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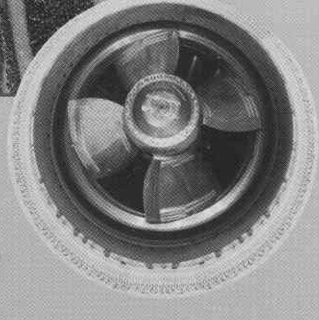

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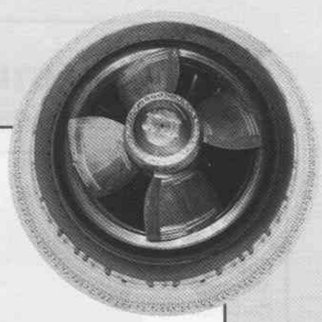

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IAHR AIRH — International Association for Hydraulic Research

ICID·CIID — International Commission on Irrigation and Drainage

WWC CME — World Water Council

IHA — International Hydropower Association

Precision monitoring of displacement over large areas

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The development and refinement of the LAS (Large Area Settlement) hydrodynamic displacement monitoring system is described. The performance of the system is discussed with reference to two cases requiring precision monitoring; the first relating to a slope stability problem on the Rhine river and the second concerns experience gained monitoring the foundation of the Albigna dam (Switzerland). A comparison is also made of other systems, including geodetic height determination.

On 4 February 1997, a slope failure destroyed a 20 m-long section of a retaining wall of the quay on the left bank of the Rhine river at Basle in Switzerland. The risk of eventual further movements causing damage to several historical buildings led to the decision to install a permanent survey system, to be able to recognise vertical components of land movements. A 22-point LAS-meter was installed to monitor the zone continuously, provide information about the slide mechanism and also predict the risk of a new slide.

The LAS-meter is based on a development which has been operating for several years to monitor a dam foundation [Meier, 1991[1]]. In this article, new results are shown from both the slope failure in Basle and the short-term effects recorded at the Albigna dam in Switzerland.

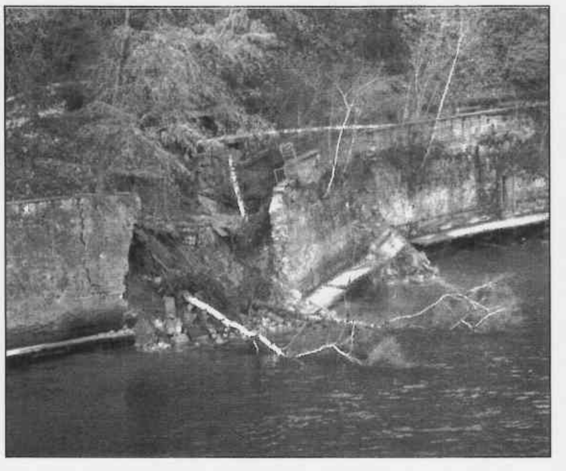
After the landslip in Basle (see photos), the immediate priority concerned safety measurements. This phase included the construction of a stable toe of the bank, with erosion protection, requiring the placement of some 900 t of granite blocks. Then, the question arose as to whether the slip zone had stabilized or could movement continue. During this phase, experts put forward a number of possible causes for the incident and the destruction of the retaining wall. Some of the suggestions included:

- influence of the local geology, that is, the complex topography of the bedrock below the unconsolidated rocks and the steep slope of the artificial fill;
- weakness of the retaining wall, which has been built as a pure gravity wall;
- influence of vibrations induced by boats; or,
- effect of hydraulic collapse and inner erosion associated with small fracture systems in a waste-water pipe during an extraordinary high discharge in 1996.

An accurate assessment of the cause was a primary requirement in the process of selecting a technical solution for the reconstruction of the retaining wall. In addition to hydraulic and geotechnical studies aimed at gaining a better understanding of the processes involved, it was also important to conduct a survey of possible future movements. A combination of continuous LAS and periodical inclinometer measurements was considered to meet these requirements.

Measuring concept

In March 1997, shortly after the slip occurred, a LAS-meter was installed to monitor further ground motions. The LAS-meter consists of one fixed central measuring unit attached to 22 measuring points. Perpendicular to the main planes of movement, two independent measurement chains were installed. Each chain consists of five measuring points (see Fig. 1). The distance between adjacent points is about 2.5 m. The difference in height between two points is a measure for the vertical component of ground movement. This monitoring has been carried out continuously since the date of installation, but no further signs of sliding have been detected.



The broken quay wall, a short time after the slide occurred. It was not clear whether the breach of the wall was a consequence of the slide or vice versa. This event happened during the day without any precursor.

The LAS-multipoint system

The LAS-meter was developed at the Swiss Federal Institute of Technology in Zurich in co-operation with the company Edi Meier + Partner AG, Winterthur, Switzerland. The product is a further development of an instrument which has been in use at the 115 m-high Albigna dam in Switzerland since 1989.

The slip zone is on the left of this picture, on an outer bend (left bank) of the Rhine in the centre of Basle. As the first course of action, granite blocks were placed on the river bank to stabilize the zone.

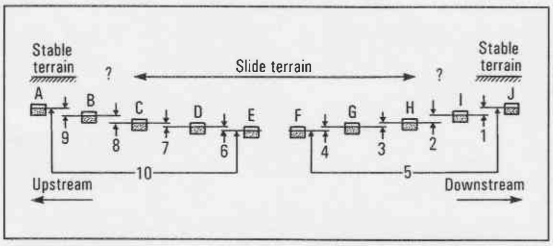


Fig. 1. Measuring concept for the control of the slide area. The measuring points E and F are in the middle of the slide area and the points A and J are in the stable terrain on each side of the slide area. The numbers 1 to 10 represent the signals of the elevation differences recorded with the LAS-meter.

Measuring principle

Conventional hydrostatic levels use the physical principle of communicating tubes. Even though the communicating tube system gives precise results, its application has several disadvantages, namely that electric cabling between measuring points is needed, reaction times are slow, and oscillations of the liquid columns can occur.

The LAS-meter described here (known as a hydrodynamic system) uses the pressure difference between two liquid columns. In the middle of the tubes a diaphragm is inserted which deforms according to the equalisation 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 of the level difference between the 'chambers' at the end of the tube.

The concept of this measuring device is shown in Fig. 2. An early instrument of this type was developed in 1977 at the University of Cambridge, UK. [Horsfall, 1978[2]]. Since 1981, another differential pressure instrument of this kind has been in use at the Black Forest Observatory (BFO) at Schiltach, Germany; it has been developed for earth-tide research using high precision electronics. The base length of the BFO instrument is 167 m [Emter *et al.*, 1989[3]]. Similar instruments have been used with base lengths of up to 1000 m.

Fig. 3a shows the central unit of an LAS-meter (Albigna) with two measuring vessels, the basic configuration for the measuring system, and Fig. 3b the configuration for multipoint operation. The central unit is equipped with an 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 operation. After installation, no further modifications to the instrument are necessary, because all operations can be carried out directly by the control unit. Full access to the measured data is possible via modem and telephone line or radio link.

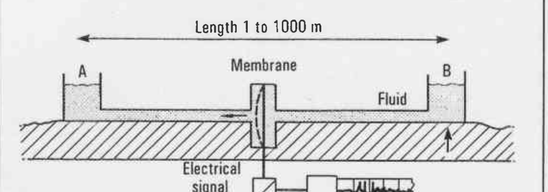


Fig. 2. Measuring principle of the LAS meter. As a result of the pressure differences between two fluid columns, the diaphragm becomes arched. The deformation of the diaphragm is transformed into an electric signal proportional to the elevation difference.

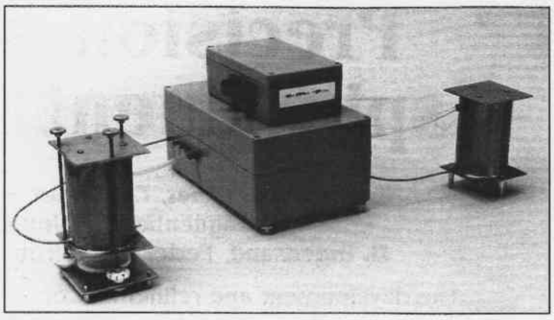


Fig. 3a. The basic configuration of the LAS-system (for example, as used at Albigna) shows two fluid vessels, left and right; the left one is equipped with a levelling mechanism. In the middle there is a central unit with a magnetic switching system, which, by reversal of the connections to the fluid vessels, periodically determines the sensor drift and automatically applies the necessary adjustments.

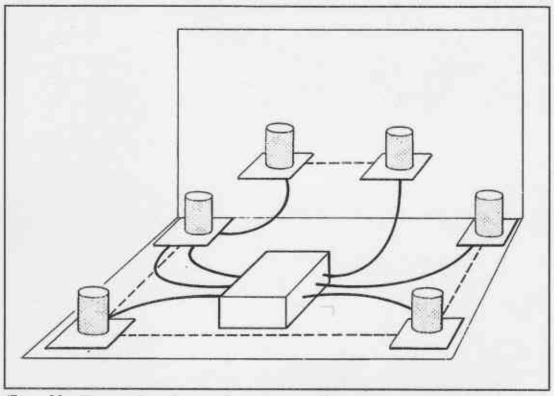


Fig. 3b. Example of a multipoint configuration of the LAS-system, where the central unit sequentially determines the elevation differences between two chambers. The instrument applied in Basle is laid out for measuring differences relating to 22 chambers.

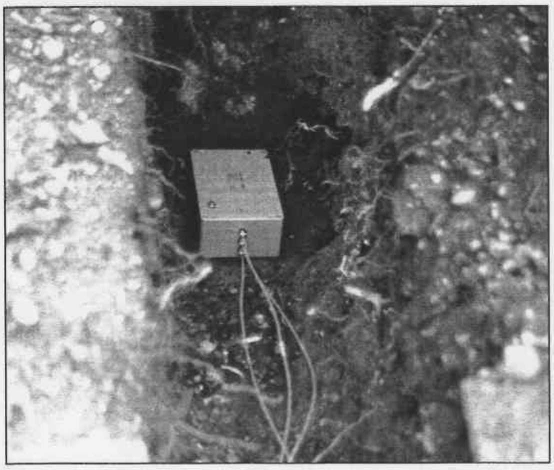
LAS system installation in Basle

After installation, access to the buried measuring points was no longer possible because of the dense vegetation and the fact that the sliding area is private property.

From each measuring point (see photo) three tubes lead to the central LAS-meter, one for the measuring signal, one for filling the chamber and one for balancing local air-pressure differences. The complete system was filled from the central LAS-meter. As shown in Fig. 1, the layout of the measuring system consists of two independent measuring chains. Chamber A is the reference point for the upstream chain, and chamber J for the downstream chain. The level difference between neighbouring vessels is measured and sampled every 30 minutes. Each chain is closed with an overall measuring line for redundancy.

Results from Basle

Fig. 4 gives an example of the quality of the data. The data set was recorded in September 1998. These data show the redundant measuring lines of the upstream chain A to E and the downstream chain F to J. The total tube length is 50 m for the upstream measuring line and 25 m of the downstream measuring line. The



Chamber positioning for the landslide measurement. From each measuring point (chamber) three tubes lead to the central LAS-meter. The unit does not contain any electronic parts. All manipulations are executed from the main unit via the tubes.

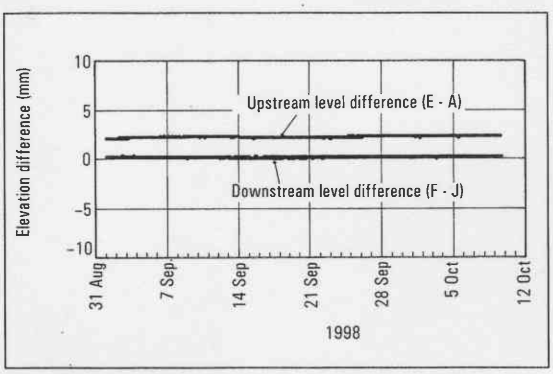


Fig. 4. Results of the redundant signals No 10 and No 5 displaying the elevation differences of the upstream chain A-E and the downstream chain F-J. Points E and F are in the middle of the slide area, A and J are set on stable terrain.

maximum deviation between the redundant lines is about 0.5 mm in the upstream and about 0.4 mm in the downstream measuring chain. The accuracy achieved with the remote filling mechanism is of the same order. With this feature, removing and reinstalling of the LAS-meter at the same site is possible at any time, even if the chambers are no longer accessible. Continuous recording at Basle has shown that the movement has stopped, but when the quay wall is reconstructed and heavy trucks enter the critical zone, the measurement system will be reactivated.

Monitoring of the Albigna dam

The stiffness of the membrane and the geometry of the tubes and chambers determine the response behaviour of the system. This response behaviour is related to the 'time constant' of a system. The time constant is defined as the time which a system needs to reach 67 per cent of its final value after moving a chamber to a new position, for example, the 20 m-long LAS instrument at the Albigna dam has a response time of 7.3 s. This fast response time makes it possible to measure surface waves of earthquakes (which have their largest amplitudes in the time period of 20 s).

Because of the rapid reaction time of the LAS systems the foundation can be monitored, therefore, the observation of long-term as well as short-duration events is possible using the same instrument. Moreover, a time window of 10 s (with a sampling interval of 2 s) indicates the peaks in fluctuation, and

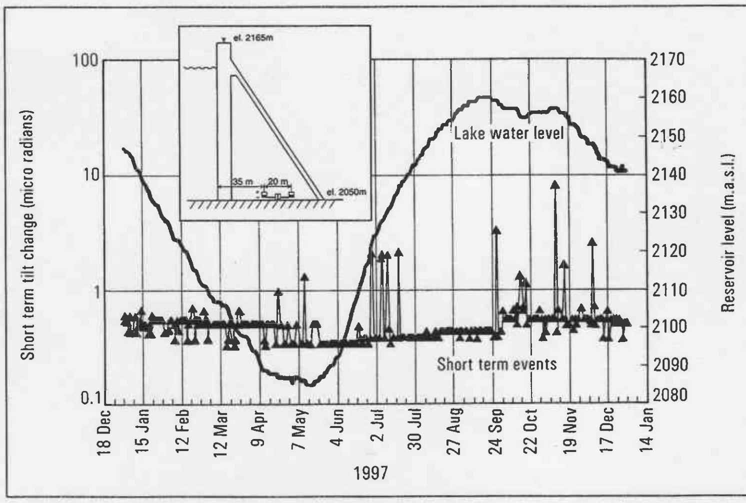


Fig. 5. Record of the short term events at the Albigna dam during 1997. For this evaluation, the LAS meter signal is sampled every 2 s. The maximum difference observed within a time window of 10 s is stored once a day at midnight. This routine allows to monitor the underground continuously with a high sampling rate and a minimum of data saving.

the maximum value which occurred during a day is recorded at midnight.

The precision measurement led to some interesting data, and the same pattern of results has been observed each year. During the spring filling period, a series of events occurred; the foundation was very stable over a period of several weeks, and then a sudden adjustment took place, followed by another period of stability. The movement was not gradual, as had been anticipated. In addition it was observed that foundation adjustments tend to fluctuate more than in summer.

System calibration

Fig. 6 shows the auto calibration set up of the Albigna instrument. The normal measurement cycle shown in Fig. 7 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 data shown are the values, collected 30 s after switching to a new measurement cycle. The inverse measurement is symmetrical in relation to the zero line and gives an idea of the inher-

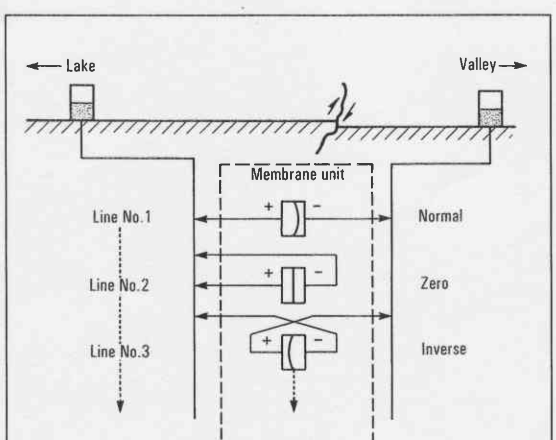


Fig. 6. The principle of the auto calibration procedure performed periodically at the Albigna instrument for elimination of the membrane drift. There are three calibration cycles which carry out normal, zero and inverse measurements.

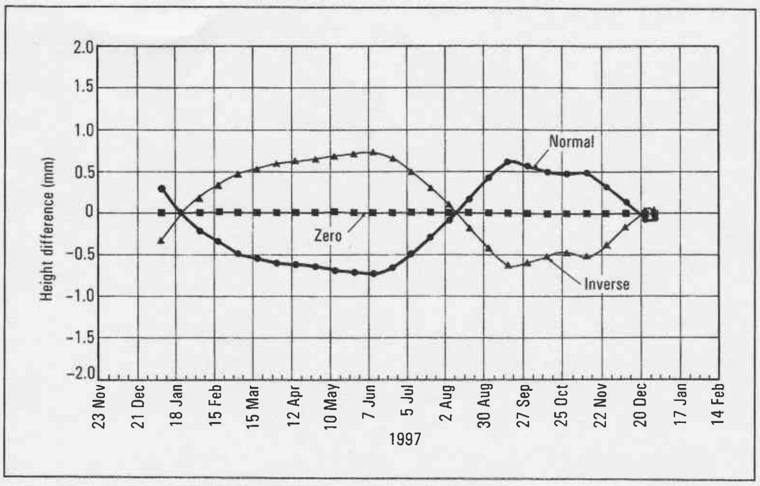


Fig. 7. The results of the system calibration during 1997. The diagram shows the same time period as in Fig. 5. Note the inverse measurement is symmetrical in relation to the zero line.

ent accuracy of the system.

Together with the short-term values, as shown in Fig. 5, the behaviour of the foundation can be evaluated easily without the use of data intensive seismic acquisition tools.

LAS monitoring versus geodetic methods

In recent years various new geodetic measurement systems, such as GPS, motorised tacheometers and digital levels, have been introduced in permanent monitoring tasks. A new generation of motorised tacheometers with automatic target acquisition enabled permanent three dimensional co-ordinate determinations. Especially the GPS and the Russian GLONASS methods gave a new impulse to monitoring tasks as these systems do not require a line of sight connection. But, except for the recently developed motorised digital levels, none of the above systems meets the submillimetre height accuracy which is achievable by hydrostatic or hydrodynamic systems. In addition, geodetic measurements, normally based on infrared and microwave methods, are affected by varying conditions of the atmosphere and troposphere.

Furthermore, optical systems require a line of sight connection which can be obstructed by fog and other impacts during the operation.

Hydrodynamic systems do not require any line of sight connection between the components. In comparison with conventional hydrostatic systems the hydrodynamic LAS has one central sensor and processing unit. In the same way as with geodetic measurements, hydrostatic and hydrodynamic systems are mainly affected by thermal gradients in the liquid which is the core component.

In all hydrostatic systems it is necessary to determine the temperature gradient. The latest development of the LAS eliminates this influence(s) by a process of refilling the system with a liquid with known parameters. In addition, the self-calibration process determines drifts and other effects. This gives a higher reliability effectiveness to hydrodynamic systems in comparison with geodetic height determination.

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Conclusion and outlook

The continuity of the LAS measuring system is its major strength, which allows for accurate measurement of vertical movements.

The extensive experience of using the instrument at Albigna dam has shown that the basic principle of the magnetic valve system is feasible. 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 for a long-term measurement. The drift caused by evaporation is linear. Therefore, in the new LAS-meter the chambers can be refilled and the whole system can be recalibrated without any loss of information.

Although not all the properties of this new system have been fully assessed, the system had been used successfully for several deformation problems. Apart from its use for monitoringconstruction deformation, new applications in the field of waste disposal monitoring and consolidation studies of soils are planned. ◊

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Edi Meier completed a BSc degree in Geophysics at the Swiss Federal Institute of Technology ETH in Zurich, Switzerland in 1981. Since graduation he has worked as a manufacturer of seismic instruments (Streckeisen, Switzerland) for six years and in 1987 founded his own engineering company in Winterthur, Switzerland. The company specializes in geotechnical and geophysical services (ground penetrating radar, as representative of Sensors & Software, Canada) and in the development of precision instruments for geotechnical and hydrogeological applications when there are no 'off-the-shelf' solutions available.

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Peter Huggenberger holds a doctorate in Structural Geology from the Swiss Federal Institute of Technology, Zurich (1985). He has since worked at the Federal Institute of Environmental Sciences and Technology EAWAG in the fields of ultra high-resolution geophysical methods and applications of these methods in non-consolidated rocks. The major projects dealt with groundwater, pollution and river restoration. Since 1997 he has been state-geologist of the City of Basle and head of the applied geology group in the earth sciences department of the University of Basle. His main fields of activity include investigations of environmental impacts of road construction, groundwater protection and pollution as well as geological risks. In 1998 he made his habilitation investigating the influence of heterogeneity in coarse fluvial gravel deposits on groundwater flow.

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Hilmar Ingensand received a PhD from the University of Bonn, Germany. He then worked as a development engineer at Leica Heerbrugg AG, Switzerland, and became head of the Basic Research and Applications group in 1989. Since 1993 he has been a full professor at the Swiss Federal Institute of Technology in Zurich (ETHZ), holding the chair of Geodetic Metrology at the Institute of Geodesy and Photogrammetry. His main research activities are geodetic metrology, sensor technology and engineering geodesy. Since 1996 he has been the head of a research group aiming at the development of methods and instruments for refraction-free, high-precision direction determination.

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