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Hydrostatic Levelling System: Monitoring of Historical Structures

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ABSTRACT: The hydrostatic levelling system (HLS) is a highly accurate technique to monitor differential vertical settlements. The monitoring system is based on the principle of communicating vessels. The working principle is outlined and the results of two case studies are presented. These case studies not only focus on the use of the HLS as an accurate way of measuring differential settlements, but emphasize the relation with the structural behaviour of the building itself. Comparisons with more conventional geodetic systems are made. This provides objective information on which further options on strengthening and consolidation of the structure are based.

1 INTRODUCTION AND WORKING PRINCIPLE

The Hydrostatic Levelling System has been developed by the French company “Fogale Nanotech” in collaboration with the European Synchronic Radiation Facility. The nominal accuracy of the system is 0.01 mm. The monitoring system is based on the principle of communicating vessels. The instrument is composed of vessels, Fig. 1 and Fig. 7, linked to a double circuit: one to let the measuring liquid circulate and another one, an air circuit, to set an identical pressure in all the vessels. The liquid used is water (normal water, non-distilled so that it can conduct electricity, treated with anti-algae and antifreeze,) with a colouring to be able to control the presence of bubbles. In each vessel, the height is measured with a capacitive sensor which measures the distance between the water level and the sensor.

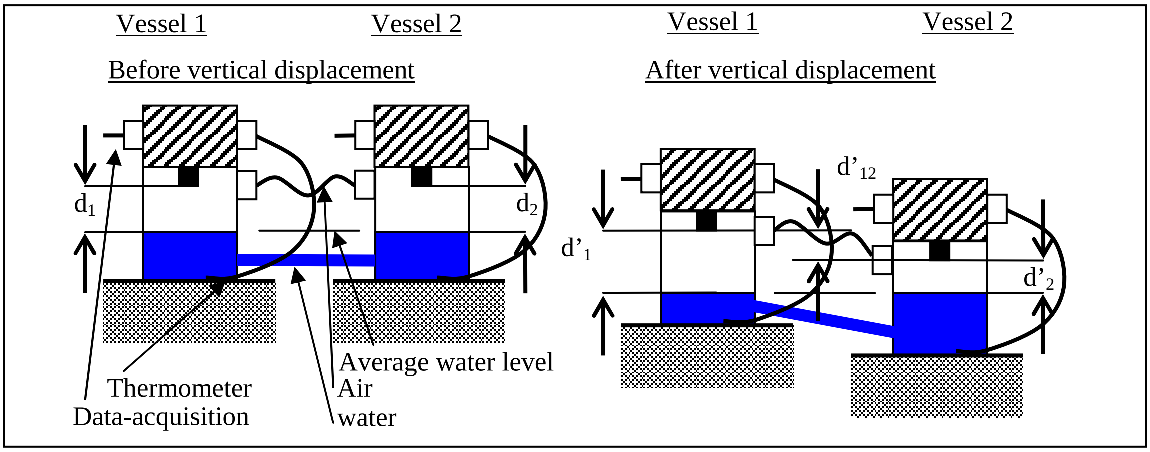

Figure 1 : Hydrostatic levelling system – measuring principle

The readings range from 5000μm to 10000μm. Measurements are taken with the system frequency (about 33 Hz) and the results are directly visible on the computer screen. The data are stored with an adjustable frequency. The values stored are the means of 100 values taken in 3s. The temperature is measured in every vessel and the rough displacement measurement is directly corrected accordingly. The tubes of the water circuit are placed as horizontally as possible in order to remove the effects of a temperature gradient. The tubes of the air circuit lead upwards from the vessels to prevent the condensation water from staying in the air circuit. The analogical response of the sensor is digitalised and linearised by a 12Bit card. Since no vessel can be considered steady, it is impossible to know the absolute values of the settlements. In practice, all the displacements are recalculated in relation to the mean level of the water in the circuit.

2 CASE STUDIES

In both case studies the measuring period extended sufficiently long – 5 months - to filter out the influences of temperature and relative humidity enabling the real influencing parameters to be identified, such as the water level of the river Demer in the first case study. Additionally, the system of hydrostatic levelling has been placed in parallel with a more conventional geodetic system. The latter has been measured at discrete moments in time. These allow to compare both measurement techniques and to draw some conclusions on the accuracy of the geodetic survey and its ability to complement the findings from a long term measurement campaign. In both case studies, the causes of the measured differential settlements could be retraced, delivering crucial information related to the structural behaviour of the historical building and its load-bearing capacity.

2.1 Duke's Mill Aarschot (Belgium)

The first case study deals with the largest water mill in Western Europe, named as Hertogenmolens (E: Duke's Mill) in Aarschot (B). Notes of the existence of a water mill at the site were retraced and date back from the beginning of the 16th Century. During the centuries, the mill underwent many changes. Moreover, in 1970 it suffered from a fire and in 1986 a part of the western facade collapsed. In 1997 it was decided to set up a global restoration plan. In 1998 and 1999 the building pathology and stability were studied and an extensive monitoring program was executed to evaluate possible differential settlements of the foundations under scientific supervision of the KULeuven and in collaboration with the Ministry of the Flemish Government and Studiegroep Omgeving, an engineering office with a department specialized in topography. The central buildings that cross the river Demer, are supported by wooden piles, as constructed in 1582. Based on this measurement campaign, the global movements of the load-bearing structure could be understood. The dependency of temperature and water level of the river Demer as well as the mutual dependency between the different load-bearing elements was quantified (Van Balen et al. 1999).

During a period of 6 months the differential settlements of the central buildings were monitored. Table 1 gives an overview of the measured quantities, measurement period, frequency and institute that took care of the measurements.

Table 1 : Overview of the executed measuring campaign

Measurement quantity	measurement period	measurement frequency	Institute
Temperature	23/07/1998-04/02/1999	0.5Hz	a,b
Water level of the river Demer	permanent	twice a day	c
HLS-measurement – 6 vessels	23/07/1998-04/02/1999	0.5Hz	a,b
Geodetic Survey	29/04/1998-25/01/1999	twice a month	d

Legend: a: Studiegroep Omgeving cvba; b: KULeuven, Department of Civil Engineering; c: DIHO Ministry of the Flemish Community, department of Hydrological Research; d: MVG-ATO Ministry of the Flemish Community, department of overall technical support

The six measuring devices (HLS-1 to HLS-6) were placed on the main floor, and attached on the transversal load-bearing walls of the central building, Fig. 2. The temperature is measured at each of the six HLS measurement devices, at the same frequency as the data acquisition of the water level in the devices. Fig. 3 presents the water level of the 6 HLS-measurement devices and the water level of the river Demer. The values shown in Fig. 3 represent daily mean values.

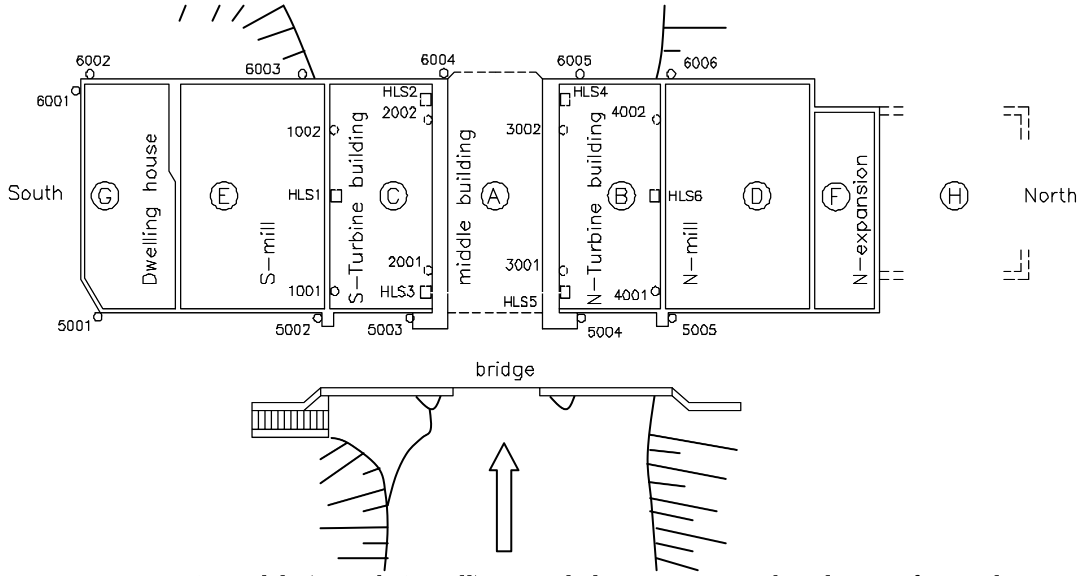

Figure 2 : Hertogen's models (E: Duke's Mill), ground plan, HLS-network and points for geodetic survey.

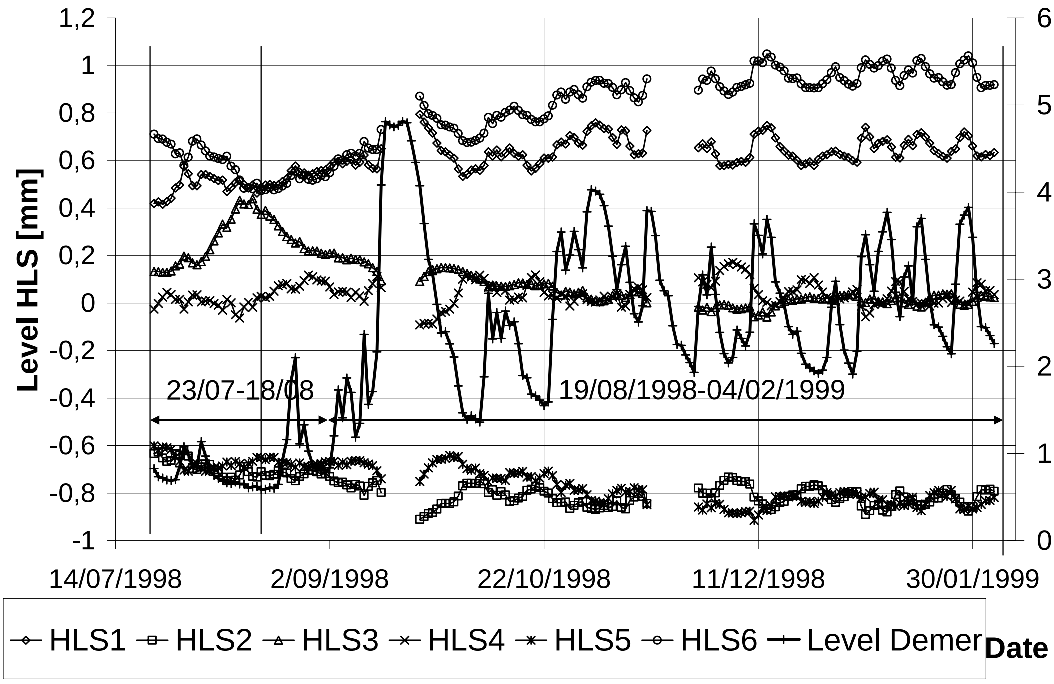

Figure 3 : Water level of the 6 HLS-measuring devices and the river Demer

For the HLS-measurements, a distinction was made between the measurements for the period 23/07/1998-18/08/1998 and the period 19/08/1998-04/02/1999. During the first period the end of the tube which interconnects the different HLS devices, was not closed airtight. The water in the tube evaporated slowly. Although this did not influence the mean value, the spread was higher, demonstrating a lower accuracy, Fig. 4. These data should not be considered lost. On the contrary, mutual comparison of both periods illustrated the high accuracy of the second period. Fig. 4 illustrate for example the centrum characteristics and the spread of the data of HLS 1 (Q(25) and Q(75) are the 25% and 75% quantiles). The values presented are daily mean values based on 144 values. Each 10 minutes, the mean value of the data captured every 0.5 s is stored, resulting in 144 data a day. In the second period, no measurements are available from 14/09/1998 till 21/09/1998. As can be seen from the water level during that period, this was because of a flood of the river Demer after a period of excessive rain. The measuring instruments fell out as the current was interrupted. No measurements are available from 16/11/1998 till 25/11/1998, due to human error.

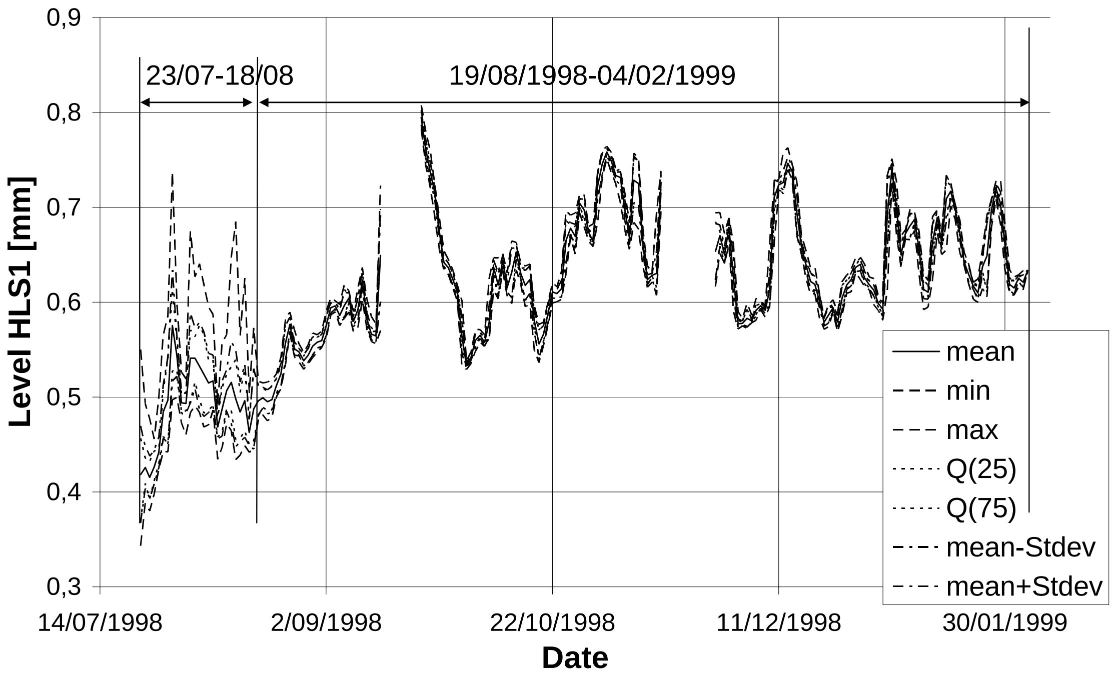

Figure 4 : Descriptive statistics of HLS-1

The correlation between the water level in the HLS-measuring devices and the waterlevel of the river Demer was studied. Based on the linear regression analysis, one may conclude that one meter of difference in water level of the river Demer results in a absolute difference of height from 48 (HLS-2) till 140µm (HLS-6). The correlation values differ from 0.51 and 0.92, Fig. 5. The water level dependency is significantly larger than the temperature dependency (Schueremans et al. 1999). As the water level of the river Demer varied between 0.6 and 4.1 m during the period of the measuring campaign, absolute settlements between 0.17 till 0.52 mm can be expected. Important also is the sign of the regression coefficients. HLS-1 and HLS-6, located at both sides of the bank of river Demer, have a strong positive correlation with water level of the river Demer. When the water level increases, their level increases too.

On the contrary, HLS-2 till HLS-4, placed on the transverse walls which are founded in the river Demer, have a negative correlation with the water level of the river Demer. Due to the additional load on the river bed in case of increasing water level, there is a downwards settlement of the piles that bear the aforementioned transversal walls. This differential movement could be related to the crack patterns on the eastern an western facades as noted in the building pathology (Van Balen et al. 1999).

The geodetic survey of levels contained two measuring cycles. An internal cycle (points: 10xx-20xx, fig 2) and an external cycle (points: 50xx-60xx, Fig.2). The main difficulties that were experienced during the measurements were the influence of the water on the execution of the measurements and the influence of the internal and external climate (dark-light, difference in temperature), connecting the internal and external cycle at the points 2002 and 6004.

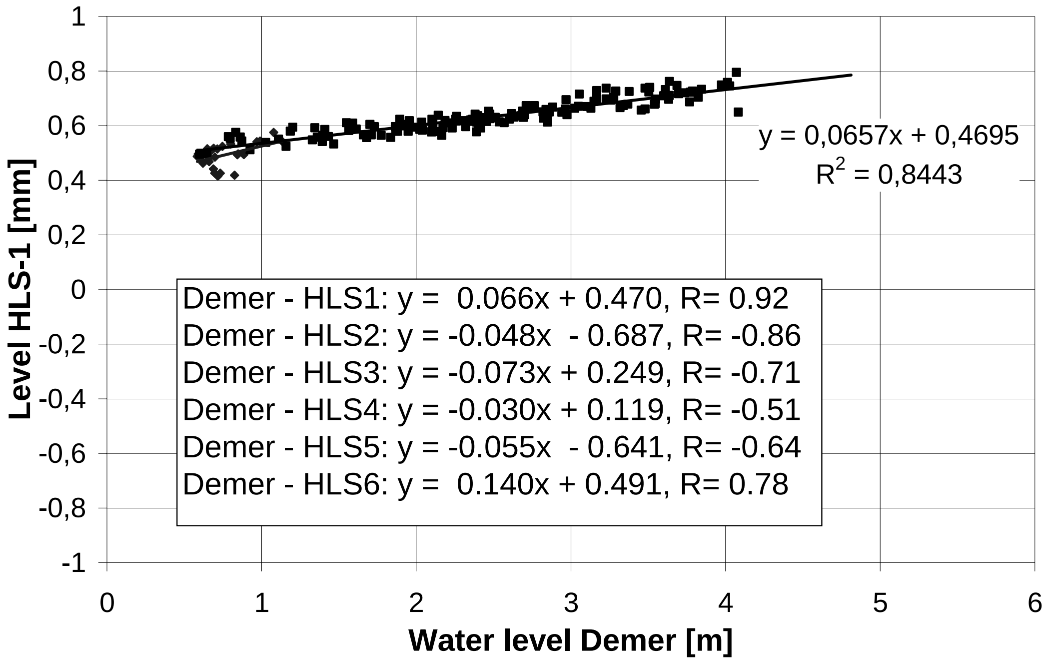

Figure 5 : Water level Demer versus level of HLS-measuring device

Based on the results, the absolute error was estimated to be 0.2 mm in case of the internal cycle and 0.5 mm in case of the external cycle. The geodetic survey was coupled at the HLS-measurements at 19/08/1998. As an example the measurements of HLS-2 and the geodetic points 2002-6004 are plot in Fig. 6. The values of the HLS-2 measurement device remain within the preset range of 0.5 mm of the external point 6004. This is not the case for the internal point 2002, indicating a lack of reliability. This is mainly because of the very small absolute values of the settlements as could be measured with the HLS-system. Due to the environmental circumstances the classic geodetic survey is not accurate enough to capture these settlements.

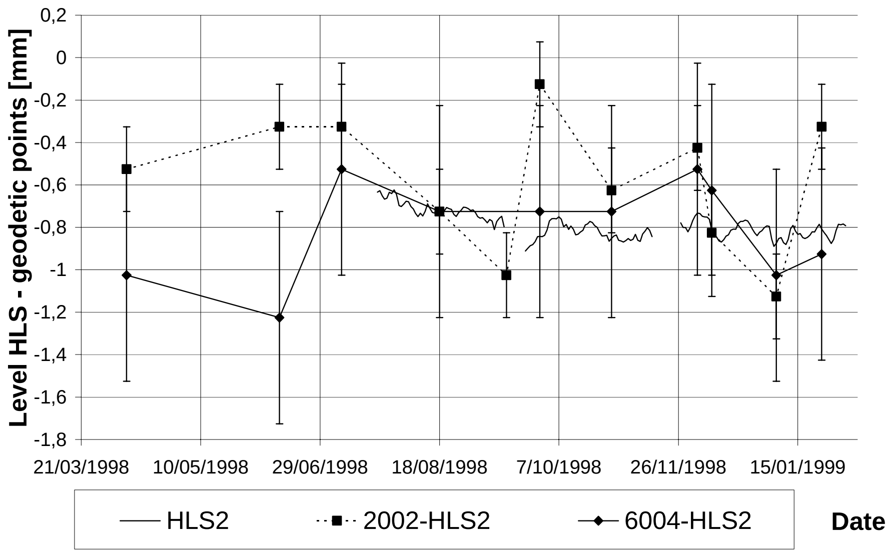

Figure 6 : Example of the geodetic survey at points 2002 and 6004 - comparison with HLS-2.

2.2 *Saint-James Church Leuven (Belgium)*

The second case study focuses on the church of Saint Jacob (St. James) at Leuven (B). The construction of the western tower dates back from 1220. During several subsequent building phases, the Romanesque church has been replaced by a gothic church, the wooden roofs in the central and side naves have been replaced by masonry vaults. The structure itself is located on a former swamp. The load bearing capacity of the subsoil is limited, causing large differential settlements. At several occasions in the past, restoration works took place. Due to the excessive cracks observed however, it was decided in 1963 to close the church envisaging its structural collapse, to remove the vaults of the side naves and to shore up the pillars of the main nave.

Eight vessels were installed in the church: four in the tower and four in the nave. The measurements range over a 5 month period (139 days), from the 8[th] of July, 1994 to the 13[th] of November 1995. In the rectangular cross section of the tower, the vessels were placed in each of the four corners. In the nave, the vessels were placed at the bottom of four columns, Fig. 7. Parallel, on each column and, more generally, on each structural node, a levelling reference mark in stainless steel and ending with a sphere, was fixed. In total, 63 marks were placed, Fig. 7. The measurements were done with a Wild/Leice N3 bubble level. This high precision device, equipped with a parallel plate micrometer, allows, if used with an invar rod, a reading to the nearest 1/100mm. Considering the path measured, a standard deviation of 0.10 mm is estimated to be realistic. In addition, 27 vertical profiles indicating the slant of the major structural components were measured, Fig. 7. These result in a graphical representation of the absolute magnitude of resulting slant of different elements, originating from the differential settlements.

Table 2 : Saint-James Church - overview of the executed measuring campaign

Measurement quantity	measurement period	measurement frequency	Institute
Temperature	08/07/1994-13/11/1994	1/15min	a,b
HLS-measurement-8 vessels	08/07/1994-13/11/1994	1/15min	a,b
Geodetic Survey -63 points	18/04/1994-27/09/2005	at 7 discrete moments in time	a,b
Leaning of tower and walls	27/09/2005	27 vertical profiles	a,b

Legend: a: Studiegroep Omgeving cvba; b: KULeuven, Department of Civil Engineering;

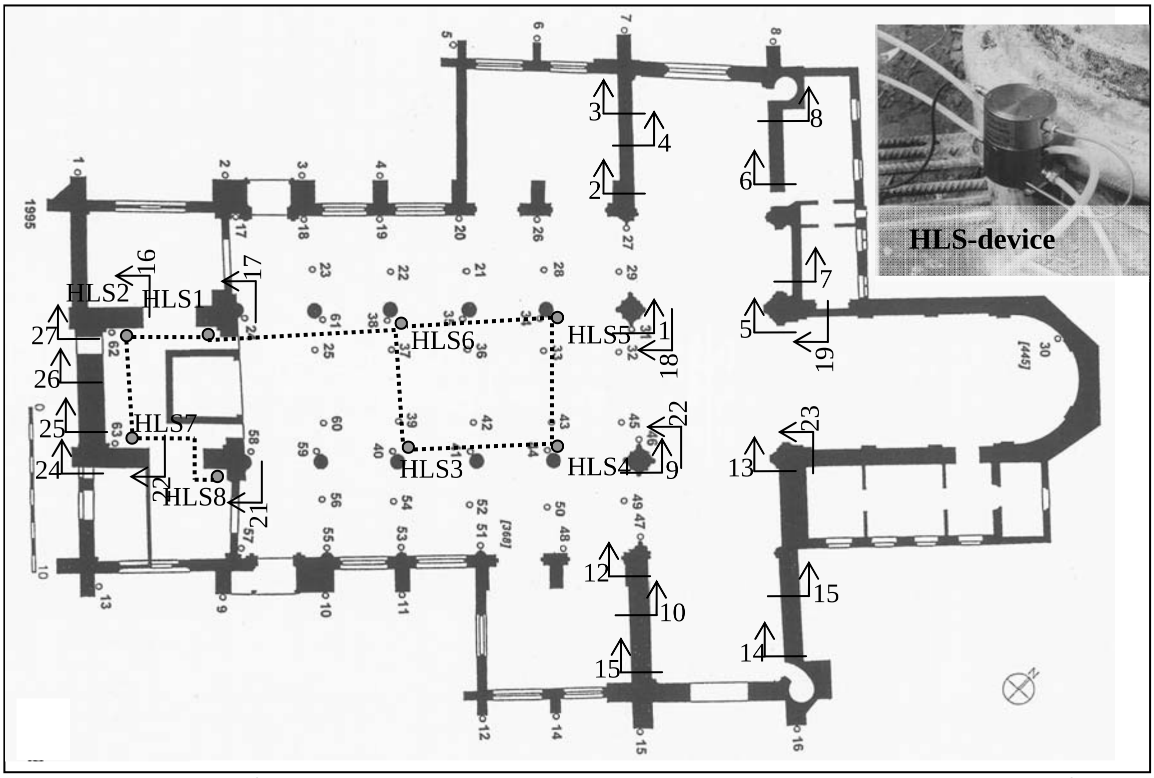

Figure 7 : Position of topographic levelling points, Hydrostatic levelling System and vertical profiles

Fig. 8 shows the evolution of the displacement (μm) as well as the temperature as a function of time. In general, the tendency of the different vessels is relatively linear or slightly curved (vessels 4, 6, 7 and 8). The curving is mainly caused by the seasonal influence. During the 5-

month period, the overall displacements were of the order of 0.10mm, from 30 µm (vessel 1) to 120 µm. The transient variations around the general trend are of the order of 10µm. If the trend where constant (200µm/5 months), this would result in a 4 mm settlement in 10 years. In practice, the settlements are expected to be smaller, because of the seasonal variation.

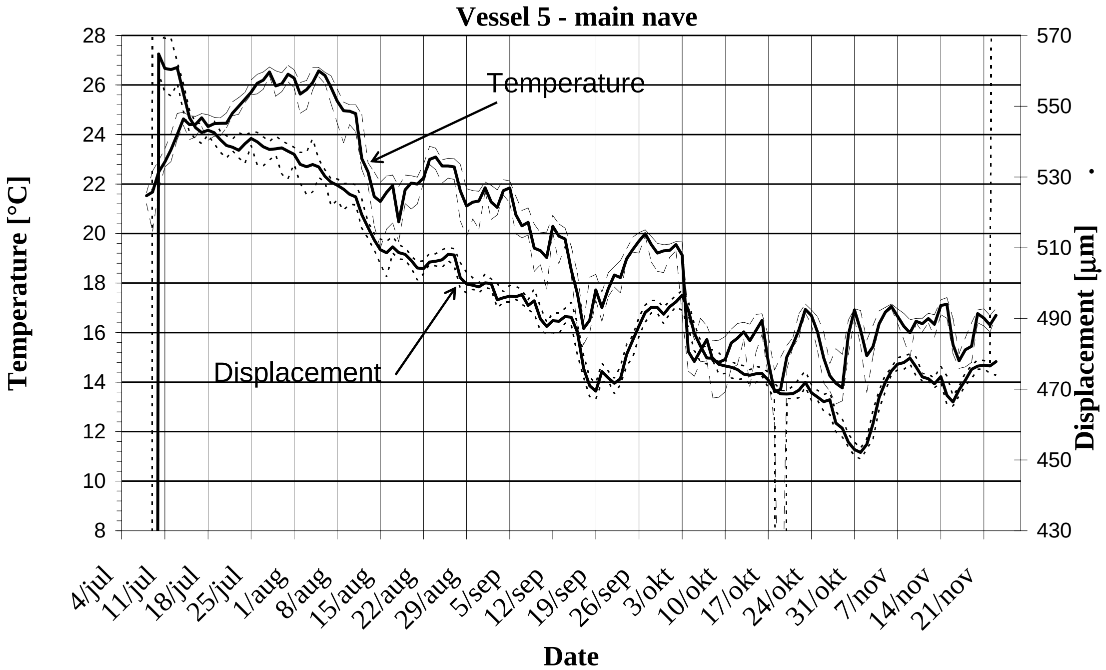

Figure 8 : Temperature and displacement as function of time – vessel 5 – main nave

From these three different sources, the slant of the tower and its evolution as a function of time can be retraced. Furthermore, since different techniques are used, the accuracy of the different techniques could be compared. The main conclusions are:

- Based on the HLS-devices (short term data-sequence of 5 months):
  - The tower is leaning to the west with a speed of 3.5 mm/m/century. This is in contradiction with the actual slant of the tower, that is significantly leaning to the east;
  - The tower is leaning to the north with a speed 0.36 mm/m/century. The latter is a factor 10 smaller than the leaning in the longitudinal direction;
- Based on the geodetic leveling points (results over a period of 11 years):
  - The tower is leaning to the east with an average velocity of 1.7 mm/m/year;
  - The tower is leaning to the north with an average velocity of 1.6 mm/m/year;
- Based on the vertical profiles of the tower from the topographic survey, an estimate of the evolution of the slant as a function of time is made related to its service life of 780 years, during which the deformation rate is assumed constant:
  - The tower is leaning to the east with a speed of 4.9mm/m/century;
  - The tower is leaning to the north with a speed of 2.7mm/m/century.

From these data it is clear that the leaning is still continuing, despite of the present shoring (Schueremans et al. 2006a,b). The actual speed is lower than the global average, which is not surprising since the clay-containing subsoil has been able to consolidate nearly for 100% over a period of 8 centuries. Attention needs to be paid to the short period over which the HLS-data are available, which biases the conclusions related to the leaning of the tower.

3 CONCLUSIONS

Hydrostatic levelling is a powerful technique. Its high precision and the automatic recording of the measurements allow the almost continuous monitoring of the various phenomena affecting a building. Its cost however will restrict its use to very delicate situations, for important monuments or for scientific reasons such as the understanding of the structural behaviour of historical structures.

The extensive study on the Dukes' Mill at Aarschot (B) made it possible to conclude that the central buildings are stable and that the major differential settlements are caused by temperature changes and the water level of the river Demer. Based on the water level range as noted during the measurement campaign of approximately 6 months, the maximum absolute values of the settlements at the measurement locations are 0.57 and 0.52 mm respectively. These are low values and are beyond the accuracy that could be reached using a classic geodetic survey, pointing out the added value of this highly accurate system.

In the case study on Saint-James Church the hydrostatic leveling system could be compared with more conventional geodetic systems. The latter are less expensive and could be repeated over a long term period and far more measuring locations. Due to the period of overlap, the accuracy of these measurements could be compared to the highly accurate hydrostatic leveling devices. Vice versa, the long term results could be used to warn for conclusions based upon short term measurements.

ACKNOWLEDGEMENTS

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