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Hydrostatic levelling systems: Measuring at the system limits

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Abstract. Three hydrostatic displacement monitoring system applications in Switzerland are discussed; the first concerns experience gained monitoring the foundation of the Albigna dam, the second relating to the underground stability of the Swiss Light Source synchrotron and the third concerning the deformation of a bridge near the city of Lucerne. Two different principles were applied, the Hydrostatic Levelling System (HLS) using the "half-filled pipe principle" developed by the Paul Scherrer Institute and the Large Area Settlement System (LAS) using the "differential pressure principle". With both systems ground deformations induced by tidal forces can be seen. However, high accuracy of single sensors is not sufficient. A well-designed configuration of the complete system is equally important. On the other hand there are also limits imposed by installation logistics and by the environmental conditions. An example is the bridge monitoring application, where the acceleration along the bridge due to the passage of heavy trucks limits the feasibility of using hydrostatic levelling measurements.

Keywords. High-precision ground deformation, long-term stability, hydrostatic leveling system, vertical displacement, synchrotron, power dam, bridge control, Earth tide.

1. Introduction

Since ancient times the surface of fluids has been used as a reference tool to determine precise level differences. Nowadays, the hydrostatic measuring principle is more often applied, when visual observation is not possible or disturbances such as air turbulence prevent optical measurements. The advantages of hydrostatic measuring systems are their high accuracy and resolution. With regard to this aspect, these systems are far superior to modern geodetic instruments such as tachymeters and digital leveling devices. Due to their simple and robust configuration, hydrostatic measuring systems are well-suited for permanent all-season monitoring, combined with remote control systems and automated data acquisition. All hydrostatic measuring systems work on the fundamental principle that a water surface which is under the influence of a gravitational field and free to move, orientates towards a certain level surface. Measuring pots, which are connected to each other, obey the law of the communicating vessels and therefore the water surface represents a stable, reliable and very accurate reference for levelling purposes. The fundamental design and computational aspects of hydrostatic measuring systems have been described in [3]. The various hydrostatic measuring systems can be divided into three groups according to their operational mode:

- Half-filled pipe (open surface)
- Hydrostatic level
- Pressure measuring system

With half-filled pipes as well as with hydrostatic levels the changing fluid-levels are measured. Depending on the precision specification of hydrostatic levels, different methods of fluid-level sensing are applied. The pressure measuring system differs basically from the first two designs, as no (or very little) fluid flow occurs. Inductive, capacitive or piezoresistive sensors are used for pressure measurements in either differential or absolute pressure transducers, respectively, depending on the task. At present the highest accuracies are obtained by capacitive pressure transducers.

The advantage of hydrostatic levelling systems is their high resolution for static and dynamic deformation applications. Therefore, hydrostatic systems are used in large research facilities such as linear and ring accelerators, as well as for monitoring settlements and tilts, movements of buildings and dams, landslides and rock avalanches. All applications have two essential aims:

- To monitor deformations
- To serve as an early-warning system in case of unexpected movements of the monitored objects.

Hydrostatic levelling systems are not only used for permanent monitoring. They also allow detection of the behaviour of buildings during specific events, such as release from snow loads, bending due to wind exposure or vibrations caused by trucks passing over a bridge. In complex buildings, in which hydrostatic levelling systems with consistent water level are not continuously applicable, the system can be disrupted and vertically displaced. Thus this requires high precision in data logging, because measuring errors accumulate with several lateral offsets.

2. The two applied systems

For the hydropower dam monitoring and for the bridge monitoring the LAS-meter, a differential pressure system, was applied. The LAS-meter was developed at ETH Zurich in co-operation with the company Edi Meier + Partner AG, Winterthur, Switzerland. The Multipoint LAS-meter described here uses the pressure difference between two liquid columns (Figure 1).

In the middle of the tubes a diaphragm is inserted which deforms according to the equalization of the liquid. As a result of pressure differences between the liquid columns, the diaphragm is deflected. The movement of this diaphragm is transformed to an electrical signal, which is a measure for the level difference between the 'chambers' at the end of the tube.

Figure 2a shows the central unit of an LAS-meter with two measuring vessels, the basic configuration for the measuring system, and Figure 2b the configuration for multipoint operation.

The central unit is equipped with the integrated magnetic switching system which sequentially connects the individual chambers to the membrane unit. The control unit collects and processes the data and controls the central unit. Operations such as zero-point calibration and correction of the sensor drift are also carried out by this unit. Zero point and span can be controlled at any time by remote opera-

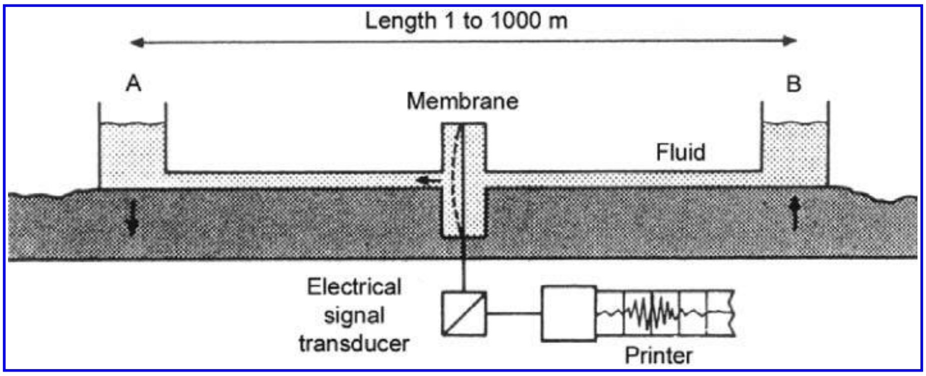

Figure 1: Measuring principle of the LAS-meter. As a result of the pressure differences between two fluid columns, the diaphragm becomes arched. The deformation of the diaphragm is transformed into an electric signal proportional to the elevation difference.

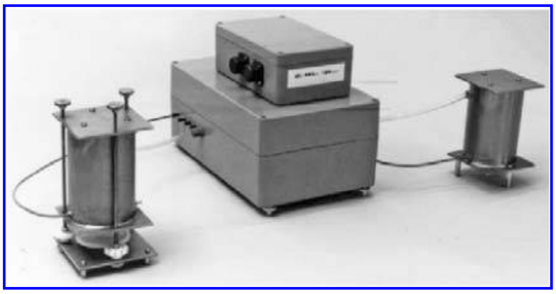

Figure 2a: The basic configuration of the LAS-system shows two fluid vessels, left and right; the left one is equipped with a levelling mechanism. In the middle there is a magnetic switching system, which, by reversal of the connections to the fluid vessels, periodically determines the sensor drift and automatically applies the necessary adjustments.

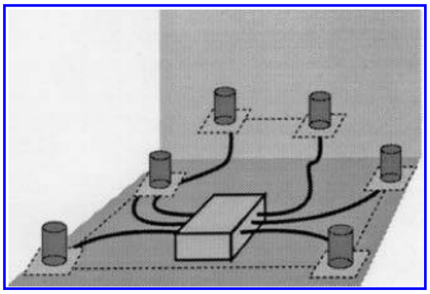

Figure 2b: Example of a multipoint configuration of the LAS-system, where the central unit sequentially determines the elevation differences between two chambers. The instrument is laid out for measuring differences relating to 22 chambers.

tion. After installation, no further modifications to the instrument are necessary, because all operations can be carried out directly by the control unit.

In the second example, monitoring the underground stability of the SLS Synchrotron, a hydrostatic levelling system HLS using the single tube layout with a half filled pipe was applied. In contrast to the differential principle, described above, the water surface always aligns at the same level. In connected measuring vessels the principle of the "communicating tubes" applies. Figure 3 shows the difference between the double tube and the single tube layout:

- Double tube layout, shown in the center of Figure 3: Conventional communicating water-level with one tube filled with water and with an additional air vent line, which compensates for the effects of the ambient air pressure.
- Single tube layout, shown on the left and on the right side in Figure 3, in which a continuous liquid surface is formed. For high precision monitoring, only single tube layouts should be used, because in this layout temperature induced errors are minimized.

The fill level is determined capacitively, where the fluid surface and the electrode act each as a capacitor plate (Figure 4a). Thus, there are no mechanical parts which can wear out, such as a pressure membrane. In order to avoid condensation water at the electrode, the levelsensor (LS) has an integrated heating device. In the event of the fluid touching the electrode, a specially designed ring ensures a quick and complete run off [1]. As a special feature each LS is equipped with a touch point. The touch point is located near the electrode. This allows a calibration of the zero-level at any time during the HLS operation within the demanded accuracy. The calibration is done by raising the fluid level slowly until the touch point is reached. After a couple of months it is necessary to compensate the fluid level for natural evaporation. At the SLS, the HLS can be refilled (or emptied) entirely by remote control over the internet. Thus, no interruption of the SLS operation is needed in order to control or recalibrate the HLS.

3. Applications at the System Limits

3.1. *Albigna power dam monitoring using LAS system*

The first LAS-meter was installed at the Albigna dam at Bergell valley (Figure 5a), near Vicosprano, Switzerland. The dam was completed in 1931 and was heightened between 1956 and 1959. The dam stands on a prominent rock barrier; the granite rock

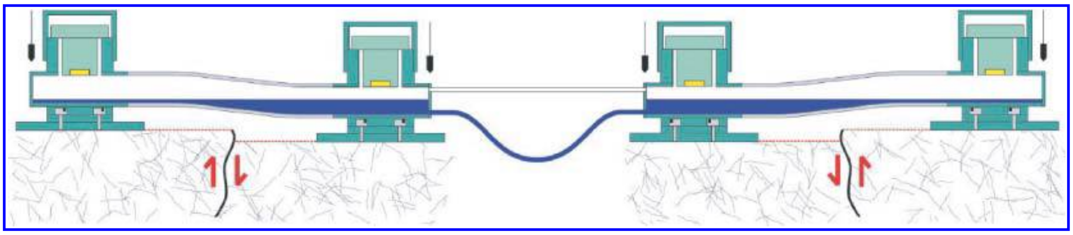

Figure 3: Single tube and double tube layout of a hydrostatic levelling system.

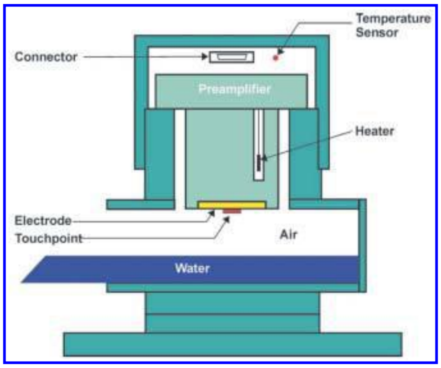

Figure 4a: Section of the HLS Levelsensor.

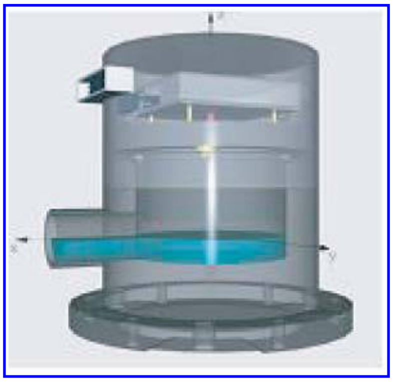

Figure 4b: Inside view of the HLS level sensor.

foundation tends to deform considerably during reservoir filling. The LAS-meter could therefore be tested over a large range. The dam is a 115 m-high and 760 m-long gravity structure, partitioned into 20 m-wide blocks. 5 m wide hollow cavities are arranged at the block joints, which reach down to the rock surface. This enabled the foundation tilt to be measured directly without the need for a special instrumentation gallery. For the measurement, the base of the base of the joint cavity in the middle of the valley was chosen. The tallest block is 115 m high. The LAS-meter was placed on three consoles, mounted on the block (Figure 5b).

Results

Figure 6a shows the auto-calibration setup of the Albigna instrument. The normal measurement cycle shown in Figure 6b indicates a change in height of about 1 mm over the whole measuring period in 1997, which agrees well with the expected dependence on the lake level. An auto-calibration cycle is carried out periodically to correct the sensor drift. The inverse measurement is symmetric in relation to the zero line and gives an indication of the inherent accuracy of the system [2].

Measurements of the tilt changes at the dam base in the period 1 November 1989 to 10 January 1990

Figure 5a: The Albigna dam, which has considerable alluvial deposits in its immediate reservoir area, deforming the dam foundation on impoundment.

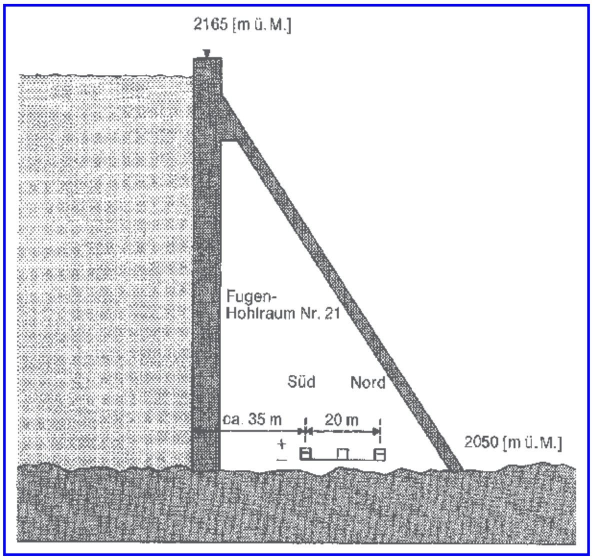

Figure 5b: Cross section through the Albigna dam. The LAS-meter is installed in a hollow chamber about 80 m high, 5 m wide and 60 m long.

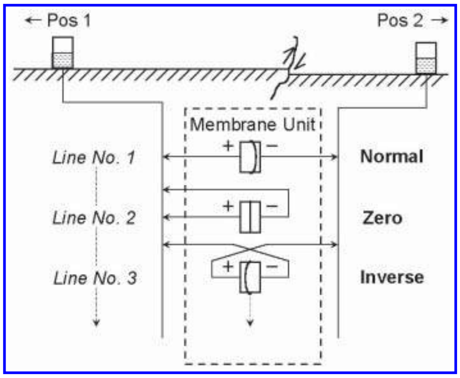

Figure 6a: The principle of the auto-calibration procedure performed periodically for elimination of the membrane drift. There are three calibration cycles which carry out normal, zero and inverse measurements.

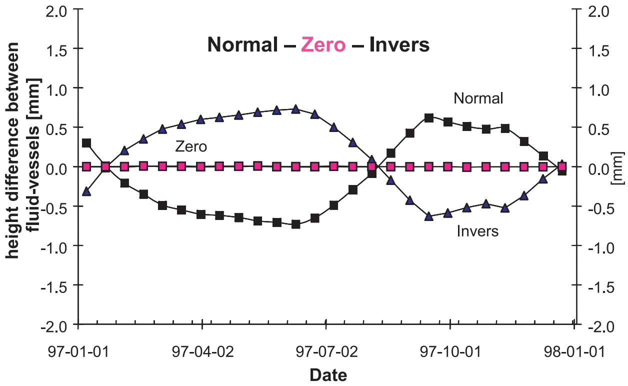

Figure 6b: The results of the system calibration during 1997. Note the inverse measurement is symmetrical in relation to the zero line.

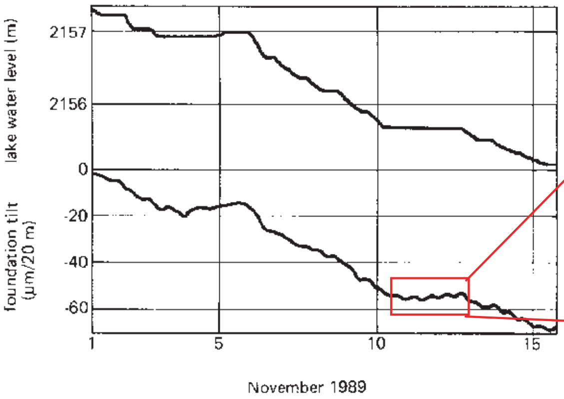

Figure 7a: Water level of the Albigna-reservoir between November 1 and 16, 1989. The upper line represents the water level (in metres above sea level). The comparison with the tilt of the dam foundation during the same period (lower line) shows the influence of the water level fluctuation on the tilt changes of the dam foundation.

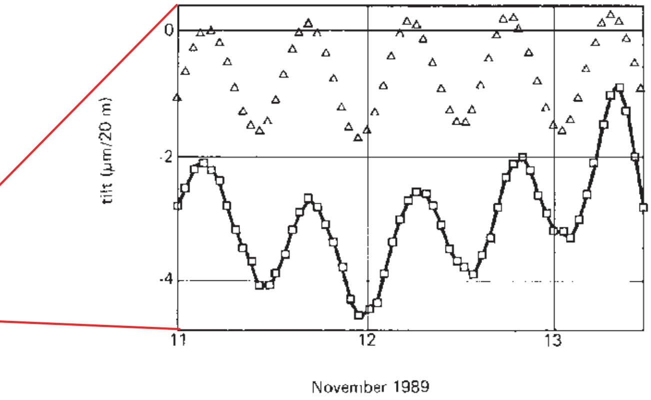

Figure 7b: Tilt measurements at the Albigna dam. There was almost no fluctuation of the reservoir water level. The lower curve shows the residual tilt changes. The upper curve shows the calculated tilt changes of the Earth tides due to gravitational forces between moon, sun and earth [1].

showed that the upstream heel of the damwall was sinking in relation to the downstream toe, almost continuously. The relationship between the reservoir level and the tilt at the dam foundation was examined (see Figure 7a) over this 16 day period, and a clear dependence can be observed. To quantify this, the level of the lake was plotted against the measured tilt for a 2 m lowering of the lake and an almost linear relationship was substantiated. If, the tilt caused by the reservoir level is subtracted from the measured tilt, the difference (residual tilt) is obtained. This was seen to vary within less than a micro-radian, despite the meteorological conditions varying greatly.

The curve of residual tilt showed a regular up and down fluctuation with a period of half a day. This led to the conclusion, that the "earth tide" influence was involved. The shape of the earth is influenced by the gravitational forces between the earth, moon and sun; the deformation is determined by the size of the forces, local rigidity and the ocean load effect. This deformation occurs at any point of the earth's surface in cycles with a 12 h period and can be calculated from models. The effect is called "earth tides". Reservoir tidal effects are much smaller in comparison to ground movements. According to information from the Swiss Meteorological Office, the air pressure during the period fluctuated by 27.7 and 27.5 millibars at the two local weather stations; temperatures fluctuated between −17 and +14 deg Celsius at the stations. As no electricity was generated during the weekend of 11 November, the reservoir level was approximately constant. Also calm weather conditions existed. The base of the dam should thus have been expected to be stable. The lower curve of Figure 7b shows the tilt change during that weekend (with a large vertical scale). The twice daily cycles are therefore clearly visible. If this is compared with theoretically calculated earth tide cycles, calculated from models at the Black Forest Observatory (top curve, Figure 7b) there can be no doubt that the cause is indeed the moon and the sun.

The provision for mechanical switching of the individual measuring points makes it possible to determine and eliminate the systematic effects of a hydrostatic measuring system. On the other hand, the loss of liquid in the vessels and tubes as a result of evaporation cannot be neglected when the system is running unattended for a long period of time.

3.2. The HLS at the Swiss Light Source synchrotron (SLS)

For monitoring the underground of the new built storage ring of the Swiss Light Source (SLS) at the Paul Scherrer Institute (PSI), Switzerland (Figure 8a), the highest resolution and long-term stability over more than 10 years was required. As liquid loss over such long periods cannot be eliminated, the use of a differential pressure system was not suitable. Thus, the principle of half-filled pipes was used instead, where a slow liquid loss is irrelevant. The HLS installed at the SLS was designed to meet the following specifications: measuring range 14 mm, resolution 0.0005 mm, accuracy better than 0.01 mm. The storage ring of the synchrotron (Figure 8b) is subdivided into 12 sectors, each containing four girders (Figure 9a) on which the focusing electromagnets are mounted. Every girder is monitored by four installed level sensors (LS) (Figure 9b). This leads to a total number of 192 LS, which are linked together by half-full steel pipes with a total length of 450 m.

The influence of the Earth tides is clearly visible on quiet days. Figure 10a shows the average values of the sectors in the four main cardinal points during a lunar eclipse [5]. To illustrate the symmetry the signals were adjusted with an offset value so that opposed signals can be compared. The single signals of the first sensor on each girder are not as quiet as the average value of the sector (Figure 10b).

Apparently, there are small local signal differences. Figure 10c shows the absolute values of the north sector and the average value of all 192 signals. In the average value no tides are visible, as the signals of the opposite sensors are cancelled out. Yet a daily cycle can be observed, presumably due to the daily variability in temperature. In addition, a slow liquid loss of about 5 µm during this period is detected. Both, daily cycle and liquid loss do not generate an error in measurement, since only the signals relative to the average value are analysed. The long-term stability of the measurements is indicated in Figure

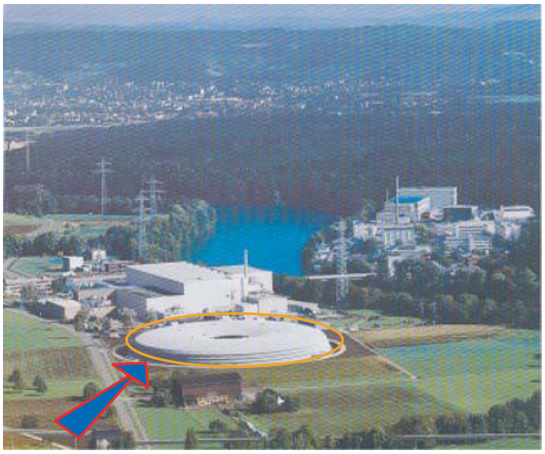

Figure 8a: Synchrotron Swiss Light Source SLS at the Paul Scherrer Institute, Switzerland, near the German border an near the river Aare.

Figure 8b: Storage ring of the SLS during construction.

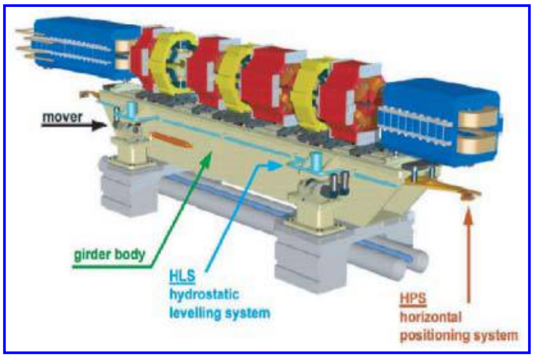

Figure 9a: Girder body carrying the electromagnets. The movers are intentioned to move the whole girder in order to re-adjust the electromagnets. The girder movement is monitored by the HLS.

Figure 9b: Level sensor (LS) mounted on the girder. Below it an eccentric cam disc is visible.

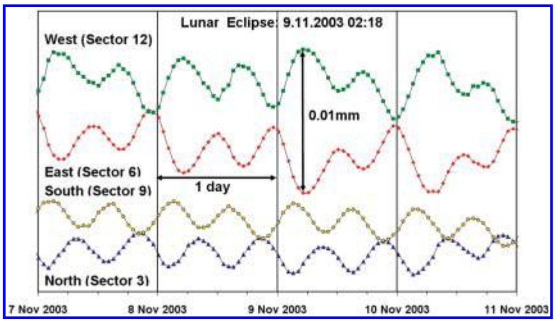

Figure 10a: A four day period of the year 2003 with a time resolution of 1 hour. The influence of the Earth tides with 2 periods a day is clearly visible. Note the high amplitude difference between East and West during the eclipse of the moon.

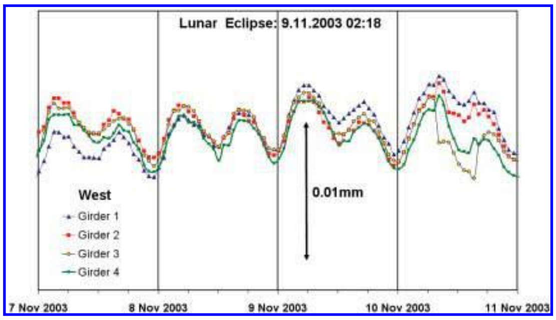

Figure 10b: Variation of single signals in sector west. Signals of the first HLS sensor on each girder are plotted.

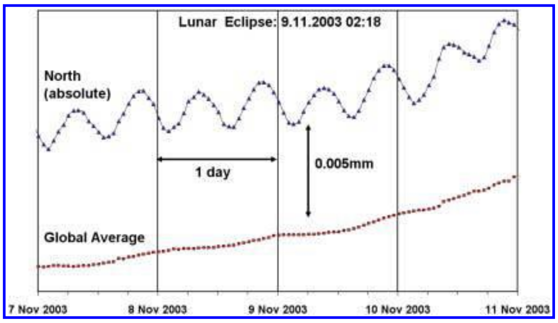

Figure 10c: Average of the absolute values of sector north und and the average value of all 192 signals, which is subtracted to balance the liquid loss.

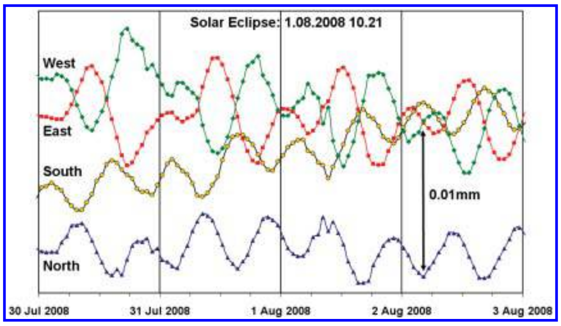

Figure 10d: Same sensors as in Figure 10a during a solar eclipse 5 years later. The signals are slightly more unstable, but they show good long-time stability.

10d. Equal sensors are compared with the same offset after 5 years. The ground is slightly more unstable and the south sector is exhibiting a small trend, though the signals generates very similar values after 5 years. These results reflect the stability of the ground on which the synchrotron was built.

3.3. Dynamic bridge monitoring

A highway bridge over the Reuss River near the city of Lucerne was broadened and strengthened (Figure 11). The static calculations concerning this modification predicted deflections and settlement of up to 27 mm. Fiber-optic strain sensors and hydrostatic measurement systems were installed in order to monitor the predictions over 5 years, with the following objectives:

- Verification of the predictions of the deflections and settlement of the structure
- Monitoring and recording of the structures behaviour during rehabilitation and operating conditions
- Issue alarm in event of excessive deformations

The tasks of the hydrostatic measurement system consisted of monitoring the long-term stability of the structure with millimetre accuracy and documenting dynamic movements with periods down to 1 s. These movements are produced by heavy trucks passing the bridge at about 80 km/h. During the evaluation of the measurement systems a highly accurate HLS system with 20 level sensors was first considered. For economic reasons however, the less expensive LAS system with 10 single channels and without automatic calibration was finally used, even if possible air pockets can lead to erroneous measurements. In order to correct for such errors, a yearly control of zero-point and fluid-level was scheduled. The accuracy of the fluid-level controls is +/−1 mm. The dimensioning of the individual LAS-

Figure 11a: Highway bridge near Lucerne after enlarging during construction phase, top view.

Figure 11b: Enlarged part of the bridge, bottom view.

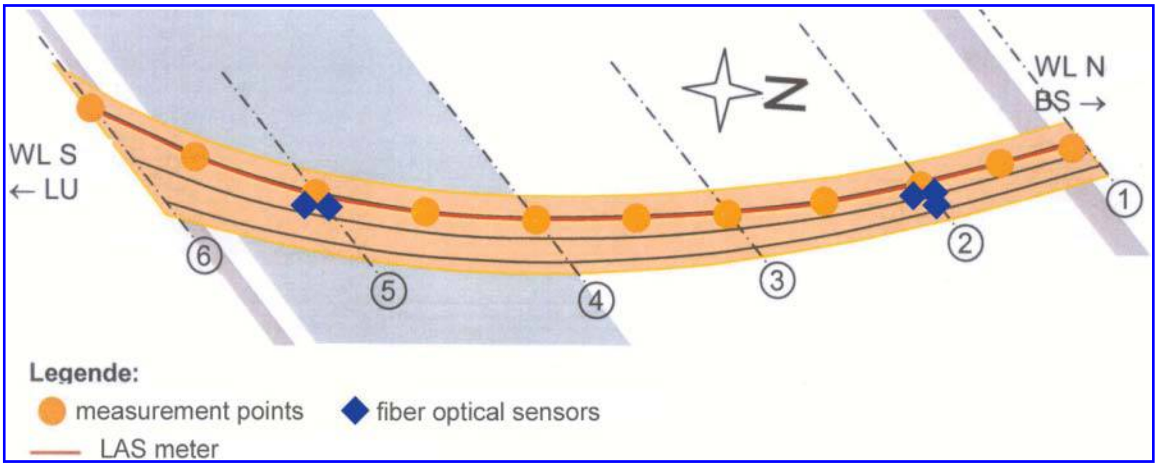

Figure 12: Instrumentation with fiber-optical strain sensors and LAS-meter [4].

Figure 13a: Mounting of a LAS-meter measuring chamber at the inside wall of the bridge, field 2, and connecting it to the pressure tube, made of copper.

Figure 13b: Mounting of a fiber-optical strain sensors on the roof of the girder box. The fiber-optic string covers 5 m on each side of pylon 2.

meter was evaluated in order to achieve a response time of below 1 s.

The 10 separated LAS-meter systems were placed upstream along the western longitudinal girder of the bridge, at the inner wall of the box girder. For each field of the bridge, separated by two pylons, two independent LAS systems were installed. For each of the two systems, one fluid vessel was mounted in the centre between two pylons, and the second vessel was installed near the pivot (pylon). This yields two opposite signals from the two systems.

Results

Heights are computed by summing the signals from all LAS systems (Figure 14).The predicted values in Table 1 are only comparable to a limited extent to the deformation values shown in Figure 14, due to the complex load history.

An in situ functional test was made in order to check if the measurement facility meets the required specifications. For this purpose, the fluid level was raised by 5 mm. The resulting signal (Figure 15) shows the expected transient oscillation curve with a response time of 0.9 s, indicating that the specifications were achieved. The amplitude of an oscillation with duration of 0.9 s is only reproduced to 63%, while faster movements are attenuated even more.

For the long-term observations, mean values over 10 minutes were computed. According to the task definition, the monitoring system should also enable detection of fast deformations produced by heavy trucks. Based on the experience gained from the dam observations, no problems were expected with the LAS system.

Figure 16a shows the results of LAS-meter No. 3, which should represent the height variations between pivot 2 (pylon 2) and the field 2 of the bridge. However, the conversion from the observed pressure differences to height differences yields values that are clearly too high.

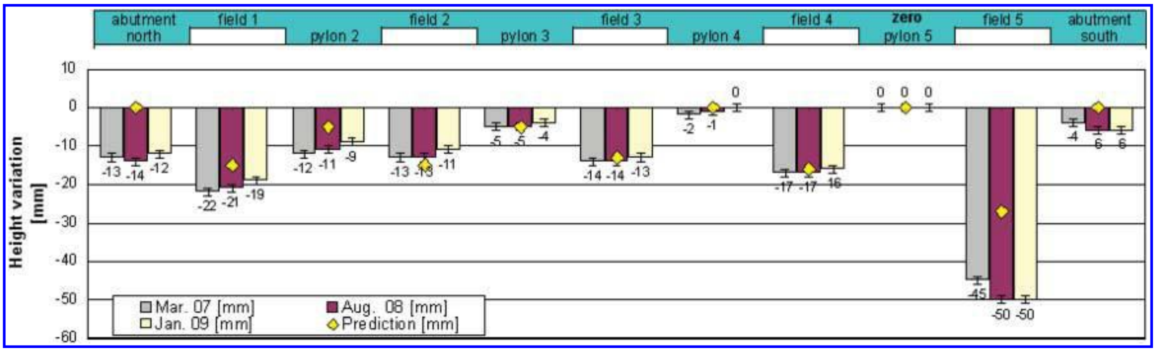

Figure 14: Predicted and measured long-term deformations since the start of construction works in 2006. Pylon No. 5 was used as reference.

Table 1: Predicted, reported and alarm values.

Building element	Point	Predicted value [mm]	Reported value [mm]	Alarm value [mm]
Abutment north (Pivot 1)	LAS 1	0	−10	−15
Field 1	LAS 1 / LAS 2	−15	−20	−38
Pylon 2 (Pivot 2)	LAS 2 / LAS 3	−5	−10	−15
Field 2	LAS 3 / LAS 4	−15	−20	−35
Pylon 3 (Pivot 3)	LAS 4 / LAS 5	−5	−10	−15
Field 3	LAS 5 / LAS 6	−13	−18	−34
Pylon 4 (Pivot 4)	LAS 6 / LAS 7	0	−10	−15
Field 4	LAS 7 / LAS 8	−16	−24	−48
Pylon 5 (Pivot 5)	LAS 8 / LAS 9	0	−10	−15
Field 5	LAS 9 / LAS 10	−27	−40	−50
Abutment south (Pivot 6)	LAS 10	0	−10	−15

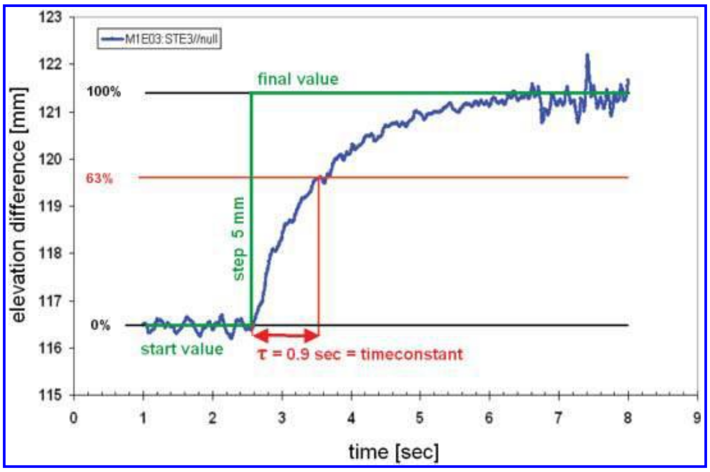

Figure 15: In-situ functional test for determination of the time constant at LAS No. 3 by increasing the fluid-level.

The fiber-optic observations (Figure 16b) do not show comparable oscillations. The fiber-optic string covers 5 m on each side of pivot 2, and hence covers the first 5 m of the range of the LAS-meter to the centre of field 2. Similar movements in the signals from both systems are to be expected.

To investigate this phenomenon acceleration and magnetic field observations were made. The sensors were installed 20 cm below the LAS-meter No. 3. This means that the observed accelerations represent events occurring in the first quarter of the bridge field. The comparison of the observed accelerations and the LAS measurements (Figure 16c) reveals a correlation between the two signals. The passing of vehicles is detected by the magnetic field observations (Figure 16d). Obviously, heavy bridge oscillations are produced by consecutive vehicles passing the bridge, yielding large accelerations. The frequency of these resonance oscillations is 2.5–3 Hz. The high correlation between the accelerations and the inflated dynamic LAS measurement values leads to the following conclusion: In contrast to the dam observations, the individual LAS systems in the bridge configuration are altogether in motion. Hence, the LAS sensors are not only measuring the pressure difference yielded by the fluid level difference and the gravitational acceleration g, but also the acceleration of the complete system. If the system is, for example, subjected to an additional horizontal acceleration $a(t)$, measurement errors of the height difference dH of the order of $dH \sim l(a/g)$ are induced, where l is the horizontal distance between the two fluid vessels. Fortunately, the measurements errors of a LAS system in motion can be eliminated if the interfering frequency is sufficiently distinct from the useful frequency. Since the LAS-meter has a response time of 0.9 s, movements with duration of 0.9 s are only reproduced to 63% (see Figure 15), while faster movements are attenuated even more.

Due to the high resonance frequency of 2.5–3 Hz, these disturbing signals can be eliminated by low-pass filtering, since such fast (high frequency) vertical movements are only partly reproduced by the LAS-meter. The remaining low-pass filtered signal is shown in Figure 14. It is much closer to the values expected for dynamic conditions. Obviously, the signals of the two LAS-meters 3 and 4 are not exactly opposite. This can be explained by differential movements within the bridge field.

Conclusions

High resolution – down to Earth tide level – can be achieved with both the half-filled pipe hydrostatic system (HLS) and the differential pressure measuring hydrostatic system (LAS). However, if a high long-term stability is required the half-filled pipe system must be used, since, due to the differentiation, a slow liquid loss will not cause errors. A liquid loss is even beneficial, since it is observed at all sensors, and hence indicates the correct functioning of the individual sensors. Economic issues are often the reason for using the less expensive differential pressure system. Even if the drift of the LAS-meter sensor is eliminated during the calibration cycle (Figure 2a), liquid loss and blistering can produce hardly detectable measurement errors.

An additional error source occurs in the case of differential pressure systems in motion: If the entire

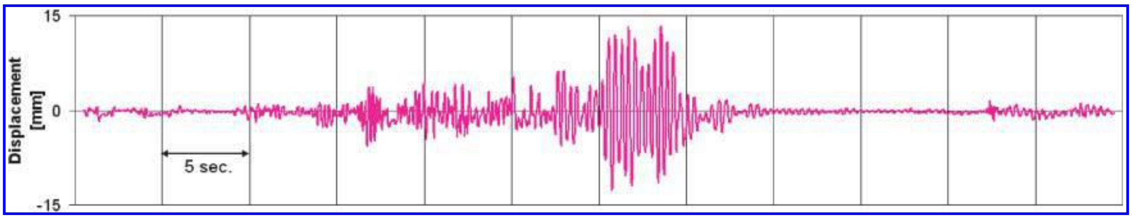

Figure 16a: Raw data of LAS-meter No. 3 from pylon 2 to the middle of field 2.

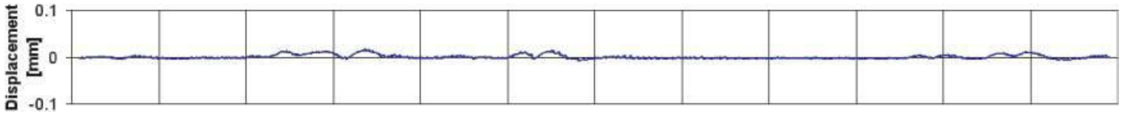

Figure 16b: Fiber-optical measurements +/−5 m on each side of pivot 2.

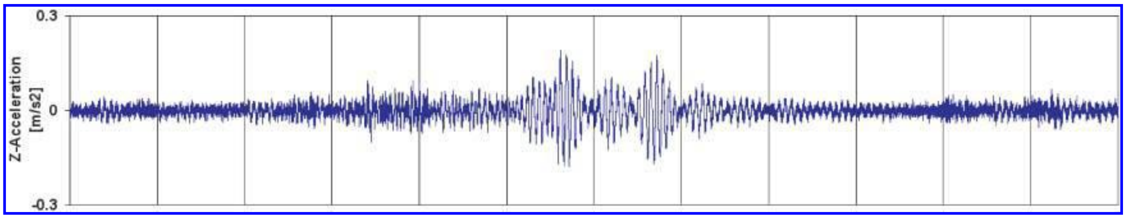

Figure 16c: Acceleration at LAS-meter No. 3 at $\frac{1}{4}$ of field 2.

Figure 16d: Magnetic field observations for detection of vehicles passing the bridge.

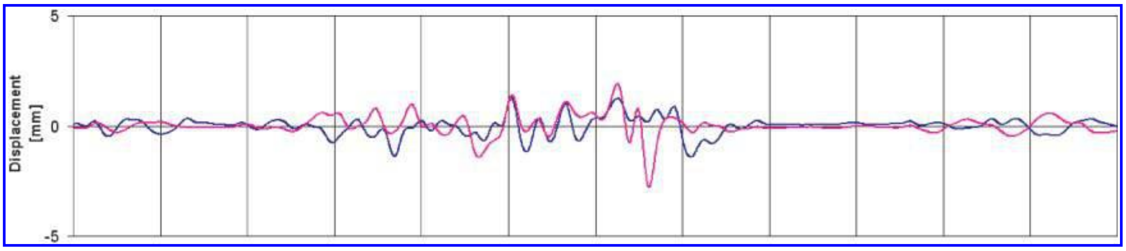

Figure 16e: Remaining signal from LAS-meter No. 3 and 4 after 0.9 s low-pass filtering.

system experiences acceleration along the measurement tube, this acceleration overlays the wanted signal and feigns a height variation of the liquid vessel. If the frequency of the acceleration is clearly higher than the one of the wanted signal, the LAS system can nevertheless be used. Two sets of information can even be obtained from the same instrument if the disturbed LAS signal is both low- and high-pass filtered: low-pass filtering of the raw signal yields the vertical movement, while high-pass filtering gives the longitudinal acceleration.

The measurements described in this paper are a first attempt to assess the errors sources of hydrostatic measurement systems in motion. To be able to draw also quantitative conclusions, additional measurements with multiple comparative systems, such as high-resolution acceleration sensors and Broad-Band Seismometers, are necessary.

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