EXPERIENCE IN THE LONG-TERM MONITORING OF BRIDGES

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ABSTRACT

At the end of the 1980's, a series of existing bridges in Switzerland were equipped with a network of hydrostatic leveling devices, with the aim of following their long-term behavior. Some of the bridges were known to exhibit a steady increase in their deformations, while others were considered in stable condition. The paper describes the measurement system, and the choices that were initially made to ensure that it would be durable. After more than twenty years of operation, the long-term experience related to the operation of this system is presented. The mode of operation of the system is discussed.

The results of the monitoring are shown for several bridges. In the mean time, several bridges have been strengthened by additional post-tensioning, one bridge was even strengthened twice. The effect of the additional prestressing and the subsequent changes on the long-term behavior are shown.

Keywords: Monitoring, Bridges, Water Leveling, Hydrostatic Leveling, Long-term Deflections, Additional Prestressing

1. INTRODUCTION

Bridges are important parts of communication networks and their condition must therefore be closely followed during their lifetime, to identify early possible disorders and to have sufficient time to plan for needed improvement of the structural condition. In many cases, a simple visual inspection provides sufficient and cost-effective information on the evolution of the bridge condition. In Switzerland, visual inspections are regularly complemented with geodetic leveling of the bridge. These measurements require restrictions of the traffic on the bridge, and often night operation, to minimize the impact on the traffic and to limit thermal effects.

In cases where more frequent measurements are required, for instance for structures on critical traffic routes, or structures that have been identified as needing further investigations, hydrostatic leveling of the bridge offers a cost-effective, efficient and sufficiently accurate alternative to conventional leveling techniques. In addition, provided that the bridge has an accessible box-girder cross section, its operation can be made during daytime without any impact on the utilization of the bridge.

The present paper reports on the hydrostatic leveling system used in Switzerland over the past 20 years and on the application of the results for the retrofitting and the evaluation of the effectiveness of the retrofitting for several bridges.

2. HYDROSTATIC LEVELING

A body of water, when not exposed to external forces, remains plane and in equilibrium under the effect of its own weight and the atmospheric pressure. If we further assume that the earth's gravitational field and the atmospheric pressure are constant throughout the body of water, and that its temperature is constant, the water level is indeed a plane reference level. This principle has been known for ages and has been applied for a long time to the accurate measurement of bridges and structures[1,2,3,4,5,6]. In the framework of a research project sponsored by the Swiss Federal Roads Office (FEDRO) at the end of the 1980s, a simple system for the long-time monitoring of vertical bridge deformations was developed and installed in a series of highway bridges[7, 8]. This aims of this system were:

- to measure the bridge deflection with a reasonable accuracy
- to be easily maintained and operated, without requiring electrical connections
- to be installed and operated without interfering with the bridge operation
- to be able to function without interruption over long periods of time
- to have a low cost of installation, operation and maintenance

These goals, some of which are contradictory, were satisfactorily solved by the development of a basic water leveling device illustrated in Fig. 1. This device is fabricated in aluminum with simple shapes[8], which leads to a low cost of the individual parts. The most expensive part is the graduated glass container. All pieces of the device can be easily disassembled, which allows easy on-site repair in case of necessity.

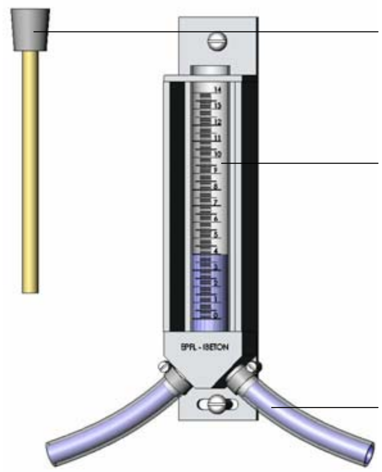


Fig. 1: Hydrostatic leveling device

A series of hydrostatic leveling devices are connected by transparent tubing in a *network*. In the initial phase of the project, several types of fluids were tested to fill the leveling devices, mostly with the aim to avoid freezing in cold weather. Unfortunately, these attempts have not been successful, as evaporation is a significant problem in that case. Indeed, when a mixed fluid (typically a mix of alcohol and water) evaporates, the two components to not necessarily evaporate in the same proportion. As a consequence, the density of the fluid changes. When replacing the evaporated fluid, the newly added fluid has the original density of the fluid, and the hydrostatic level is not in a plane any more. One solution would be to regularly circulate and mix the fluid in the system, but this would be too complicated in the current situation.

Consequently, it was decided to opt for a fluid in which the density remains constant in the presence of evaporation. This fluid currently used in the system is demineralized water. The water lost by evaporation to be simply replaced before proceeding with the measurement. The density of demineralized water changes with temperature, however. This is the reason why a supply of additional water is kept in the bridge, at the same temperature as the water of the networks. This allows simple refilling the network in which evaporation has been too strong before proceeding with the readings.

Of course, using pure, demineralized water means that freezing of the water cannot be avoided in the winter time. Water contained in the transparent plastic tubing can expand transversally, so that no damage results. The situation is different in the glass containers, which are quite stiff, and must keep their shape so that the readings can be accurately made. To prevent the expansion of freezing water from breaking the glass containers, they are equipped with a soft foam cylinder placed in the water of the glass container when it is not in operation, which offers an inward expansion possibility. This simple system effectively prevents the breaking of the glass cylinders under freezing conditions. In the rare event that a cylinders breaks, it is simply replaced the following spring, with little loss of water and time in the process. Another consequence of freezing is the formation of a large number of air bubbles in the water all along the length of the tubing. These bubbles, which can prevent or damp the movement of water in the hydrostatic leveling system, must be removed before the first spring measurement, a time-consuming operation. This is the reason why all tubing must be transparent, to be able to see and remove the air bubbles.

Once the system has stabilized, all water levels in the individual hydrostatic leveling devices are in same horizontal plane. The water level can be easily read at each device thanks to the graduated scale on the glass container. Differences of level between the various devices on the network can be obtained. As such, hydrostatic leveling only provides differential measurements. This means the absolute position of one point in the system must be known to be able to give absolute measurements. In practice, it can often be assumed that points near the abutments of the bridge do not move, which can be periodically be checked, by geodetic triangulation for instance. At least in one case, however, it happened that one of the abutments of the monitored bridge was moving. It took some years before this became clear, as this was not the primary focus of the monitoring.

In many cases, it is not possible to monitor an entire bridge with a single network. In such a case, several networks can be installed, the transition from one network to the next being assured by placing two leveling devices in the same vertical plane, at different heights. This is for instance necessary for the monitoring of bridges with a longitudinal slope. Figure 2 shows the schematic layout of the leveling devices along the Lutrive South bridge[8,9,10]. Multiple networks of leveling devices (33 devices organized in 13 networks for that bridge) have been disposed in the bridge to account for its longitudinal slope and to ensure that the leveling devices are not located too high in the box girder, which would make the readings more difficult, and thus less accurate.

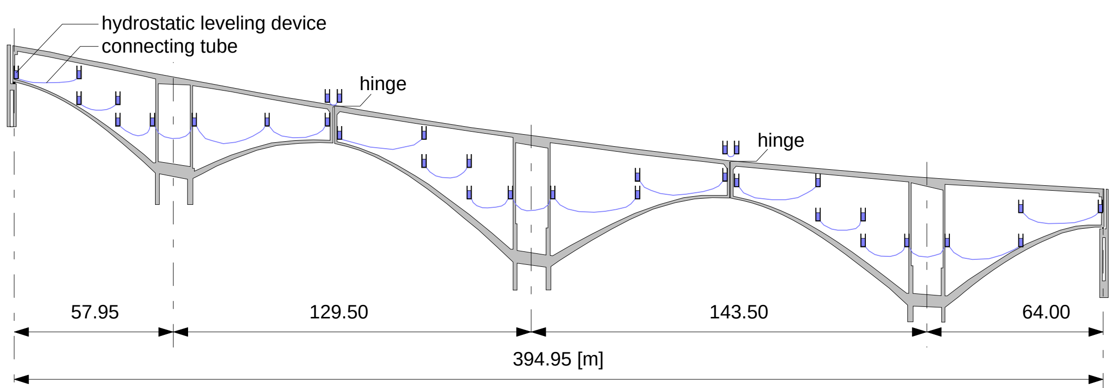


Fig. 2: Schematic disposition of hydrostatic leveling devices in the Lutrive bridge. Some devices are shown outside the bridge for clarity's sake. Vertical scale exagerated.

3. OPERATION

At the end of the aforementioned research project, a total of 11 bridges were equipped with a hydrostatic leveling system. Over the past 20 years, some of these systems were continuously operated, while others were discontinued, or even dismounted. In addition, 7 bridges were equipped with the system to follow their long-term deflections[11,12,13], for a total equipped bridge length of almost 6000 m.

The long-term operation of this large number of hydrostatic leveling systems allows the following observations:

- The system is simple and easy to operate; over the years, several measurement teams were trained to efficiently perform the measurements and maintenance.

- The durability of the system is very good. Even the transparent tubing used to connect the hydrostatic leveling devices has been found to be very long-lasting. The replacement of the tubing in several bridges after approximately 8 years of operation did not reveal discrepancies in the measurements. The foam expansion devices efficiently protect the glass containers from frost cycles in the winter time.

- The system is quite insensitive to traffic passing on the bridge, on the contrary of optical leveling, which can only be performed in the total absence of traffic.

- The accuracy of the measurements is adequate for the missions assigned to the hydrostatic leveling system.

- To improve the accuracy of the measurements, they are always made in the early morning hours. This limits the effect of direct sunlight on the bridge. In addiction, the traffic is less intense, which makes the readings more accurate than in the peak hours, with large traffic-induced vibrations.

- The cost of operation is well controlled. Most of the cost is related to the human interventions for the measurements themselves. For example, the reading of the measurements in one of the Lutrive bridges (Fig. 2) typically takes less than an hour. Including small maintenance work and preparation of the system, an entire reading takes approximately 3 hours to two people. Travel time to and from the bridge is not included.

- The cost of operation is proportional to the number of measurements performed per year. Reporting and project management costs are a fraction of the measurement cost (approximately 25 % for 3 measurements per year).

The system has some limitations, however:

- The measurements are only made manually, with higher costs for frequent measurements. In some instances, monthly measurements have been made (outside of winter time). For a short period of time, this was a cost-effective solution.

- For bridges in remote locations, the travel time to access the bridge can become a significant part of the cost. This can be somewhat mitigated by training local personnel to perform the measurements.

- The method is only reasonably applicable to bridges with an accessible box girder cross section. Bridges with an open cross section can also be equipped, provided that there is an access to the bridge superstructure (inspection pathway for instance), but the proliferation of algae in the transparent tubes and temperature variations along the bridge, larger than within a box girder cross section, may hamper the quality of the results and require significantly increased maintenance.

- Weather conditions limit the applicability of the method: in areas where the freezing period extends over more than 3 – 4 months (as is the case for the bridges mentioned here), the measurement period may be too short, especially considering that summer measurements exhibit a larger scatter. On the contrary, bridges located in very hot and dry environments may be exposed to high water losses due to evaporation, which may complicate the operation. Bridges exposed to frequent wind gusts cannot reliably be monitored by hydrostatic levelling, because the atmospheric pressure cannot be assumed to be uniform.

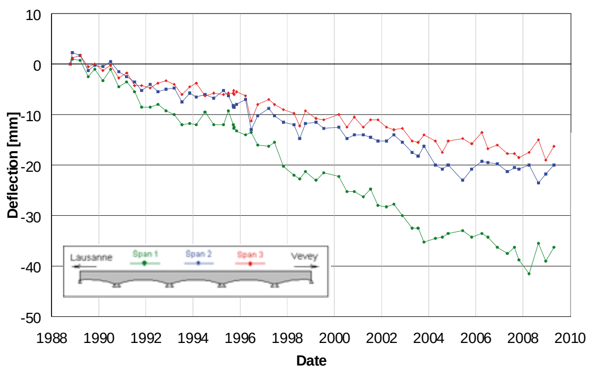
4. EXAMPLES OF MEASUREMENT RESULTS

4.1. Paudèze viaducts

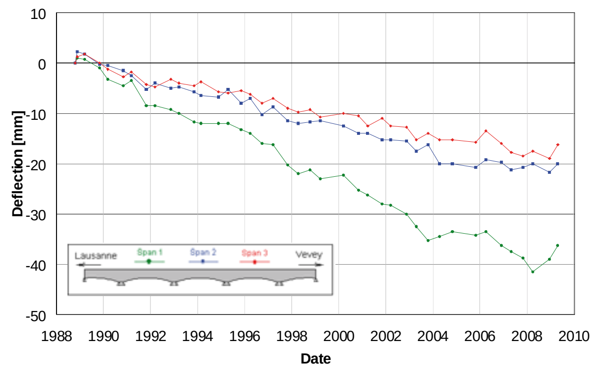
Fig. 3(a) shows the Paudèze North Viaduct near Lausanne. The twin Paudèze viaducts were built by the balanced cantilever method. The viaducts were completed in 1973. Fig. 3(b) shows the evolution over time of the mid-span deflection for the three main spans of the Paudèze North Viaduct since 1988. As can be observed, the deflections increase for all spans, but, in particular for the span on the Lausanne side. The irregularities in the curves are mainly caused by seasonal temperature changes, but may also occasionally be the consequence of small measurement errors. Fig. 3(c) shows the same results, but with summer measurements removed. The curves are smoother.

After more than 20 years of observation, the bridge will be retrofitted by additional external prestressing in the box girder in 2010. The monitoring system will remain in place and will allow observing the effect of the additional post-tensioning on the long-term deflections.

(a) Overall view of the Paudèze North Viaduct



(b) Evolution of the mid-span deflections over time since 1988 (all measurements)



(c) Evolution of the mid-span deflections over time since 1988 (summer measurements removed)

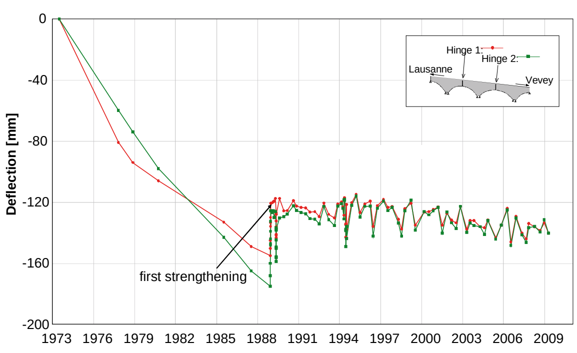
Fig. 3: Paudèze Viaducts near Lausanne

4.2. Lutrive viaducts

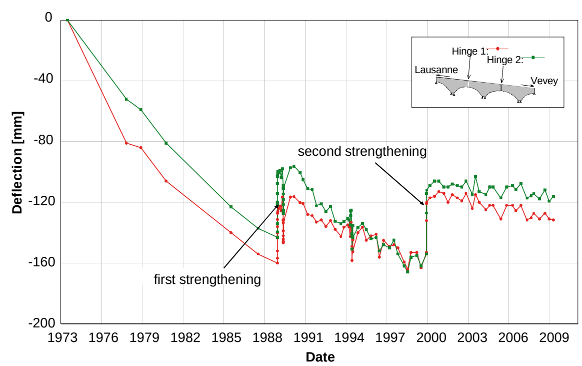
The Lutrive viaducts are twin bridges built by the balanced cantilever method and completed in 1973 also (Fig.4a). The static system is slightly different than that of the Paudèze viaducts, because they have a hinge at mid-span (Fig. 2). The long-term deflections of the two bridges have evolved much faster. Figures 4b and 4c show the evolution of the mid-span deflection of the Lutrive Viaducts since their completion in 1973. In 1980, the deflection had reached 120 mm already. By the end of the decade, it had almost reached or exceeded 160 mm.

A first strengthening by additional post-tensioning was installed in the box girder in 1989. Shortly before that, a hydrostatic leveling system had been installed in the two bridges, complementing the regular topographic leveling that had been performed previously. The results of this system were useful to check the upward movement resulting from the additional prestressing and in following the behavior of the bridges after that. For the North Bridge, the deflections stabilized almost entirely. For the South Bridge, on the contrary, the deflections kept increasing at a rate similar to that prior to the strengthening. On the basis of the results of the monitoring, it was decided to add a second series of post-tensioning tendons within the box girder of the South Bridge. This second strengthening took place in 2000. Since then, the deflections have not completely stabilized, but they are increasing at a very slow rate, comparable in the last years to those of the North Bridge. The monitoring of the bridge will be pursued in the following years.

(a) Overall view of the Lutrive Viaducts



(b) Long-term mid-span deflections of the Lutrive North Viaduct



(b) Long-term mid-span deflections of the Lutrive South Viaduct

Fig. 4: Lutrive Viaducts near Lausanne

5. CONCLUSIONS

After more than 20 years of operation, the hydrostatic bridge monitoring system developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL – IBETON) has proven very efficient for the monitoring of deflections of existing bridges. The system has been operated continuously in some bridges for over 20 years, and has been useful for the surveillance of bridges with increasing deflections. It was also used to follow the strengthening operations and to quantify the displacements induced by additional post-tensioning.

Most large-span bridges have an accessible box-girder cross section, in which installing a hydrostatic leveling system is possible and its operation under traffic simple. One to three measurements per year give a good picture of the movements of the bridge within three to five years of the installation.

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REFERENCES

1. MARECOS J., *The measurement of vertical displacements through water levelling method*, Materials and Structures, 11 (5), pp. 361-370, 1978.
2. MARECOS J., *Water levelling method in observation of structures*, RILEM Technical Committee 20 TBS, Matériaux et Constructions, 14, n° 79, pp. 69-73, 1981.
3. LADNER M., *Unusual Methods for deflection measurements*, ACI, Vol. 88, pp. 165-180, USA, 1985.
4. ESTLER W. T., EDMUNDSON K. L., PEGGS G. N., PARKER D. H., *Large-scale metrology - An update*, CIRP Annals - Manufacturing Technology, 51 (2), pp. 587-609, Netherland, 2002.
5. PARKER D. H., RADCLIFF B., SHELTON J. W., *Advances in hydrostatic leveling with the NPH6, and suggestions for further enhancements*, Precision Engineering, 29, 367-374, Netherland, 2005.
6. BURDET O., MUTTONI A., *Evaluation des systèmes existants pour le suivi à long terme des déformations des ponts*, Swiss Federal Roads Office, N° 607, 57 p., Bern, Switzerland, 2006.
7. MARKEY I. F., *Enseignements tirés d'observations des déformations de ponts en béton et d'analyses non linéaires,* EPFL Doctoral Thesis N° 1194, Lausanne, Switzerland, 1993.
8. FAVRE R., CHARIF H., MARKEY I. F., *Observation à long terme de la déformation des ponts*, Swiss Federal Roads Office, N° 86/88. Switzerland, 1990.
9. FAVRE R., BURDET O., CHARIF H., HASSAN M., MARKEY I. F., *Enseignements tirés d'essais de charge et d'observations à long terme pour l'évaluation des ponts en béton et le choix de la précontrainte*, Swiss Federal Roads Office, Recherche 83/90. Switzerland, 1995.
10. BURDET O., BADOUX M., *Long-term deflection monitoring of prestressed concrete bridges retrofitted by external post-tensioning - examples from Switzerland,* IABSE Rio 1999, Rio de Janeiro, Brazil, 1999.
11. BURDET O., ZANELLA J.-L., *Long-Term Evaluation vs Short-Term Measurements : the Case of the Riddes Bridges*, *fib* Congress, Osaka, Japan, 2002.
12. BURDET O., ZANELLA J.-L., *Automatic Monitoring of the Riddes Bridges using Electronic Inclinometers*, IABMAS, First International Conference on Bridge Maintenance, Safety and Management, Barcelona, Spain, 2002.
13. LARDI R., ABT L., *Schwarzwaldbrücke in Basel*, tec21, No 5, pp. 13-20, Switzerland, 2001.
14. BURDET O., ZANELLA J.-L., *Automatic Monitoring of Bridges using Electronic Inclinometers*, IABSE Lucerne Congress Structural Engineering for Meeting Urban Transportation Challenges, pp. 398-399, Zurich, Switzerland, 2000.