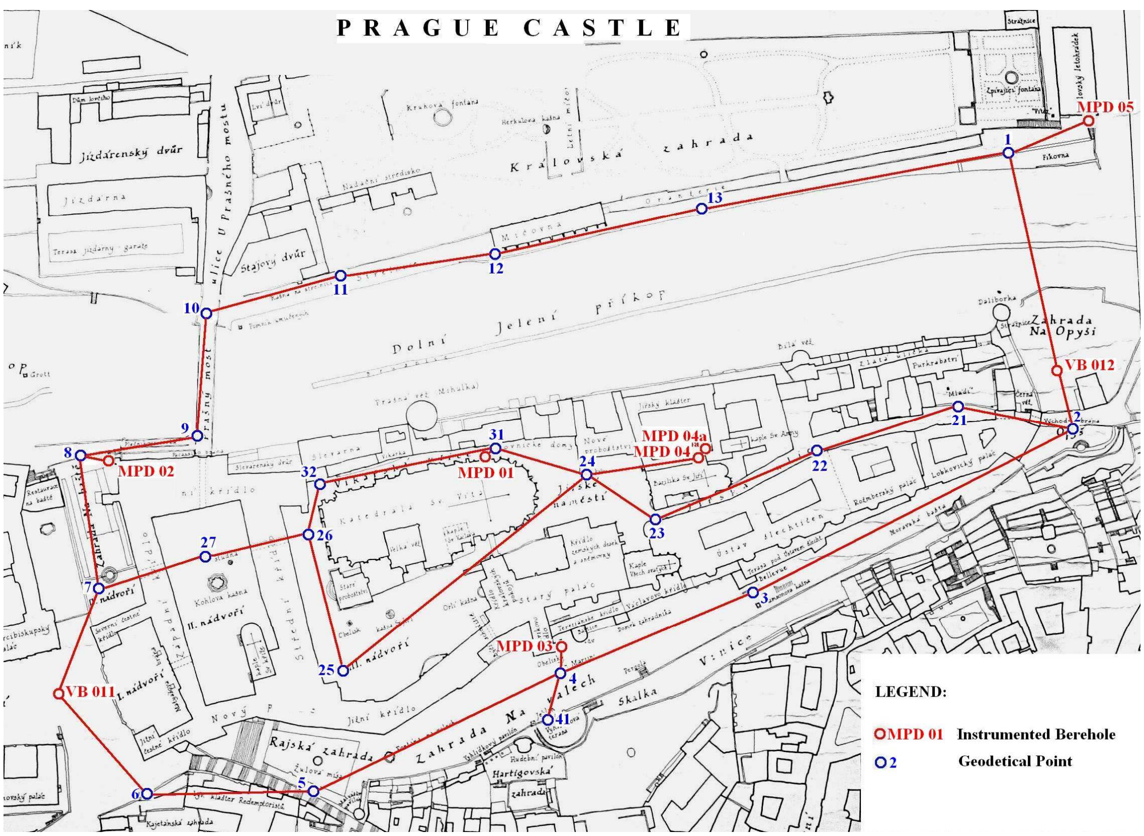

Figure 1 - Site plan of instrumented area of the Prague Castle

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 horizontal and vertical displacements as well as to determine effect of the subsoil in development of local structural displacements. These instrumented borings 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 and
- another result is confirmation of assumed stability of the toe of geotechnical borings.

These boreholes offer direct connection to geodetic network founding reference points. The connection of geodetic and geotechnical measurements is provided by a high-precision insert tool of our construction (Zalesky et al 2003b) with determined shifts by geotechnical high accuracy means of measurement.

The toe of geotechnical borings should be deep enough in sound rock which sometimes means to provide longer boreholes but it rather difficult or impossible to use heavy and robust boring machines in areas of cultural heritage. 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 instrumented borehole. It is used in consequence of above concerns of instabilities of the area.

The boring VB 011 is located in the western part of the area and is situated on a flat part of the hill. It is used as a reference point only. A new reference point VB 012 was made by re-instrumentation of an existing borehole in 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 crest of the hill, surrounding the St. Vitus Cathedral,
- northern part crossing the Lower Deer's Vale and located on the north side of it and
- on the south placed in southern gardens of the Castle.

One reference point was founded with use of high precision casing in front of the Faculty of Civil Engineering in 2002. Besides testing of different measuring instruments the point is used as a base for reference station in GPS monitoring. This point is located about 2 km distance from the Prague Castle area.

Determination of coordinates and attitudes of the points of the local network is provided by parallel measurements in cooperation of geodetic a geotechnical groups. It is composed of line-wise measurements in boreholes by sliding micrometer and modified inclinometer (accuracy of displacement on the top of the casing in order of 0,01 mm in vertical and 0,1 mm in horizontal direction), high accuracy levelling and accurate polygonometry (accuracy in order of 0,1 up to 1,0 mm) and GPS measurements with use of base and rover stations.

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 are measured by laser contactless thermometer.

3. EXAMPLES OF MONITORING OF SELECTED BUILDINGS

Monitoring of vertical structural displacements and tilts related to temperature and time is provided with use of geodetic methods four times a year, as well as by geotechnical measurements in the boreholes.

Development of shifts and deformations of selected buildings of the Prague Castle as St. Vitus Cathedral, which falls within the UNESCO World Heritage reserve, Pleasure House of Queen Anna, Vladislav Hall in Old Palace and St. George's Basilica are monitored with use of the above mentioned network. Vertical displacements and tilts of supports of structures due to temperature changes and direct sun exposure are periodically measured. The measurements are carried out in various year seasons when the temperatures reach average or extreme values. The results of the coupled geodetic, geotechnical and temperature measurements are used for development and calibration of numerical models of selected super structures behaviour. Models verified by monitoring make possible to study development of stresses in the structures, fatigue effects and structural health assessment.

Besides that two seismic stations are installed in Old Royal Palace and St. Vitus Cathedral to monitor dynamic effects. These stations are equipped with three-component accelerometers accompanied with temperature and humidity sensors and data logging. The stations are close to the basement of the buildings and they are synchronized using GPS system.

3.1. Saint Vitus Cathedral

Development of tilts of the northern supporting pillar in the oldest part of the middle aisle in St.Vitus Cathedral (Figure 2 – points 41, 43, further referred as section 4) during seven and half years is described thereinafter as an example of a long term monitoring of displacements.

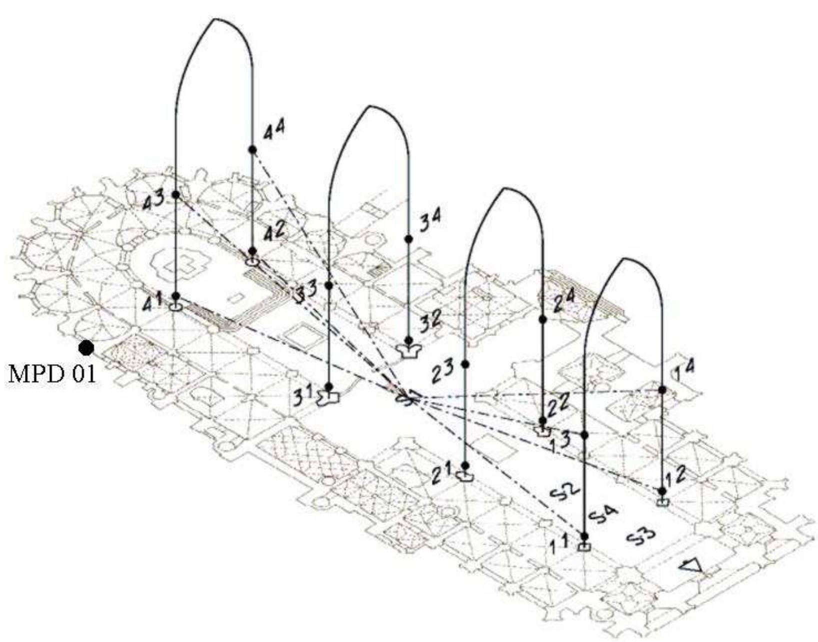

Figure 2 - Deployment of measuring points in the St. Vitus Cathedral

The measurement of four cross sections has been running since June 2000. Couples of measuring points are fixed at selected pillars. The lower points are approximately 2 m above the floor and the upper ones are at the level of the triforium about 17 m above the floor, Figure 2.

At the beginning of geodetic measurements, precise levelling was related to the point 11 in the first section presented in Figure 2 because of lack of reference points near by the Cathedral. Available reference points of the state network are quite far, in more than kilometre distances. Levelling indicated small but differential vertical shifts inside the Cathedral. This was the reason for founding of our own local network in the Prague Castle area.

The activities connected with the network development have been started in Vikarska street by boring and instrumentation of borehole MPD 01 by the end of 2001. The 15,3° from vertical inclined boring was driven through the footing of the Cathedral to the rock base. The borehole is located in the section four in the oldest part of the Cathedral, Figure 2. Total length of 5,5 m of sandstone core was extracted from the footing followed by weathered shale (about 2 m thick) and layered shale which is more compact in depths from 7,5 m to 10,6 m (the toe of the casing). Footing level of this part of the Cathedral was indicated by the boring in 5,3 m depth.

Geotechnical measurements in the inclined MPD 01 borehole indicated vertical shifts in range of ±0,3 mm at the top of combined casing and small activity below footing depth in weathered shale up to ± 0,1 mm/m (the first 1m below the footing). Vertical shifts are mostly related to temperature changes of the masonry close to ground level.

The system of supporting structures is very smart and slender with respect to dimension of the structure of the Cathedral (Beran and Maca 2007), Figure 3.

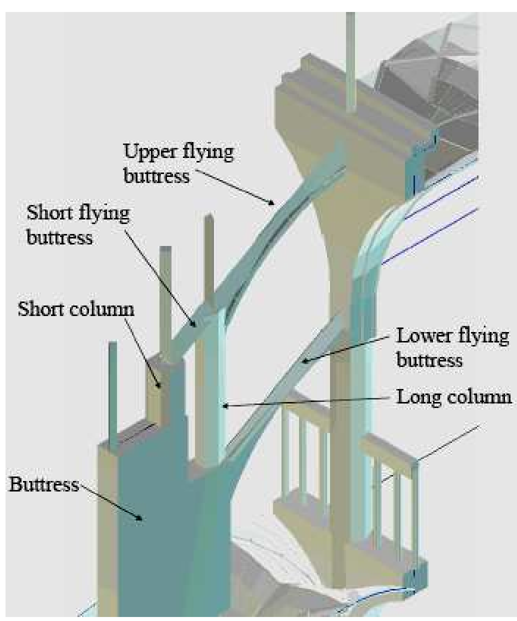

Figure 3 - Detail of bearing system of the St. Vitus Cathedral

The calculation of effects of time and temperature on the tilt value compared with the first episode (19/06/2000) was carried out by means of the least square method. Air temperature was 20° C inside the cathedral and 16° C outside in the initial episode.

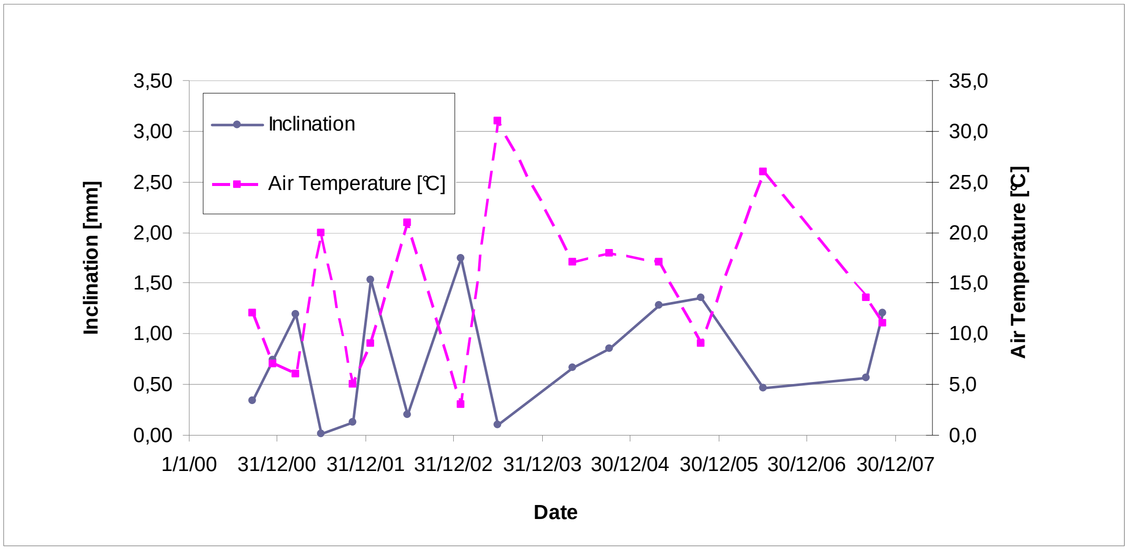

Figure 4 - Tilt of the pillar between measuring points 41 – 43 due to the outer air temperature

It is clear the tilts correspond to the temperature changes outside the Cathedral. Internal pillars tilt towards central nave of the cathedral in case of rising outer temperature and vice versa. This fact is interesting and not expected, but this behaviour is caused by thermal expansibility and stiffness of the outer supporting system.

The values the coefficients and their standard deviations after adjustment for the assessed pillar is:

- In case of the time effect $b = +\,0{,}014$ mm/month, $s_b = 0{,}002$ mm/month and
- temperature changes $c = -\,0{,}057$ mm/° C, $s_c = 0{,}015$ mm/° C.

Assuming extreme temperature range from -20° C to +30° C, the maximum value of the tilt of the assessed pillar can reach $c_{p,max}$ = 5,7 mm (for the vertical difference of observed points about 15 m). The change of a cross horizontal distance at the level of triforium can be up to 12 mm considering the present tilt of the opposite pillars. Thermal expansibility calculated with use of measured values is $\alpha = 12.10^{-6}$ °C^{-1}, which corresponds well with the range of values of sandstone.

In the Figure 5, there are displacements calculated in case of lowering the air temperature, (section 4 of the Cathedral) (Beran and Maca 2007). The results of modelling fit to monitored displacements very good, FEAT, finite elements code.

Distribution of internal temperature of structural elements was modelled in ADINA software taking into account delays caused by the air temperature changes with respect to location of elements inside / outside of the Cathedral and to sun exposure and moisture changes.

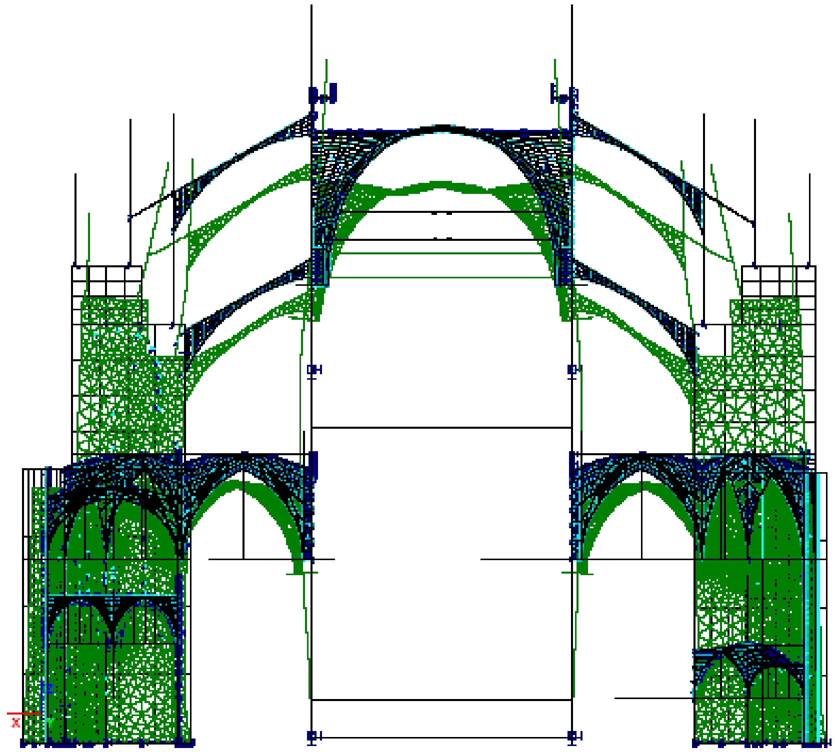

Figure 5 - Displacements of the section of the St. Vitus Cathedral – numerical model in Feat

3.2. Northern tower of Saint George's Basilica

There are two towers built in the 12st century as a part of the Basilica. Particular attention is given to the northern one which actual tilt is about 550 mm in direction to the north. In the Gothic period the Basilica became a part of Cloister of Jiri (Jirsky Cloister) and the northern tower was connected to the ambit and quadrangle. At the time of the reconstruction, there were three openings broken in the masonry of the tower resulting in increase of contact stress acting on the subsoil. The tower was shallow footed and estimated footing depth was 0,7 m.

In the sixties of the last century, there were provided archaeological investigations prior to huge reconstruction of the quadrangle of the Cloister. Two graves were discovered directly inside the tower and many more in the Basilica. One floor of reinforced concrete was made under the quadrangle and two additional supporting pillars connected to the northern wall of the tower, Figure 6.

To take into account the role of subsoil, there was drilled inclined borehole (MPD 04 inclined 26° from vertical) close as much as possible to the tower. Footing depth was not determined but an assumption about shallow footing in direct contact with rock base was indicated as highly improbable. The next step was inclined drilling (MPD 04A inclined 23° from vertical) inside the tower. The footing depth was recognised at 0,8 m below the floor. In both borings the boundary of the shale was determined at about 3,8 m depth. Layered soil between the footing and the rock base consists mostly of silty soils of diluvia of firm to solid consistency (Zalesky and Salak, 2007).

Combination of digging graves, breaking openings to the tower together with subsoil quality contributed to differential settlement of the tower resulting in significant tilt to the north. The instrumented borehole MPD 04A inside the tower will contribute to assess actual role of the subsoil to development of the tilt. Boring MPD 04 located in the quadrangle is used for subsequent judgement of impact of the concrete floor slab to behaviour the northern tower. At the moment, the period of line-wise measurement in above mentioned borings is too short for any conclusions.

The tilt of the tower is measured by several independent methods because of a difficult access to measurement points. We use methods of space combined intersection of directions and distances measured at targets with reflecting plates fixed in the upper tower windows and in the lowest visible part of the tower, Figure 7.

Vertical line was established with use of plumb line in the sixties of the last century and used for few years only. The plumb line was later removed. The application of the plumb line will be renewed in 05-06/2008.

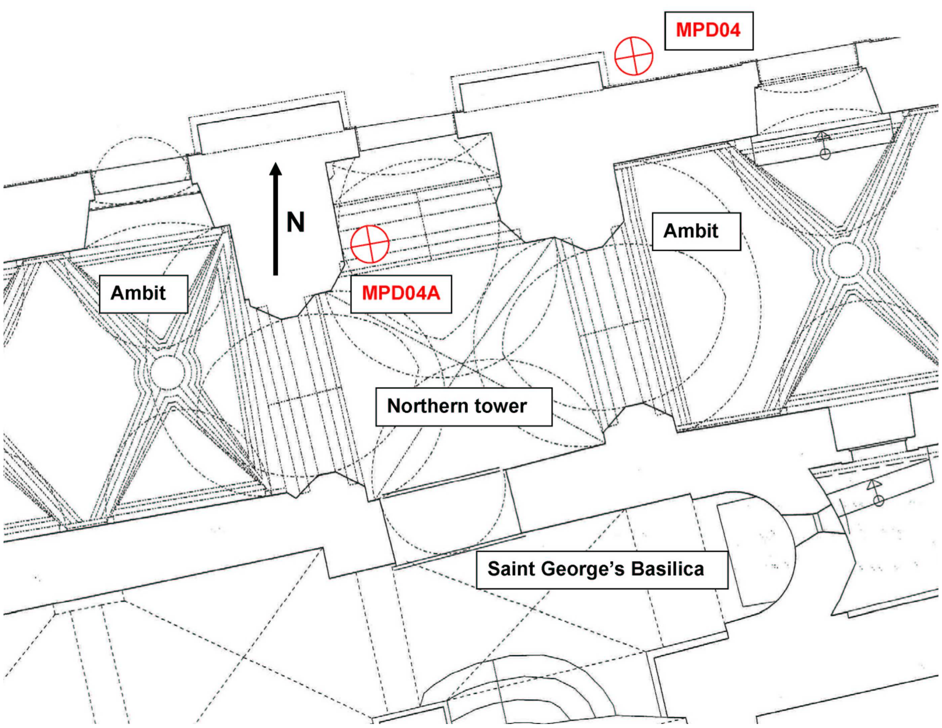

Figure 6 - Site plan with instrumented boreholes in northern tower of the St. George's Basilica

Cross-comparing of monitoring methods will be enhanced by application of four tilt plates inside the tower at the level of 26 m at each side. Another will be deployed at 7 m height on the northern tower wall. Manual readings are accurate enough but they will not discover full range of tilts and there is no chance to describe hysteresis diagram of expected cyclic behaviour of the tower. This is the reason for deployment of vibrating wire tilt sensor with temperature readings and data logger for long term monitoring, which is under testing now. The independent tilt monitoring by different means enable their mutual comparison and objective evaluation of accuracy and to determine possible development trends.

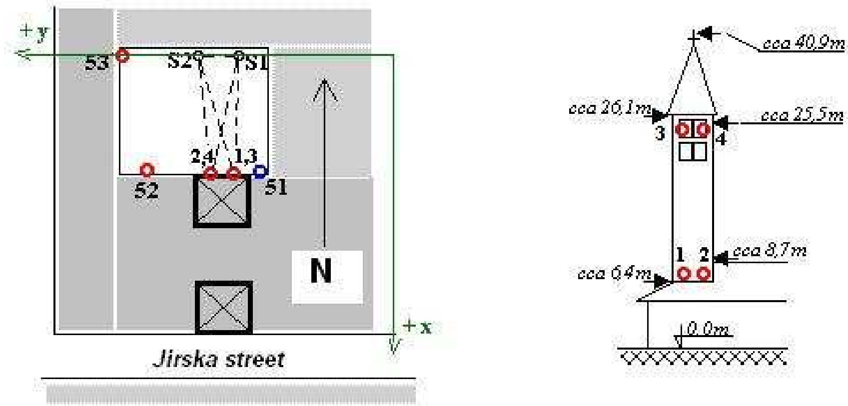

Figure 7 - Schematic view and section of the northern tower of the St. George's Basilica

4. CONCLUSIONS ANS RECOMMENDATIONS

Measuring the changes on historical buildings is a category of monitoring with special features because of entering extremely long processes with small changes to measure and due to a large set of reasons:

- Poor records describing structural changes are only available and almost no reliable information about foundations can be gathered.
- High accuracy and long-term measurements for recognition of processes with annual cycles and possible trends are basic requirements of the monitoring because soil consolidation is already over, mostly creep can contribute to deformation development together with effects of traffic, weathering of subsoil and deterioration of masonry and structural elements.
- Monitoring is usually designed ad-hoc according to occurrence of particular faults. In order to determine the cause of structural defects it is often extended. Application of different monitoring methods followed by static / numeric analyses are used to get feedback resulting in better understanding the processes.

Cooperation of geodesy and geotechnics is essential.

Acknowledgments

The authors greatly appreciate the support of the project GA 103/07/1522 by the Czech Science Fund and the cooperation of the Prague Castle Administration Office.

References

Zalesky, J., Lamboj, L., Pruska, J., Voborilova, P. (2003a). *Methods of monitoring of historical buildings and slopes.* Prague: Proc. of XIIIth European Conference on Soil Mechanics and Geotechnical Engineering. Vol. 1, ISBN 80-86769-00-3. The Czech Geotechnical Society CICE, pp. 285-290.

Zalesky, J., Voborilova, P., Pruska, J., Prochazka, J.(2003b). *Monitoring of displacement of vide range focused on historical buildings and slopes.* 11. FIG Symposium on Deformation Measurements, Santorini Island, Greece, 25-28 May 2003, CD ROM by

Patras University, Greece.Beran P., Maca J. (2007). *The Influence of Temperature on the Deformation of Columns in the Nave of Saint Vitus Cathedral at the Prague Castle.* Journal of Building Appraisal, Vol. 2, No. 4, p. 313-322. ISSN 1742-8262.

Zalesky, J., Salak, J. (2007). *Instrumentation for 3-D displacement monitoring. South wing of the Prague Castle - MPD 03, St. George's Basilica – MPD 04, St. George's Basilica – MPD 04A (inside the tower), Pleasure House of Queen Anna – MPD 05.* Technical Report. Czech Technical University in Prague, Dept. of Geotehnics, 31p.

Corresponding author contacts

Jan ZALESKY
zalesky@fsv.cvut.cz
Czech Technical University in Prague, Faculty of Civil Engineering,
Department of Geotechnics, Thakurova 7, CZ-166 29 Praha 6
Czech Republic