The paper was published in the proceedings of 10th International Symposium on Field Measurements in Geomechanics and was organized by Prof. Pedricto Rocha Filho.

The conference was held in Rio de Janeiro, Brazil, on July 16-20 2018.

FMGM 2018
INTERNATIONAL SYMPOSIUM ON FIELD MEASUREMENTS IN GEOMECHANICS
Rio de Janeiro - PUC-Rio, 16-20. July | 2018

Reference Pressure Cell, An Effective Solution for a Challenging Matter in Soil Mechanics

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1 Abstract

Design, construction and sustainable operation of civil infrastructures have always to do with geotechnical monitoring. Two most important categories of geotechnical monitoring by instrumentation are the measurement of pressure and displacement. In many instances of measurement technologies, these two physical parameters help each other to measure a quantity of them. Besides the displacement of soil mass is a source of inconsistent total pressure data. This issue is a challenging matter in geotechnical monitoring of embankment structures which experience a considerable displacement during construction or consolidation phases.

In case of rotation of total pressure cell without knowledge of the final inclination, correction of measured values through the theoretical assumptions is either impossible or not completely reliable.

This paper describes an innovative outcome of a project for developing a new measuring instrument which solve the above-mentioned problem, increase the reliability of monitoring data and reduce the errors and the costs of instrumentation. The important critical success factor of this measuring system is an optimal mechanical and electrical integration of a inclination sensor and a pressure insert in a tight heavy-duty housing. This type of total pressure cell is capable to measure the inclination in two axes up to 90°.

The new developed solution by Glötzl GmbH for measuring the inclination of pressure cells prepares a good information for correcting the critical soil mechanics stress ratios such as pore water pressure and arching ratio.

Key Words: Instrumentation, Monitoring, Total Pressure, Reference Pressure Cell, Rotation

2 Literature Review

2.1 Source of Errors; How challenging the matter is?

A total pressure cell installed in the body of an earth-fill, e.g. in the clay core of an embankment dam, must be capable to measure the total stress in a special direction. In many instances, the position of pressure cell changes continuously due to the development of displacements and functionally changes the value of measured pressure. This is the most important reason for the inconsistent total pressure data and uncertainty of monitoring results of embankment structures. This uncertainty can cause some misunderstanding of pressure data and related pressure ratios – such as Arching Ratio - and following mistakes of safety monitoring.

The potential for rotation of the total pressure cells in the soil material during compaction of an embankment is very likely. Therefore, the analysis of pressure data in an embankment without knowledge of final inclination of the pressure cell is a challenging matter which sometimes causes resign form installation of total pressure cell.

For reviewing the literature of researches and studies, it would be very helpful starting with the GIN (Geotechnical Instrumentation News) which included an article by Ali Mirghasemi about total pressure cells of Karkheh dam in the 46th episode and subsequently discussions in the next episode. The exchange of ideas mentioned as below about no consistent total pressure data is being still discussed among the manufacturers, geotechnical institutes and consulting companies. The final conclusion of Mr. Dunnicliff for this very interesting theme is generally accepted for principle of stress monitoring in high embankment projects.

> ″ A total of 102 clusters, each of five earth pressure cells, have been installed to determine the total stresses in the embankment – a total of 510 cells. This number is

about half of total number of instruments installed in the dam. No consistent data was achieved from the earth pressure cells. ″ *Ali Asghar Mirghasemi, Assistant Professor, University of Tehran; GIN March 2006 [Ref. 1]*

″ In summary, measurement of total stress in an embankment is extremely difficult and should not be done unless absolutely necessary and, if necessary, particular care must be given to installation details. ″ *Elmo DiBiagio, Norwegian Geotechnical Institute (NGI); GIN June 2006 [Ref. 2]*

″My experiences with free field total pressure cells have also been disappointing and the cost of their installation in the clay core of a dam is not justified, in my opinion. The results are rarely reliable. ″ *P. Erik Mikkelsen, Geoengineering & Instrumentation, Geometron Inc.; GIN June 2006 [Ref. 2]*

″ My experience is, and that of many authors at ICOLD Congresses and other Conferences seems to be, that it is very difficult to interpret and rely on the readings from earth pressure cells installed in embankment dams, especially rockfill dams. Many investigators have spent time and money installing such cells, but have, in general, found the measurements of little value. **There are examples of pressure cells giving valuable readings when the cells are installed on a structural interface, but not inside the dam body.** ″ *John Dunnicliff; GIN June 2006 [Ref. 2]*

The conclusion of Mr. Dunnicliff specially his mentioning of a solid subsurface implicates the rotation of total pressure cells as a main source of inconsistent data inside the embankment. Till that time there were a number of tries to reduce the local initial rotation of total pressure cells which happens during the earth-filling of first layers. However, there is no documented tests attempting to measure the rotation of total pressure cell precise and long-term.

There are a wide range of studies which have focused on stress-strain status in embankment projects specially for the verification of monitoring results or numerical back analysis by the instrumentation. These researches have addressed a lot of uncertainties and generally mentioned to the rotation of pressure cells.

A similar study which has already implicated this inconsistent total pressure data, there is a research on the stress status of Taham dam in Iran. The difference between the numerical modeling and instrumentation data for total normal pressure is shown in figure 1.

Normally if a total pressure cell in an embankment rotates, the measured values are less than vertical stress at the point of measurement. For a better imagination of rotation, two displacement profile of Taham dam shown in fig. 2 are helpful. In this dam it is expected to face a rotation of total pressure cells under these large displacement conditions.

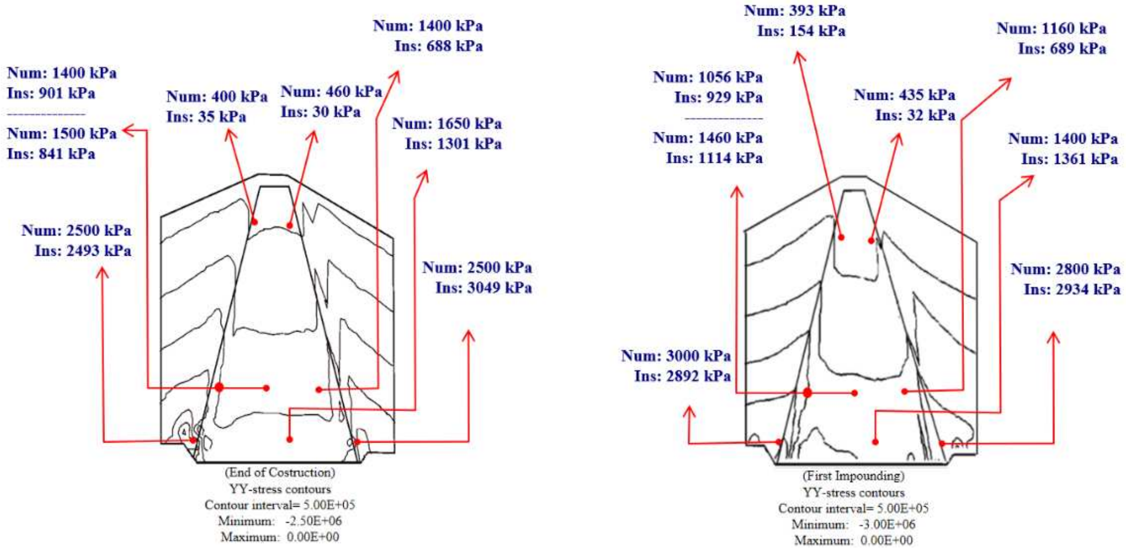

Fig. 1: Total normal pressure before and after impounding of Taham dam reservoir; Numerical analysis: Num. / Total pressure data: Ins. [Ref. 3]

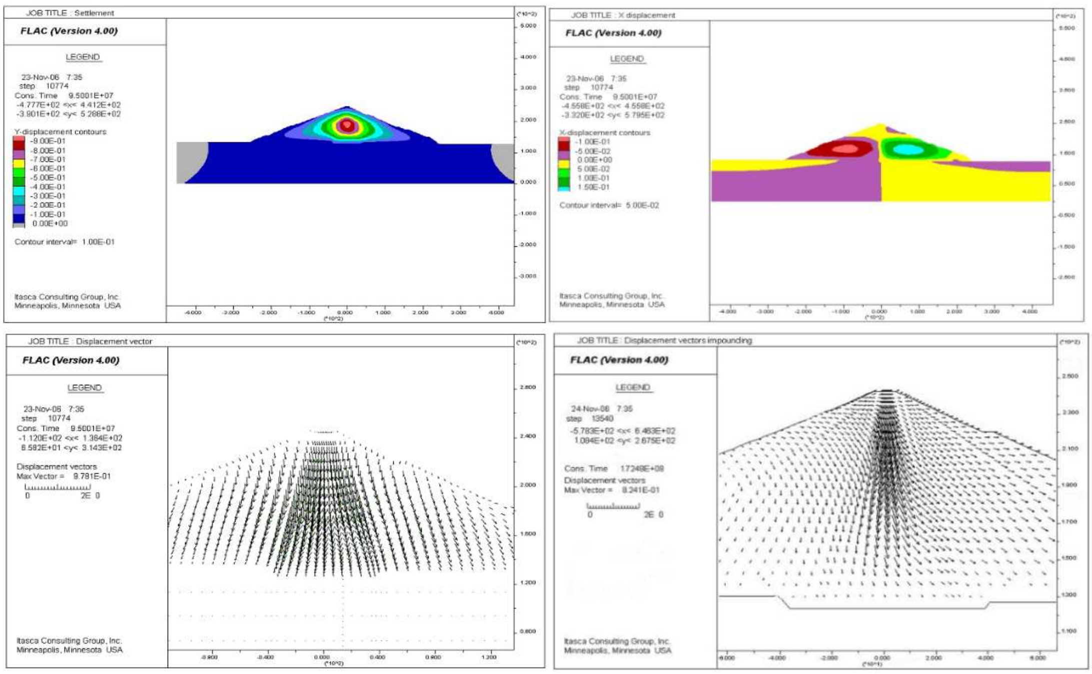

Fig. 2: Numerical Modeling of displacement profiles and vectors of Taham dam; [Ref. 3]

As shown in the figure 1, there is a considerable difference between numerical model (Num.) and instrumentation (Ins.). The best compatibility of the pressure data with the calculated values belongs to the lowest level of installation. This level of installation is located in the bottom of clay core only 30 cm above the roller compacted concrete (Fig. 3). It is very likely that the rotation of total pressure cells in this level is very negligible (remember the conclusion of Mr. Dunnicliff: ″the structural interface″).

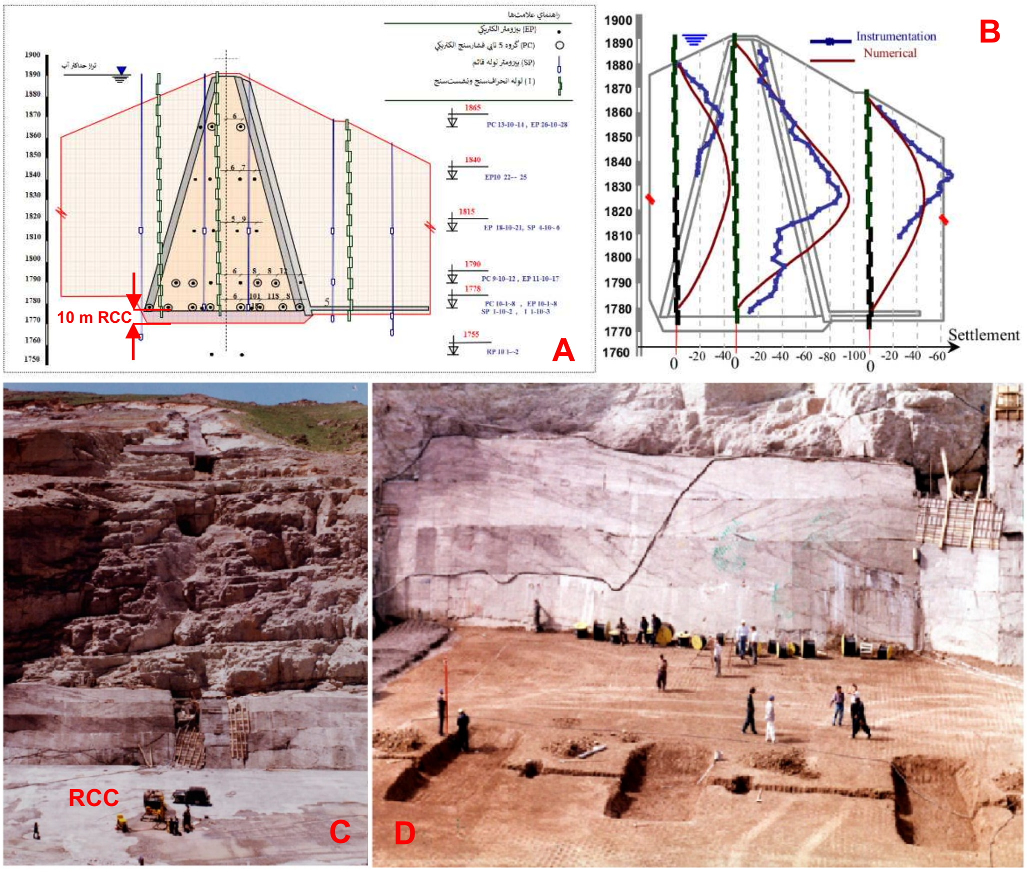

Fig. 3: A) Instrumentation sec. 10 Taham dam; B) Settlement profile sec. 10
C) Interface of RCC and clay core; D) Excavated banks for installation of instruments [Ref. 3]

There are a lot of discussions about some other technical source of errors, in spite of the rotation, which would be mentioned here very briefly. For a better understanding of these technical difficulties, a review of the components of a total pressure cell is unavoidable.

The *Total Pressure Cell* (TPC) consists of one or two active pressure pad(s), hydraulic oil tube, and a housing for diaphragm-type insert as well as hydraulic/pneumatic compensation valve (Fig. 4). The grooved pressure pads are expressly mentioned as *Active Pressure Pad* which cause a quite uniform deformation of pressure pad (Fig. 5). For installation of total pressure cell on a structural interface, grooving the lower pad side is sometimes not recommended or not ordered by users.

Two common electrical pressure sensors for the embankments are the Vibrating Wire and Piezoresistive sensors which are selected dependent on construction method.

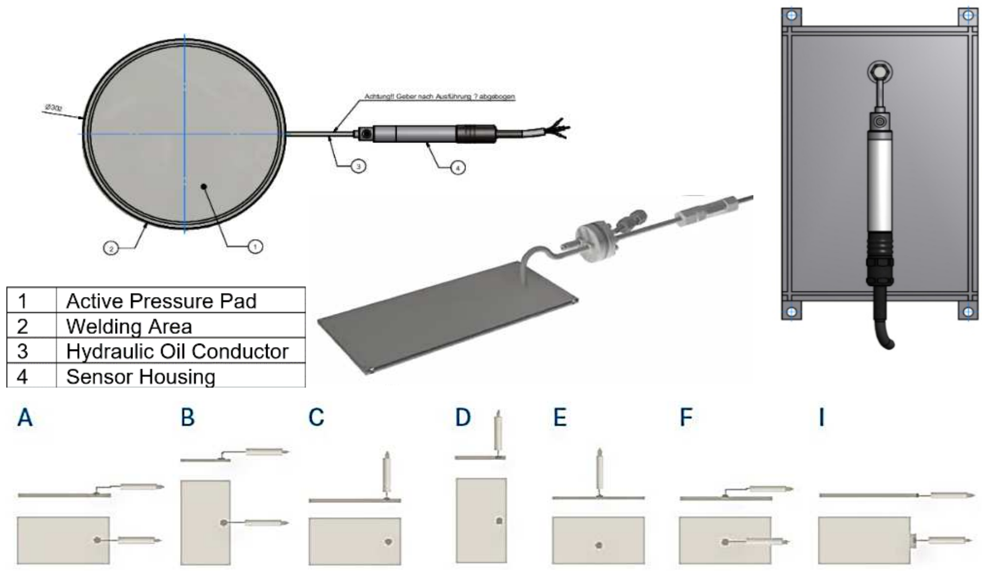

Fig. 4: Total Pressure Cells; Variations of electrical and hydraulic/pneumatic sensor, circular and rectangular, sensor housing connections

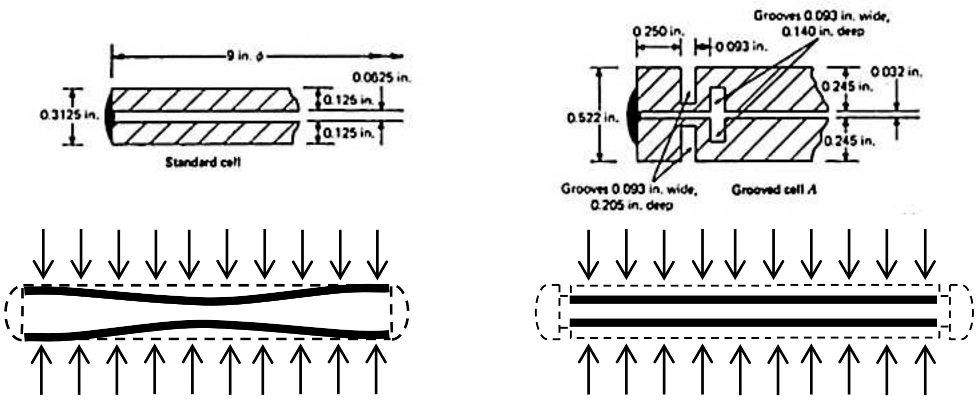

Fig. 5: Deformation of welded edge and grooved edge pressure pads under uniform pressure in fine soil materials

The unqualified mechanical and electrical components are the prior source of errors and inconsistency of data respectively. Each mechanical component of an instrument as well as electrical components are involved in the final precision.

The assembly of the loading pads and the insert in an appropriate housing are all-over important. A thigh housing with one-tenth millimeter tolerance or a slim housing prone to this deformation can reduce the precision tens of percent. In a similar manner the electrical components are enough sensitive to cause the errors.

2.2 Source of Errors; How helpful the conventional solutions are?

There are some methods which are presented again and again by engineers and researchers which try to overcome these uncertainties either by some technical considerations during manufacturing, installation or by some recalculating of measured stress values.

First, some special changes in material and configurations of sensors, e.g. reducing drift and creep effects, the heavy-duty housings for inserts, short length hydraulic oil tubes, circular ventilation oil filling, grooving the loading pads, etc. would be listing as important achievements of manufacturers for overcoming the technological sources of errors (Fig. 6). But they don't definitely warrant an on-site consistent measurement of total pressure.

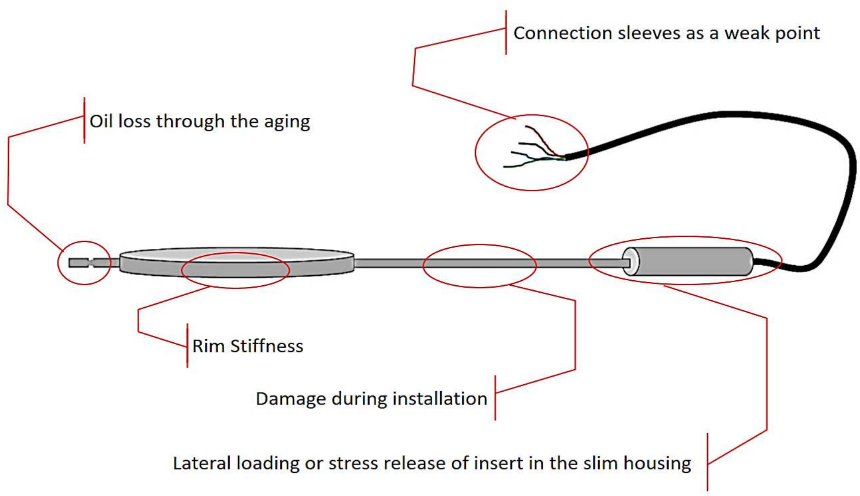

Fig. 6: Total Pressure Cell, Some sources of manufacturing errors

Second, the technical considerations during installation on site for positioning, installation, material filling and compaction don't guarantee in any case a steady fixed direction of installed pressure cells. These methods generally try to make a same compaction conditions around the total pressure cell for preventing local rotation and short-term local arch-action.

On the other hand, the theoretic recalculations are based on many assumptions. There are some methods which are a combination of both practical and theoretical methods for reducing the negative physical effects and increasing the accuracy of theoretical calculations. Although these methods have certainly some limitations and disadvantages.

The conventional theoretical solutions, applicable considerations for installation and technological achievements of manufacturers are generally limited to the mechanical aspects of instrument and don't present any solution for overcoming the measuring errors due to the long-term rotation. Consequently, the theoretical, technological and technical solutions for inconsistent pressure date in an embankment under a large displacement conditions are effective for reducing the sources of short-term errors.

It is to be noticed that there is a considerable quantity of the embankment structures, especially embankment dams, in which projects the designer has preferred to resign the stress monitoring by total pressure cells. The current technical and academic literatures implicate that this attitude is becoming rapidly as an accepted design method of instrumentation of embankment structures. In that case the only remaining solution for approximating the pressure ratios is evaluating a pressure value by the average density of overburden materials regardless of unequal layer compaction and arching phenomenon.

3 Solutions

3.1 Conventional Solutions; Cluster Cells without excavation of an installation Bank

The most known practical method for overcoming non-uniform compaction of installation area which causes a short-term local arching and additional rotation, is embedding the cell by spreading soil without excavation an installation bank. The compaction of soil in the bank by using a light-weight roller results lower stiffness at the embedded sections than surrounding fill.

In case of embedding the cell without excavation, using heavy machines for compaction of first soil spreading is possible (Fig. 7). The installation of total pressure cell in the large embankment projects through this method for overcoming the short-term local arching and initial rotation is quite accepted everywhere. However, these phenomena can cause an inconsistent pressure data during the filling of first overburden layers which is negligible compared to the full-scale pressure and displacement. It would be very careless to account the short-term non-uniform compaction which would be adjusted during the construction time for long-term source of error.

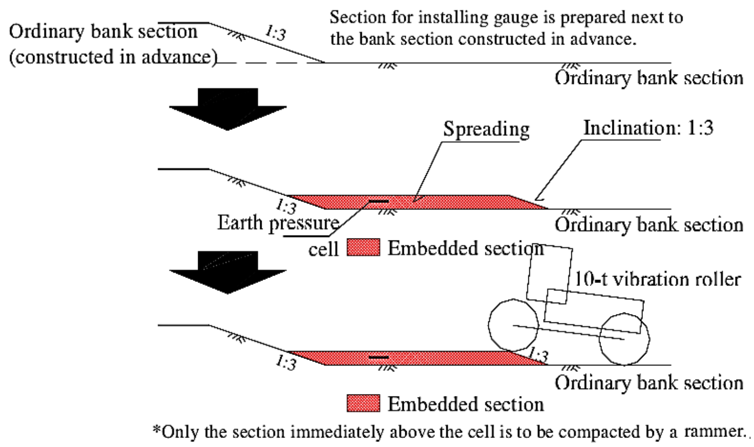

Fig. 7- Embedding cell by spreading soil; Minamiaiki dam (Ref. 4)

As a combination of practical and theoretical method, the installation of a cluster of cells make the recalculation of the rotation possible. In this method, the pressure cells are installed with maximum possible compaction ratio and minimum disturbance of surrounding fill in a cluster form up to five directions. In figure 8, the arrangement of embedded total pressure cells in a cluster of five cells is shown.

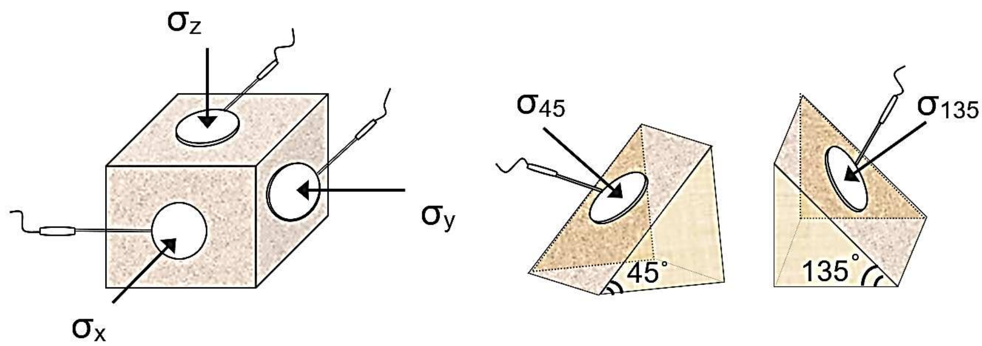

Fig. 8- The angles of embedded total pressure cells in a cluster of five cells.

Since the total pressure cells in one cluster are close enough to each other and adjust equally with the soil mass deformation quite all of them, an equal change of installation angle – the rotation - of whole pressure cells is expectable. Therefore, they can be considered as stresses in different directions for a single point in the embankment.The evaluation of stress ratio (normal stress to lateral stress; σ_{max} and σ_{min}) and the angel of pressure pads (θ) as follows is possible by theoretic recalculating of pressure data. For this reason, the Plain Strain formulation of strength of materials is used. The maximum and minimum principal stresses will be calculated by following equations.

$$\sigma_1 = \sigma_{max} = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau^2_{xy}} \quad (1)$$

$$\sigma_3 = \sigma_{min} = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau^2_{xy}} \quad (2)$$

Lateral stress (σ_x) and normal stress (σ_y) are recorded by total pressure cells which are installed vertical and horizontal. The shear stress (τ_{xy}) is obscure in the equations. To calculate τ_{xy} the equations of plain stress model must be referred to. Therefore, if an element rotates the angle θ, the magnitude of normal and horizontal stresses applied on the plates of this element – Active Pressure Pads- can be derived by following equations.

$$(\sigma_x)_\theta = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + 2\,\tau_{xy} \sin\theta \cos\theta \quad (3)$$

$$(\sigma_y)_\theta = \sigma_x \sin^2\theta + \sigma_y \cos^2\theta - 2\,\tau_{xy} \sin\theta \cos\theta \quad (4)$$

Usually in each cluster of five cells, two total pressure cells exist with angles 45° and 135° relative to horizon. The stress coordinates in a rotated element are present in Figure 9. So by assuming the installation angels 45° and 135° as angle of rotated element (θ) the evident quantities are θ, $(\sigma_y)_\theta$, σ_x and σ_y. The only obscure quantity is τ_{xy}. After calculating the value of shear stress, σ_1 and σ_3 can be derived by equations 1 and 2.

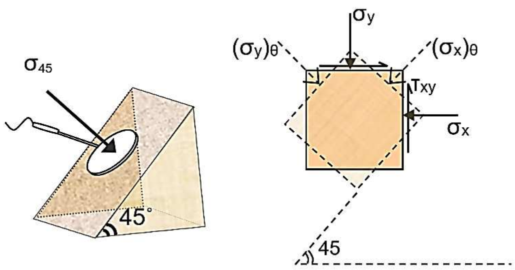

Fig. 9- The normal stresses on the rotated element recorded by the cell embedded 45°

One step further is using the Mohr circle from Mohr-Coulomb failure envelope. By this assumption that the behavior of soil materials is dominated by Mohr-Coulomb failure criterion, there is a possibility to evaluate the direction of total pressure cell and correcting the values of total stresses. With knowledge of stress ratios form the installed pressure cells and using the pole method of Mohr circle, finding the direction of pressure pad is possible. Any straight line drawn from the pole will intersect the Mohr circle at a point that represents the state of stress on a plane inclined at the same orientation (parallel) in space as that line. In figure 10 and 11, the Mohr-Coulomb failure envelope and pole of Mohr circle are shown.

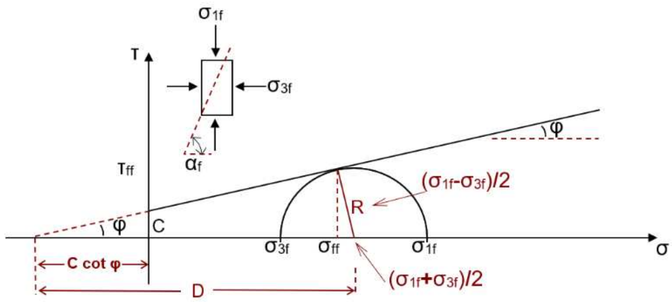

Fig. 10- Mohr circle and Mohr-Coulomb failure envelope for a cohesive soil

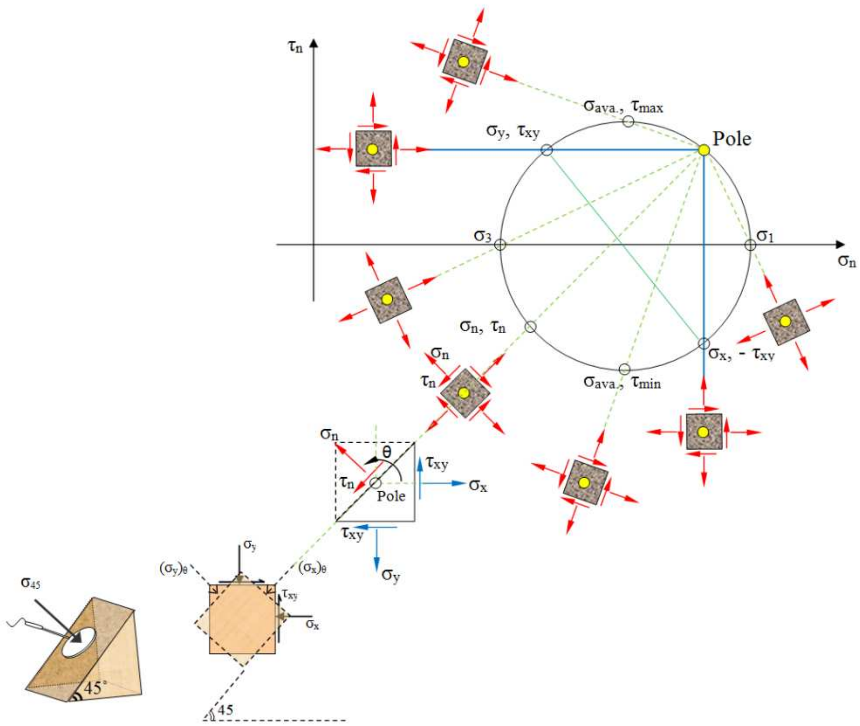

Fig. 11- Mohr's circle for plane stress and plane strain conditions

3.2 The Effective Solution; Measuring the Inclination of Pressure Pad

The idea behind the new instrument for measuring the rotation of total pressure cells was very simple. However, there were many limitations to develop this simple idea. One of these limitations which play a big role in the final product is the geometry of instrument. The first comment for this idea was to combine a total pressure cell with a building inclinometer (fig. 12). In spite of that the selected inclination sensor for the first idea is very accurate, but the geometry of the product was not appropriate for installation in an embankment.

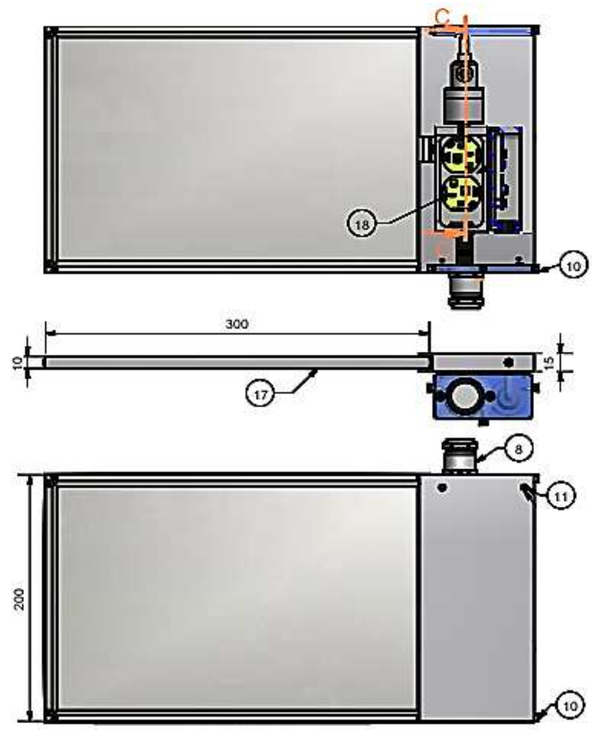

Fig. 12- The first idea for combination of pressure cell with biaxial building inclinometer

The final comment on the idea was an integrated on-board sensor in the available standard heavy-duty housing of pressure insert. The standard available Glötzl heavy-duty housing and its mechanical components present an optimum ratio with active pressure pad. Therefore, the maximum dimensions of the electronic board were limited to 44x14 mm (LxW). The sensor which should be printed on the board can only place in a half-round space with maximum 3,5 mm height (fig. 13).

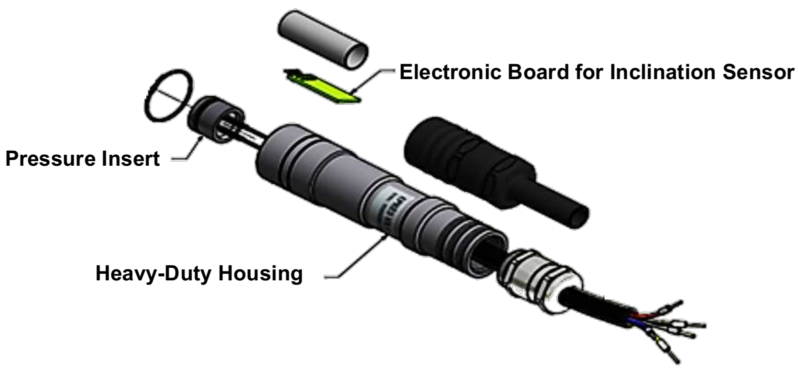

Fig. 13- Integrating an on-board inclination sensor in the standard Glötzl heavy-duty housing

Thank the rapid rise of electronic technologies, there are numerous types of reduced size inclination sensors available on the market. To make a decision for selecting an appropriate precise sensor which is convenient for a thin electronic board, the significant approaches were as follows.

- Dimension of sensor
- Precision and reproducibility
- Long-term stability
- Mechanical shock capacity
- Temperature sensitivity
- Price

The last factor is very decisive. The final price of this product depending on the precision of the sensor should not be expensive and possibly limited to the reasonable value of 30 percent of total pressure cell. On the other hand, the reasonable precision for measuring the rotation of a total pressure cells in an embankment dam are considerably less than a building inclinometer. Therefore, between a wide range of sensors the MEMS-Sensor appears to be appropriate for the reason. The technical specifications of selected biaxial sensor are as follows.

- Type of sensor: Lifetime calibrated MEMS sensor
- Measuring range: ± 30° and ± 90°
- Measuring accuracy: 1 mm / m
- Resolution: 0.06 mm/m
- Mechanical drop shock: 1 m onto a concrete surface
- Temperature operating range: -40°…+125° (limited to the pressure insert -25°…85°)
- Temperature sensitivity: 0.01 % /°C

The next step for actualizing the idea was data measurement with available hand-held readout units. The output signals of the selected sensor are measured in two axes by Glötzl NMA09 and converted to the sinus values (fig. 14).

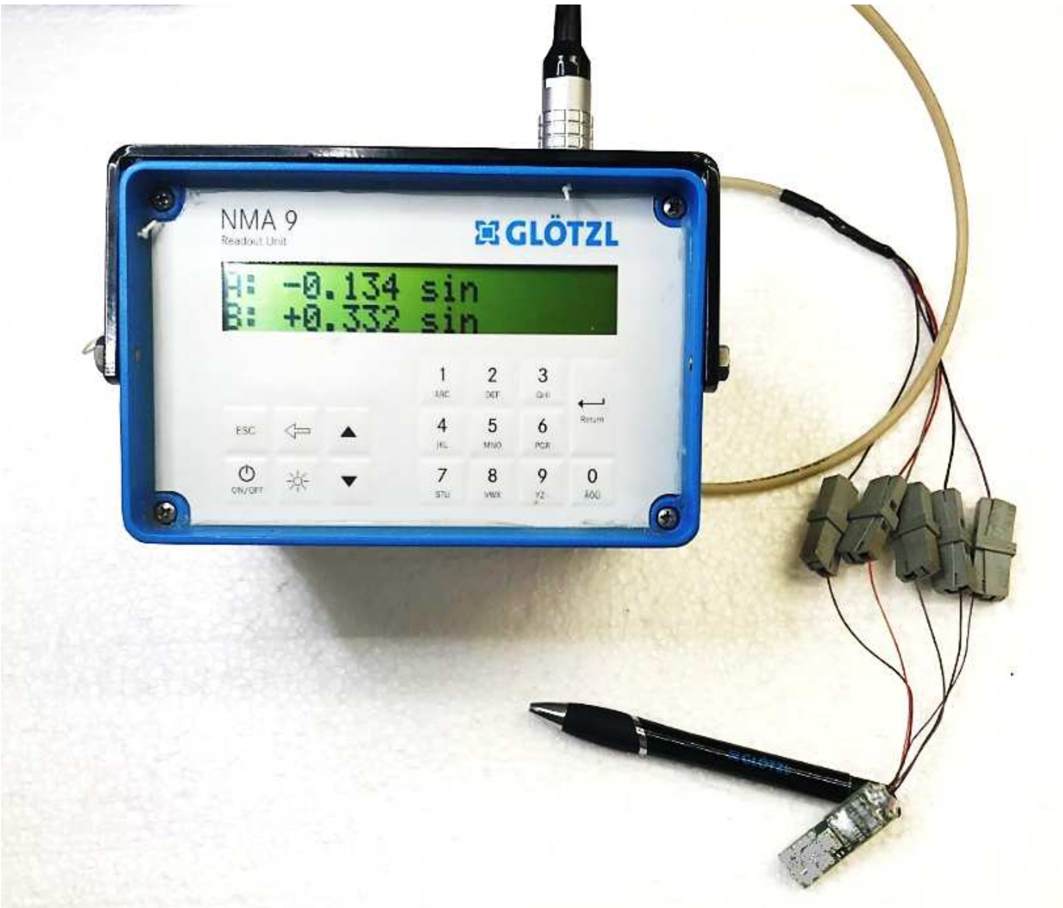

Fig. 14- Glötzl hand-held readout unit for inclination sensors connected to the MEMS

Two most important advantages of this development are sealing and dimensions. The dimensions are limited to the above-mentioned size and could be assembled in whole measuring instruments which include the housing. For example, the settlement gauges, load cells and borehole camera modules. For this reason, it is important to fix the housing with special brackets for preventing any waggle effect. In the fig. 15 the brackets for a total pressure call and a pile load cell are shown.

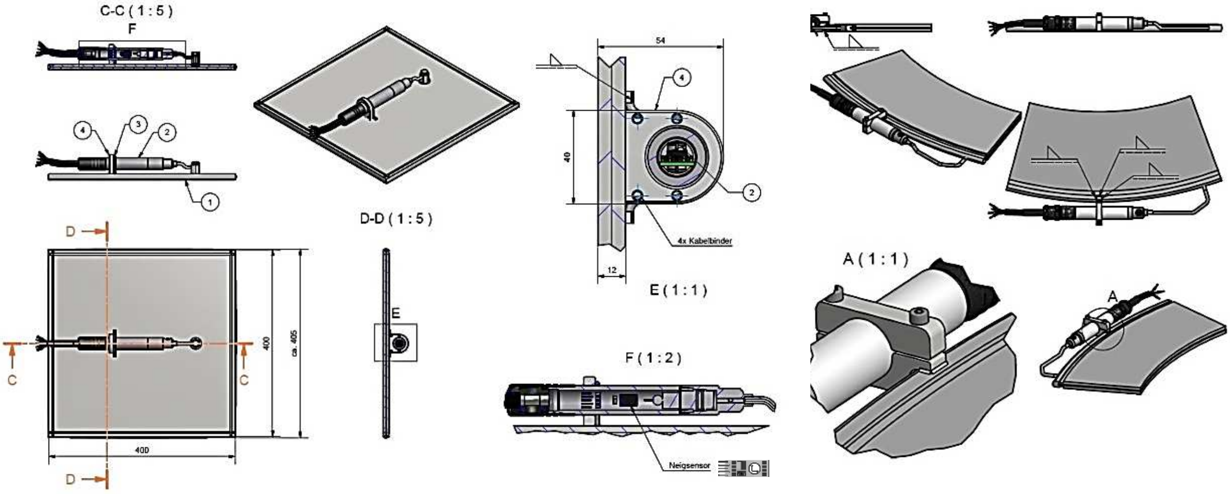

Fig. 15- Special fixing brackets of heavy-duty housing

Since the total pressure cells in a cluster of cells are close to each other, it is enough to equip a total pressure cell with the inclination sensor and making it as reference instrument. For this reason, the total pressure cells equipped with biaxial inclinometer are characterized as Reference Pressure Cell (RPC).

As already mentioned there is no limitation for integrating a biaxial inclination sensor in the housing of whole pressure sensors. Therefore, Glötzl GmbH has developed a new generation of settlement gauges and load cells which are capable to measure the inclination. This possibility helps the engineers to achieve a better understanding of stress status and load distributions in the structures.

4 Conclusion

The installation of reference pressure cells in an embankment enables the engineers to recalculate the normal pressure and verified pressure ratios.

Glötzl GmbH has achieved the success by focusing on mechanical and electrical components of a total pressure cell and trying to find an optimal solution for measuring the rotation of total pressure cells. A Reference Pressure-, Load- or Settlement Cell could be used in various type of projects which need to measure the pressure and the displacement.

An accurate measurement of rotation of total pressure cells installed in an embankment is a grate possibility for geotechnical monitoring for overcoming the uncertainties of stress monitoring. The arching (Ar.) and pore water pressure ratio (R_u) are the critical relationships which are calculated through the knowledge of normal total pressure. It is possible if the rotation of total pressure cell is clear.

Acknowledgements

The authors thank Mr. Leonhard Roller and Mr. Michael Zopf from Glötzl GmbH for their assistance in this project.

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