A Multipoint Hydrostatic System
for Permanent Deformation Monitoring

Un système hydrostatique multipoints
pour l'observation de déformations permanentes

Ein hydrostatisches Vielstellenmesssystem
zur Deformationsüberwachung

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ABSTRACT

A hydrostatic deformation monitoring system is described for measuring large area deformations over baselines of 10 to several 100 m. An instrument installed in the Albigna Dam (Switzerland) recorded the tilts resulting from the water load in the lake and due to lunar tides.

RÉSUMÉ

Le système hydrostatique multipoints à pression différentielle décrit, permet des mesurer de déformations à grande échelle, de l'ordre de dix à plusieurs centaines de mètres. Un instrument de ce type, installé au barrage d'Albigna (en Suisse), a enregistré des mouvements résultants des variations de charge hydrostatique dans le lac et induits par les marrées lunaires.

ZUSAMMENFASSUNG

Es wird ein hydrostatisches Messsystem für die grossräumige Deformationsmessung beschrieben, das auf der Basis der Druckdifferenz zwischen Flüssigkeitsbehältern arbeitet. Eine Installation in der Albigna Staumauer zeigte die erwarteten, durch den Wasserstand verursachten vertikalen Bewegungen der Staumauer an. Sie sind überlagert von den Gezeitenänderungen.

1 INTRODUCTION

Since ancient times the surface of fluids has been used as a simple reference for precise differences in level. Nowadays, the hydrostatic measuring principle is again used more often, when visual observation is not possible or disturbances such as air turbulence prevent optical measurements.

2 THE HYDROSTATIC MEASURING PRINCIPLES

The various hydrostatic measuring systems can be divided into three groups according to the operational method:

- 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. The classical hydrostatic levels are the most well-known ones. According to the demands on precision 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 the 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.

3 PHYSICAL PROPERTIES OF HYDROSTATIC MEASURING SYSTEMS

3.1   Statics

The effects on hydrostatic measurements by external forces can be analysed using the abbreviated Bernoulli equation [Thierbach, 1979].

It is:
$$\frac{1}{2}\rho v^2 + p + \rho g h = \text{const.}$$

with:
ρ = fluid density v = local velocity of the fluid
p = local pressure g = local gravitational acceleration
h = height of liquid

Capillary forces, viscosity of the fluid as well as differences in local air pressure are not taken into account in this equation.

With a multiple point measuring system of n identical fluid-vessels, a change in height Δz at the position of one vessel leads to:

fluid level change Δh_m at the moved point:

$$\Delta h_m = \frac{n-1}{n} \Delta z$$

with n = number of vessels

fluid level change Δh_f at the fixed point:

$$\Delta h_F = \frac{-1}{n} \Delta z$$

Δz = vertical shift of the moved vessel

The more measuring points (vessels) available, the more precisely the location of vertical movement can be determined. But this applies only when the number of the points moved at the same time is considerably smaller than the number of fixed points.
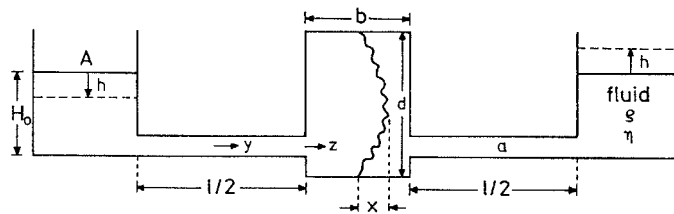
3.2   Dynamics

Fig.1:   Scheme of a differential pressure measuring system.

For comparison of the dynamic behaviour of hydrostatic systems, we use the equation of motion.
The equation of motion for the differential pressure [*Zürn et al., 1986*] system is:

$$\underbrace{\left\{ \underbrace{\rho \ell \frac{A}{a}}_{\text{pipe}} + \underbrace{2\rho H_o}_{\text{vessel}} + \underbrace{4\rho b \frac{A}{\pi d^2}}_{\text{sensor}} \right\}}_{\text{inertial forces of liquid}} \ddot{h} + \underbrace{\left\{ 8\pi\eta\ell \frac{A}{a^2} \right\} \dot{h}}_{\substack{\text{friction of the fluid within the pipe}\\ \text{(Hagen-Poiseuille)}}} + \underbrace{\left\{ \underbrace{2\rho g}_{\text{gravity}} + \underbrace{\kappa \frac{8}{\pi} \frac{A}{d^2}}_{\substack{\text{reactive force}\\ \text{of the diaphragm}}} \right\} h}_{\text{driving forces}} = 0$$

with:
ρ = fluid density	a = diameter of tube
η = fluid viscosity	A = cross section of vessel
κ = stiffness of the diaphragm	g = local gravitational acceleration
l = length of the tubes	h = height of liquid
d = diameter of diaphragm	

and for a hydrostatic level:

$$\left\{ \rho\ell \frac{A}{a} + 2\rho H_0 \right\} \ddot{h} + \left\{ 8\pi\eta\ell \frac{A}{a^2} \right\} \dot{h} + \underbrace{\left\{ 2\rho g \right\} h}_{\text{gravity forces of the fluid only}} = 0.$$

3.2.1   Time constants

The time constant is defined as the time a system takes to reach $1-1/e$ of its final value after the system has been driven by a step-function.

The equation of motion for a differential pressure measuring system has a solution where the time constant [*Emter et al., 1989*] τ is:

$$\tau = \frac{\ell}{\kappa}\pi^2 \eta d^2 \frac{2}{3a^2} = \text{const} \cdot \frac{\ell}{a^2}$$

As hydrostatic levels have no diaphragms providing an additional restoring force onto the fluid, they always have larger time constants than the differential pressure systems.

For example, the differential pressure tiltmeter (tube length: 260 m, $\varnothing$: 5 mm) at the Black Forest Observatory (BFO) Schiltach, Germany, has a time constant $\tau = 15$ min in comparison to the corresponding conventional hydrostatic level (tube length etc. as above) with time constants of $\tau = 60\ h$.

3.3   Temperature sensitivity

All hydrostatic measuring systems show temperature sensitivity. The following figure indicates the specifications in the formulas for their calculation.
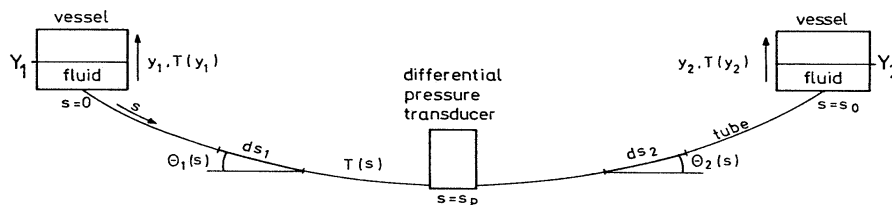

Fig.2 - This sketch illustrates the calculation of temperature effects on the differential pressure measuring system.

Temperature dependence [*Beavan & Bilham, 1977*] of the differential pressure system:

$$\Delta p(S_p) \;=\; -\rho_0 g \gamma \int_0^{S_0} T(s)\sin\theta(s)\,ds \qquad\qquad \text{change of fluid density along the tube}$$

$$+ \rho_0 g(\gamma - 3\alpha_1)\frac{a_0}{A_0}\left\{\int_{S_p}^{S_0} T(s)\,ds - \int_0^{S_p} T(s)\,ds\right\} \qquad \begin{array}{l}\text{change of fluid level in the vessels}\\ \text{due to fluid transport out of the tubes}\end{array}$$

$$- 2\rho_0 g\alpha_2\left\{\int_0^{Y_2} T(y_2)\,dy_2 - \int_0^{Y_1} T(y_1)\,dy_1\right\} \qquad \text{thermal expansion of the vessels}$$

with: ds = element of the tube A_0 = undist. cross sect. Area of the vessel
        θ(s) = slope of the tube γ = temp. coefficient of the fluid
        ρ_0 = density of the undisturbed fluid α_1 = temp. coefficient of the tube
        Y_i = fluid level in the vessel α_2 = temp. coefficient of the vessel
        a_0 = undisturbed cross sectional area of the tube

The temperature dependence is reduced to the first term of the above equation for a hydrostatic level. Depending on accuracy requirements for the measurement, the measured values can be corrected using the above equation.

4 THE LAS-MULTIPOINT SYSTEM

4.1 Origin of this system

The measuring principle used is presented in fig.3. A first instrument of this type was developed in 1977 at the University of Cambridge (GB) [*Horsfall*, 1978]. Since 1981 such a differential pressure instrument has been in use at the BFO at Schiltach and was further developed for earth-tide research using high precision electronics. The base length of that instrument measures 167 m [*Emter* et al., 1989].
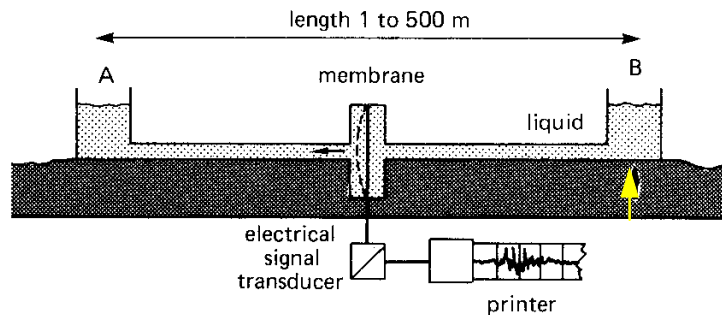

Fig.3 - Principle of the differential pressure system. Due to the pressure differences between two fluid columns, the diaphragm is arched. The deformation of the diaphragm is transformed into an electric current proportional to the elevation difference.

With respect to high resolution and fast reaction time i.e. small time constants, further instruments with shorter base lengths have been built. Figures 4a) and 4b) show two results.

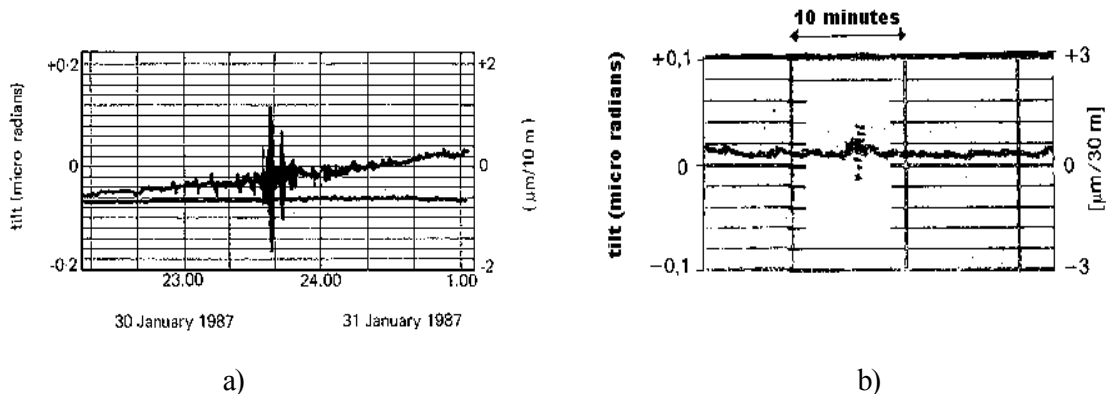a)   b)

Fig.4a - Registration of an earthquake (magnitude 6.9) which occurred near the South Sandwich Islands on January 30, 1987. That system with an base length of 10 m was installed at the BFO, Germany, for this measurement.

Fig.4b -Tilt record with a system located in an old quarry near Walenstadt (SG, Switzerland). The peak in the record coincides in time with seismic arrivals from the disastrous landslide in the Veltlin (Italy) on July 28, 1987. The instrument was oriented NS with a base length of 30 m.

4.2   The Albigna-instrument - the first application of a hydrostatic multipoint instrument

The Albigna-instrument represents an entirely new system, that is adapted to the needs of the monitoring engineers: the LAS (Large Area Settlement) system.

a)   b)
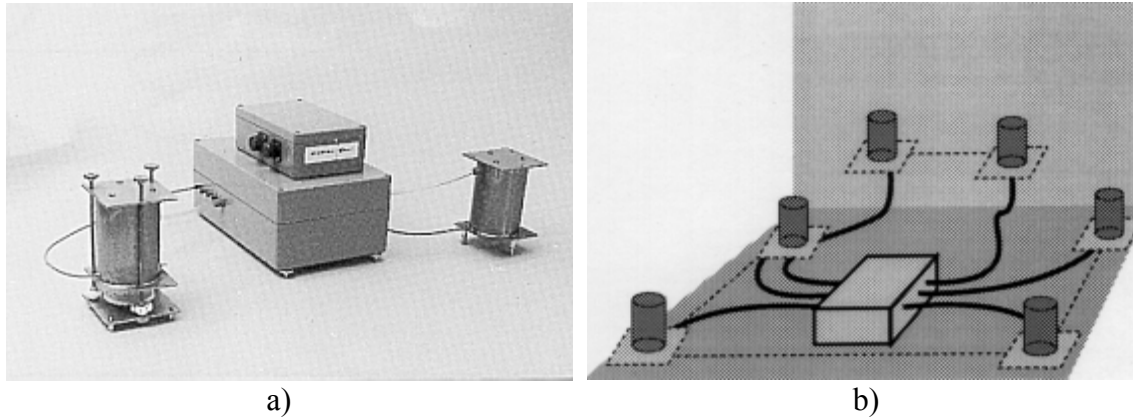
Fig.5a -   The minimal configuration of the LAS-system (Large Area Settlement) shows two fluid vessels, left and right; the left one is equipped with a levelling mechanism. In the middle there is a central unit with a magnetic switching system, which, by reversal of the connections to the fluid-vessels, periodically determines the sensor drift and automatically applies the necessary adjustments.

Fig.5b - The configuration of the Albigna-instrument: The central unit successively determines the pressure differences between various vessels. The four front measuring points are interconnected and the two back ones are set up as an independent base-line.

Fig.5a shows the central unit with two measuring vessels, the basic configuration for the measuring system, and fig.5b the configuration for a multipoint operation. The functional principle is based on the differential pressure measurement. The central unit is equipped with an integrated magnetic switching system which sequentially connects the individual vessels to the membran unit. The control unit collects and processes the data and controls the central unit, which can perform an additional zero point calibration, for correction of the sensor drift. Zero point and span can be controlled at any time by remote operation. Further modifications to the instrument are not necessary after installation, 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.

4.2.1   The installation at the Albigna Dam

This instrument has been installed for the underground monitoring of the Albigna dam (Bergell valley, Canton Grisons, Switzerland) which lies 2000 m above sea level. The dam was built in the years 1956 to 1959 on a prominent rock barrier (fig.6). Towards the mountains this ridge marks the end of an approximately 120 m deep, moraine filled syncline. This ridge slopes very steeply towards the main valley. Thus the rock basement tends to deform considerably during reservoir filling.

The dam is a 760 m long concrete construction, partitioned into 20 m wide blocks. At the block joints 5 m wide hollow cavities are arranged, reaching down to the rocks. The instrument was installed at the base of the joint cavity in the middle of the valley. The block is 115 m high and the measuring system is placed on three consoles mounted right at the bottom of the block (fig.7).

4.2.2 Data logging and remote access

A modem link to the data acquisition unit was installed using one of the existing telephone lines in the dam. Thus we have access to the latest measurements at any time, even under difficult climatic conditions. Remote system diagnosis and calibration can also be carried out, if necessary.

Fig.6 - The Albigna reservoir in the Bergell valley, Switzerland. An arrow marks the place where the hydrostatic measuring system is mounted in the dam. The dam has the direction East-West with the reservoir in the South.
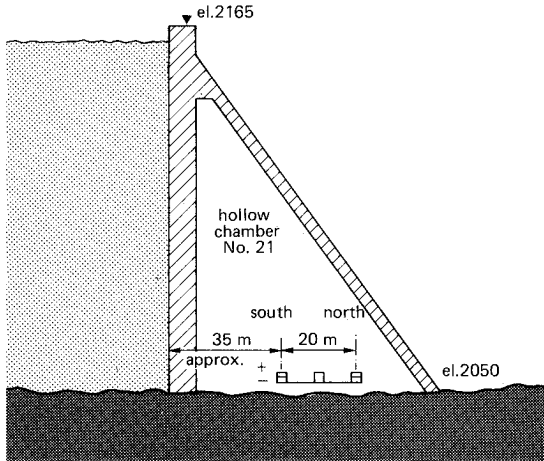

Fig.7 - Cross section through the Albigna dam. The tiltmeter is installed in a hollow chamber about 80 m high, 5 m wide and 60 m long at the base.

4.2.3   First measurement results

Fig.8 shows the level of the reservoir and the related change of tilt at the dam base in the period from November 1st to 16th, 1989. The 2 m lowering of the lake level shows an almost linear dependence between water level and change of tilt.

From the Swiss Meteorological Institute we obtained the air pressure data from the nearby Piz Corvatsch (3315 m above sea level) which fluctuated around 27 hectopascals, and from the airport Samedan-St. Moritz (1705 m above sea level) with 26 hectopascals. The temperatures on the Corvatsch fluctuated between -15 and +1°C and at the airport Samedan - St. Moritz between -16 and +14° C.

On the right hand side of fig.8, lower curve, a regular up and down fluctuation can be observed during a half day period. We concluded that an "earth tide" influence was involved. During the weekend of November 11th no electricity was generated. Therefore the reservoir level remained almost stable. The weather was calm this weekend so that no atmospheric disturbances influenced the data.

Fig.9, lower curve, shows the change of tilt that weekend. The raw data are the same as in fig.8, but notably enlarged, so that the earth tides, occurring twice a day, are clearly visible. Comparing this signal to the theoretically calculated earth tides (fig.9, upper curve), there is no doubt that the moon, resp. the sun are cause of it. Both, the phase of the up and down movements as well as the amplitude coincide well with the theory.
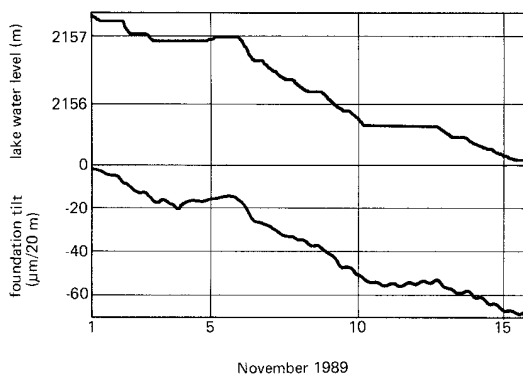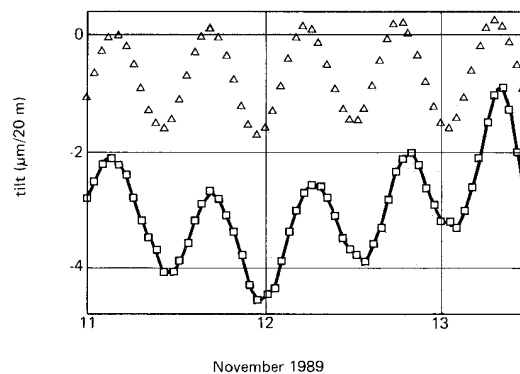

Fig. 8   Fig. 9

Fig.8 - Water level of the Albigna-reservoir between November 1st and 16th, 1989. The upper curve represents the water level (in meters 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, even with a fluctuation of the water level of only 2 m during this period.

Fig.9 - Earth tides, registered at the Albigna-Dam between November 11th and 13th, 1989. The lower curve shows the measured tilt. The water-level was almost constant. On November 13th, the moon was full, which caused maximum earth tide deformations. The upper curve shows the theoretical change of tilt calculated by W.Zürn from BFO at Schiltach. This fluctuation is driven by gravitational forces between moon, sun and earth.

4.2.4 Measurements in the multipoint mode

To illustrate the multipoint mode used for surveys, the calibration cycle of the LAS system is demonstrated. Fig.10 shows the set up of the measurement system in its basic configuration.

The first three measurement lines (normal-, zero- and inverse measurement) are used for the system calibration. The normal measurement mode, fig.11, indicates a change in height of about 1 mm over the whole measuring period 1997 which agrees well with the expected dependence on the lake level. Once a week an auto-calibration-cycle is carried out, used for correcting the sensor drift. The data shown are individual measurement values (no averages), collected 30 seconds after switching to a new measurement mode. The inverse measurement is symmetric to the zero line and gives an idea of the inherent accuracy of the system.
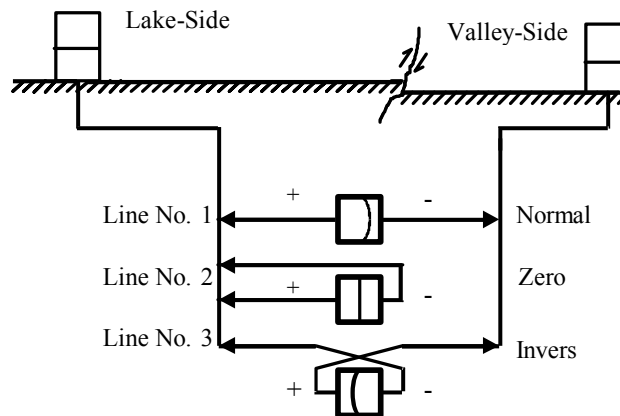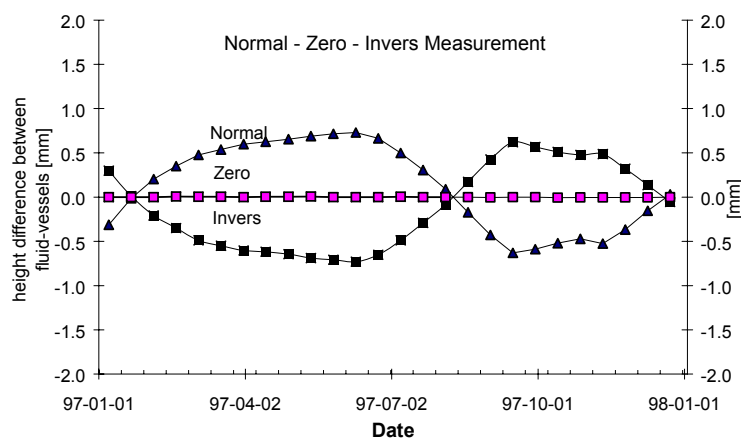

Fig.10 - Example for multiple measurement mode

Fig.11 - There are three measurement modes, 1-3, in the instrument used to carry out normal, zero and inverse measurements. These are the basic elements for the auto-calibration of the system performed every week.

4.2.5 Permanent monitoring for the detection of critical incidents

Owing to the rapid reaction time of the LAS-systems the foundation can be monitored with the same instrument for short time events (fig.12). This option has been developed especially for the monitoring range and is of interest for liability -specific analysis. Moreover, a time window of 10 seconds (sampling interval 2s) indicates the peaks in fluctuation and records them hourly and daily. The measuring example in fig.12 covers the same period of time as in fig.11. Remarkable is, that the ground was very stable over a period of several months. Together with the mean values, as presented in fig.8, the behaviour of the of the underground can be evaluated at first glance.
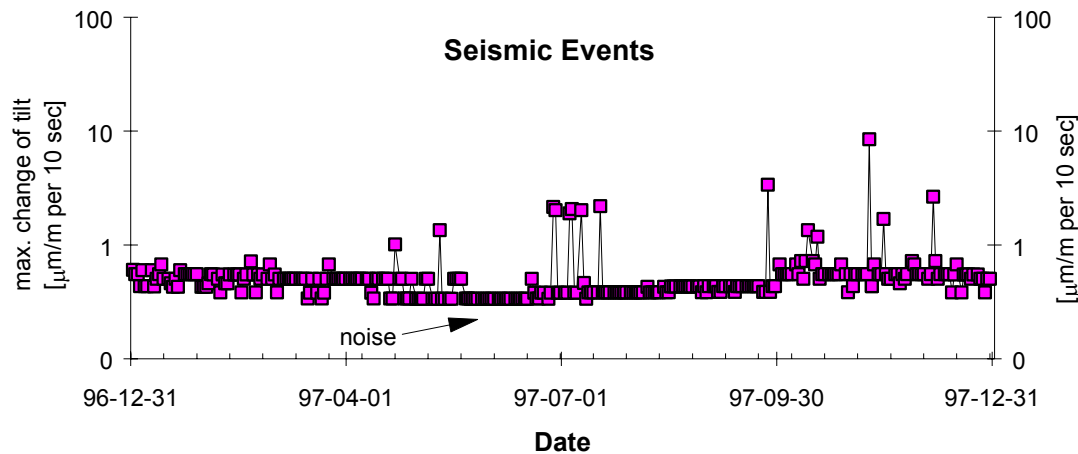

Fig.12 - Monitoring of seismic events at the Albigna dam. An optional evaluation routine gives information about short-time ground movements.

4.3 Advantages of the LAS-System

- High resolution and fast reaction time

- Large measuring range

- Minimal interaction exists between the measuring points
  (With conventional hydrostatic level, the movement of one measuring points influences all other measuring points of the system)

- The electronics is mounted only at one point (no electrical cabling to the different measuring points is necessary)

- The measuring points don't have to be accessible anymore after installation

- Low cost for maintenance (repair and service)
  (in case of repair, only the portable central unit has to be removed)

- Easy handling

- Low cost installation procedure

- High security - negligible risk of electrostatic discharge

5 CONCLUSION AND SCOPE

The herein described further development of the differential pressure technology in a precision hydrostatic measuring system is feasible due to the progress in sensor as well as in computer technology. The combination with a mechanical switching of the individual measuring points enables the determination and elimination of systematic effects of a hydrostatic measuring system. Although not all the properties of this new system have been fully worked out, the system had been used successfully for several deformation problems. Apart from the use for construction deformation, new applications in the field of waste disposal monitoring and consolidation studies of soils are planned.

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