Geotechnical Pressure Cell Using a Long-Term Reliable High-Precision Fibre Optic Sensor Head

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ABSTRACT

Geotechnical measurements are producing various data which are used for interpretation and e.g. safety calculation. The reliability of such data is of most importance as every decision on civil engineering action needed is based on this data. Known and also unknown influences changing data are a basic demand for deeper investigation and research. In present time we have limited tools only to minimize perturbing influences. One of these demands - the long-term development of data also called long-term stability - is described in this paper.

The paper describes a sensor head for long-term high-precision measurements of very small deflections of a diaphragm used for pressure gauges. High precision deformation measurement is assured by using a fiber Fabry-Pérot interferometer sensor; identification of zero-point changes, and thus, long-term stable measurement is achieved by a specially designed absolute interferometer sensor. Several fiber optic solutions based on fiber Fabry-Pérot technique have been investigated to find out a reliable sensor design. The presented sensor design has reached prototype status and allows to measure unambiguously static deformations with high precision. In order to evaluate repeatability and possible changes of zero-point reference if the head has been disconnected, validation of the described pressure gauge has been started. This validation work includes calibration and enables to evaluate possible drift effects, and to identify mechanical or thermal hysteresis. Thus, the highlight in this paper is the observation and measurement of zero-point development over time.

Keywords: pressure sensor, Fabry-Pérot interferometer, geotechnics, deformation measurement, long-term stability

1. INTRODUCTION

In geotechnics compressive or tensile stresses are often measured by flat pressure pads (Flat Jacks) or by hydraulic concrete stress transducers using common pressure pads. The measurement principle is that a deformation of surrounding material, e.g. concrete, exerts pressure on the pressure pad. The fluid in the pressure pad is compressed and the hydraulic pressure change is measured by scanning the deformation of an elastic acting diaphragm. This diaphragm is located in a cylindrical head connected to the pad. In order to achieve reliable measurement data over a long operation time, a high standard of quality is set concerning accuracy, repeatability, application technique, temperature influence, drifts and so on. In general, these requirements are very difficult to meet if atmospheric discharges or lightning strokes happen, e.g. in the vicinity of dams or bridges. Therefore, it was demanded to measure the deflection of a diaphragm inside the head without being influenced by electromagnetic interferences. Other requirements have to be considered, too:

- reproducibility of static measurement results over 20 years, at least;
- indication of zero-point drift over time because recalibration of the measuring head is not possible after installation respectively test loading;
- minimum of ageing;
- control of influences caused by leading cables or other components;

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- water-tightly protected (IP 68), safe against aggressive media;
- compatible to fiber optic sensor networks.

In order to fulfill these requirements, a fiber optic sensing head has been developed to measure very small deformations of elastic diaphragms.

2. FIBRE OPTIC MEASUREMENT PRINCIPLE USED - GENERAL REMARKS

In order to measure precisely very small strain changes in industry or at university level, interferometric techniques are used. Fiber optic interferometric sensors are increasingly preferred because of their advantages: e.g. measurement resolution down to the picometer range, tiny sensing elements, almost no reaction to the measuring object. However, not yet completely solved are the problems arising from the fact that interferometric sensors deliver periodic signals. This feature makes the use of interferometric methods difficult for precise static and long-term displacement or strain measurements, if the sensor has to be disconnected. On the other hand, considering the continuously varying distance between two mirror planes in a fiber interferometer, especially for small distance changes, it is not possible to draw conclusions only from the cosine-like signal - which additionally decreases exponentially - to the direction of the mirror shift. The measurement result is then ambiguous. When the measurement device is switched off or disconnected, the zero-point reference is lost. This problem is not really significant for dynamic measurements, such as for measurement of acoustic emissions. However, measurement of static quantities is not easy to carry out. It requires sometimes extremely high signal resolution as well as unambiguity and zero-point reference.

Since about ten years, very different designs have been proposed to solve these problems. The basic idea in these proposals is to get or to create, at least, more information, which can electronically or mathematically be combined with the original interferometer signal. From this, one can get unambiguous and absolute measurement information. The most interesting solutions, which solve these problems, are: a) the current of the laser diode is driven by a feedback of the interferometric signal; a Serrodyn characteristics of the output signal is created from which the shift direction of the sensing interferometer arm can be detected unambiguously [1]; b) several defined laser wavelengths are used. An absolute measurement of distance changes is then possible by using the beat wavelength [2]. The cited methods suffer from two problems: either the signal resolution respectively the accuracy is not sufficiently high for some measurement tasks, or a reliable detection of absolute measurement signals is not really possible if the device or components of it have to be renewed. On the other hand, a re-calibration of embedded, that means, not any more reachable sensors is not possible, if the sensor-assembled structure component cannot be tested separately. These unsolved problems were the decisive factor to develop innovative and completely new solutions to get absolute and long-term stable measurement information from fiber Fabry-Pérot sensors. Following, one of the methods developed including first test results will be presented.

3. MEASUREMENT TASK AND REQUIREMENTS

The deformation of a metallic diaphragm has to be detected up to a deflection of 10 µm (rather less) perpendicularly to the plane of the membrane. Electric components are not accepted because of the probability of damage by lightning. Data recording is planned only from time to time, and long-term reproducibility of the deflection within a range of 5 % (full-scale) has to be ensured. Long-term measurement means, that the sensor has to work reliably for several years. Additionally, the diaphragm behavior must not be influenced by stress-induced reactions of the sensing element to the tiny membrane. The sensing head including the read-out device should be not expensive. Finally, the data recording system should work automatically.

From the data scanning point of view, there is sufficient scanning time (about 5 min) because the measurement signal varies extremely slowly. The data scanning could run once per hour or once a day. A very important requirement is that the measurement device must be disconnected from the sensing head after each measuring event. A central data acquisition unit is not scheduled. Electric links between sensing head and device should strictly be avoided. On the other hand, non-electric auxiliary power supply, e.g. for calibration purposes, is allowed.

4. FIBRE OPTIC HEAD WITH ZERO-POINT IDENTIFICATION

In order to meet the measurement requirements and to enable a multiple calibration of irretrievable sensors (that means, the sensors are embedded or installed inside of large structures that the sensors are no longer attainable), a special compensation method has been developed. It uses an auxiliary energy. The principle of the measuring head is shown in Fig. 1; Fig. 2 shows a sample of the sensing head. Inside the measuring head, a nearly reaction-free Fabry-Pérot interferometer (FPI) sensor, which is able to slide in a tiny capillary [3], is used as measuring interferometer. This movable fiber Fabry-Pérot sensor is driven by a change of the measurand (here: by deflection of the diaphragm). The calibration and measurement procedure is started by introduction of the auxiliary energy (in this case: compressed air) into the head. Due to this action, the elastic element (see Fig. 1) is slightly deformed and the measuring interferometer will be shifted back until a well-defined reference position. This position which represents the stable zero-point position is detected by a second interferometer sensor (stop trigger FPI). Finally, the evaluation of the interference signal of the measuring interferometer sensor delivers the difference between the value following from the actual measurement and the value defined by the reference point. Thus, measurement and calibration procedure is directly connected.

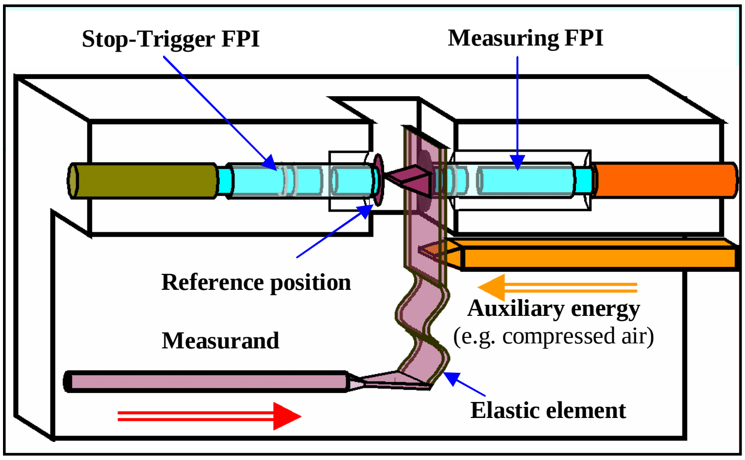

Fig. 1: Scanning principle using fibre Fabry-Pérot sensors

Fig.2: Photograph of the sensing head

5. TEST OF THE SENSING HEAD

In order to get reliable information about the performance of the scanning head, a test program corresponding to the rules of validation [4] has been started. A number of tests has to carry out to verify whether the sensing head fulfils the requirements for the intended use. The most important questions concern:

- evidence of zero-point stability, that means, the estimation of the zero-point deviation from the original reference value; two test cycles are carried out: cyclic pressurization for constant temperature with a certain stop time, and cyclic pressurization at two temperature levels. All measured values are compared with a high-accuracy measuring device (reference standard);
- identification of sensor characteristic including existing hysteresis, drift, zero-point shift;
- evidence of precise functionality after disconnecting and reconnecting of the recording device;
- identification of possible influences on the sensor characteristic due to changes in temperature of leading fiber and components;
- evidence of mechanical stability.

Following, a selection of achieved results of the validation are presented. The validation of the performance revealed the quality of the sensing mechanism so that necessary work of optimization could be done. In order to control the linearity of the characteristic curve, the pressure was increased up to a value of 3.0 bar in 10 percent steps. Fig. 3 shows three pressurization tests within 8 minutes in the above defined pressure range. The linearity is quite satisfying in the operational pressure range of 1 bar. Overloading up to 3 bar does not destroy the sensing head or the membrane. The mechanical hysteresis is sufficiently small as expected. A reliable quantification of the measurement uncertainty is, at the present stage of investigation, not yet possible. However, the results give evidence that the sensor works reliably.

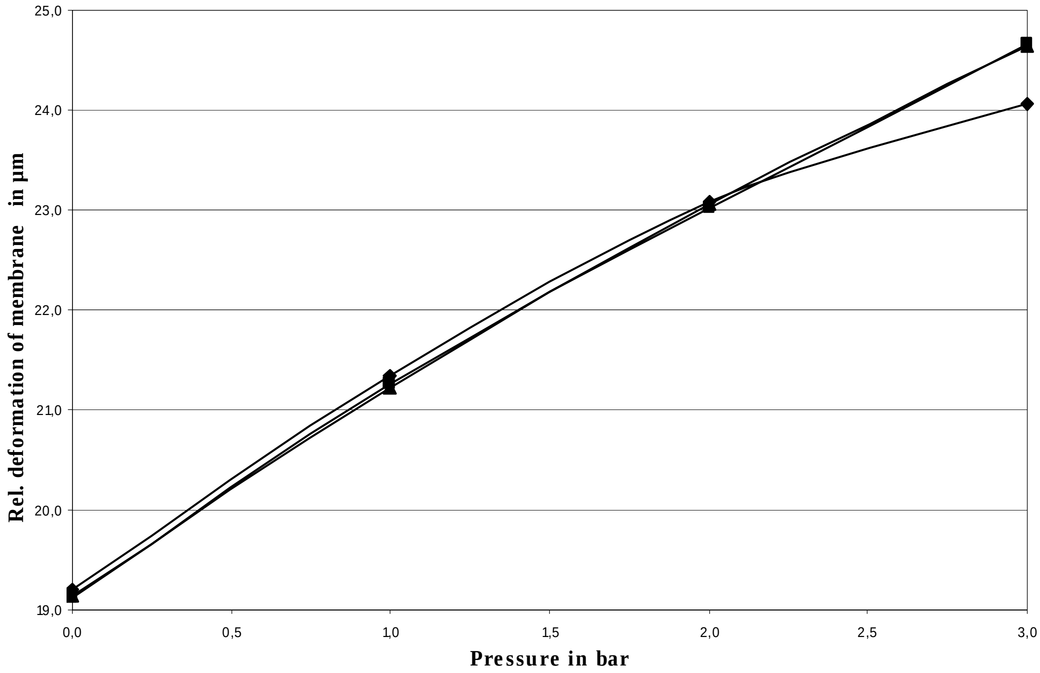

Fig. 3: Characteristic of the sensing element over pressure changes

Fig. 4 shows how reproducibly the "zero-point" reference position can be achieved when the sensor head was disconnected or when measurement values are to be taken after a long period of sensor inactivity. The deviation of the unbiased mean zero-point position (internal reference of the sensor head) is ±90 nm. From this rough estimation of deviation of the reference uncertainty follows an uncertainty in the pressure measurement of ±42.5 mbar which corresponds to 4.25 %.

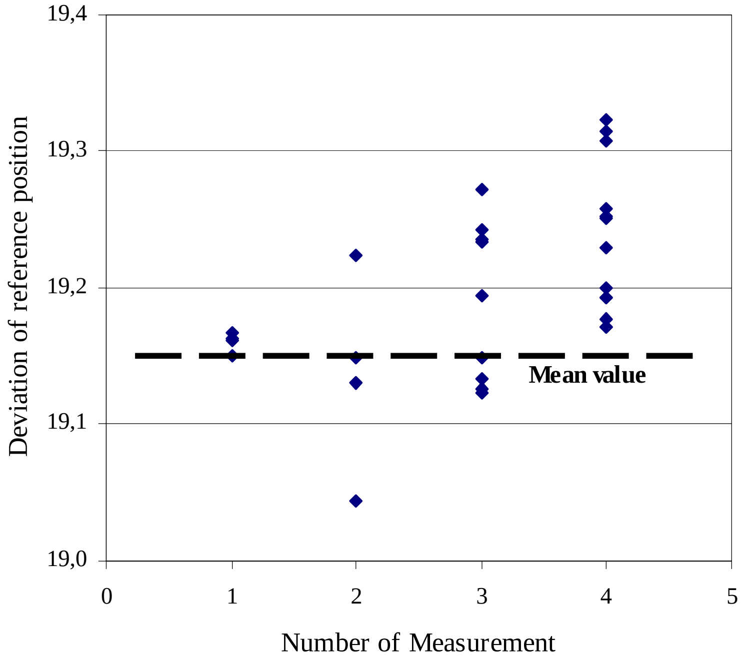

Fig. 4: Reproducibility of the "zero-point" reference position (without pressure signal); the measured values shown on the ordinate correspond to the membrane deviation in µm.

Fig. 5 shows the drift of the sensing head under a permanent pressure load of 1.0 bar over 70 h. It is clearly to see that - after a warm up time of about 5 hours - the drift is within a range of 34 nm of the diaphragm deflection which corresponds to a drift within a range of 16 mbar (1.6 % drift).

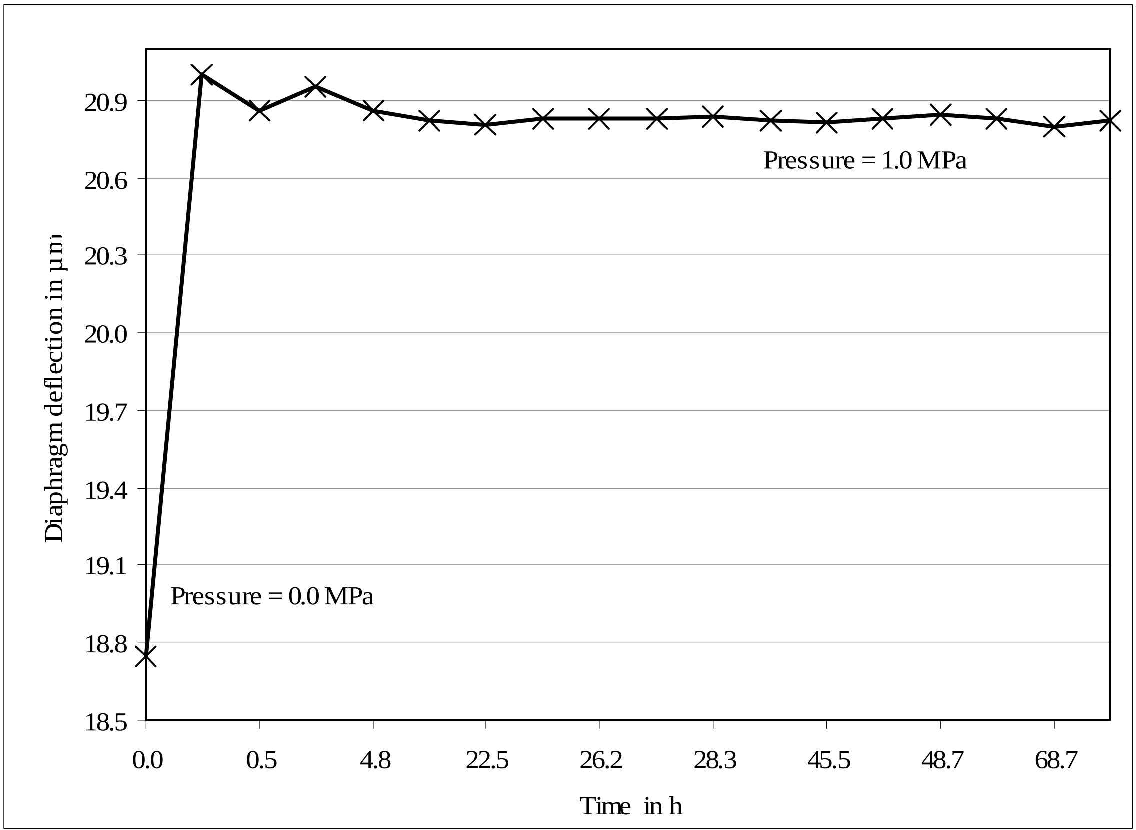

Fig. 5: Drift of the sensing head under permanent loading for 70 h.
[Environmental temperature: (19.8 ± 1.0) °C, atmospheric pressure: (1013 ± 4) mbar].

6. CONCLUSIONS

A fiber optic sensor head based on a fiber Fabry-Pérot interferometer sensor has been developed. The sensing head can be used in hydraulic measurement systems for geotechnical applications to scan precisely very small deformations of a diaphragm. However, this head can also be used in other measurement systems. The special feature of this high-precision sensing head is its ability to enable long-term measurements with internal zero-point reference, especially needed when the power supply is switched off or if components of the measurement system have to be exchanged. One version of different solutions at laboratory level has been validated concerning repeatability of results, stability of zero-point reference, drift and hysteresis effects. It was shown that reliable long-term static or quasi-static measurements are possible and zero-point stability information is available even if the recording device has been disconnected.

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