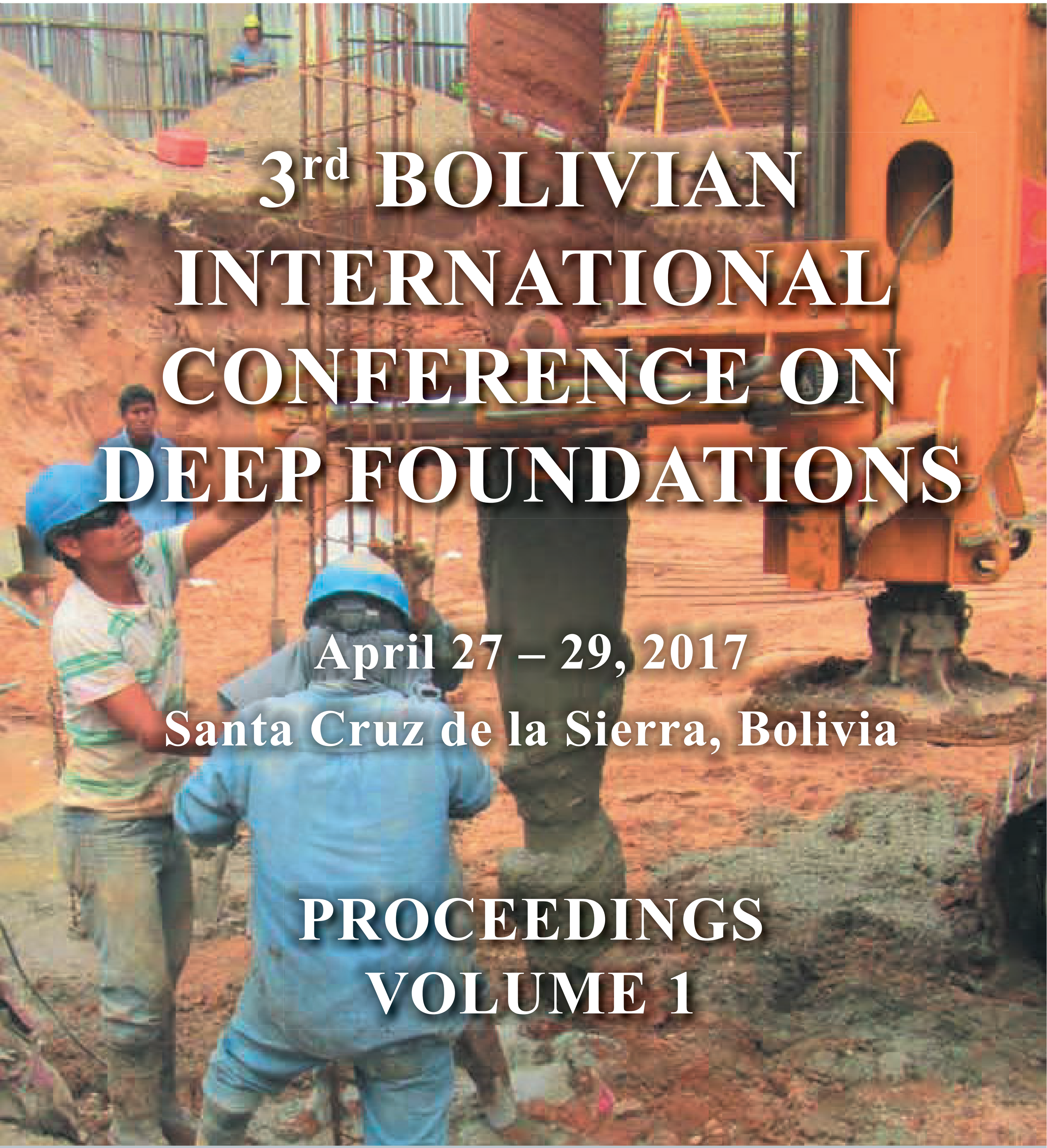

3rd BOLIVIAN INTERNATIONAL CONFERENCE ON DEEP FOUNDATIONS

April 27 – 29, 2017

Santa Cruz de la Sierra, Bolivia

PROCEEDINGS
VOLUME 1

3° C.F.P.B.

3° CONGRESO - SEMINARIO INTERNACIONAL
DE FUNDACIONES PROFUNDAS
DEL 27 AL 29 DE ABRIL DE 2017

SIMSG ISSMGE

PROCEEDINGS
of the
3rd BOLIVIAN INTERNATIONAL CONFERENCE ON DEEP FOUNDATIONS

April 27 – 29, 2017
Santa Cruz de la Sierra, Bolivia

VOLUME 1

Invited Lectures

Edited by

Bengt H. Fellenius
K. Rainer Massarsch
Alessandro Mandolini
Mario Terceros Herrera

Design, execution, monitoring
and interpretation of deep foundation methods

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Volume 1

PREFACE

The 3rd International Conference on Deep Foundations is held April 27 – 29, 2017 in Santa Cruz de la Sierra, Bolivia. It follows two successful conferences held in 2013 and 2015. The conference is organized with the support of INCOTEC SA in association with the Society of Engineers of Bolivia, the Bolivian Society of Soil Mechanics and Geotechnical Engineering and the Chamber of Construction of Santa Cruz. It is held at the UPSA Campus (Universidad Privada de Santa Cruz), the main private university of the city and arranged with the support of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), Technical Committee 212, "*Deep Foundations*".

The principal objective of the conference is to bring together local engineers and international experts in order to facilitate the exchange of experience and to introduce to the region new design concepts, methods and equipment for the application to deep foundations. The conference program is composed of invited lectures, discussions, a field demonstration, and a pile testing prediction event where international experts have been invited to predict the load-movement response of piles in static loading carried out prior to the conference.

During the first two days of the conference, speakers of international repute have been invited to present papers on specific topics, covering different aspects of deep foundations. The third day of the conference is devoted to the presentation and discussion of tests a comprehensive pile testing program. The Bolivian Experimental Site for Testing Piles (B.E.S.T.) was adopted by ISSMGE TC 212 as a reference site for investigations on piles and pile groups. B.E.S.T. offers a unique possibility to enhance the understanding of the performance of different pile types and pile groups when subjected to load. The geotechnical conditions at the B.E.S.T. site have been documented by detailed investigations, using state-of-the art testing and interpretation methods. The results of the field testing programme, including interpretation of in-situ methods and results of the pile loading tests will be presented during the third day of the conference.

Volume 1 of the proceedings comprises the papers presented at the conference. All papers have been reviewed by at least two members of the Review Committee. The dedicated work by the reviewers and their valuable contributions is gratefully acknowledged.

Volume 2 contains a description of the geological setting and the results of comprehensive geotechnical investigations carried out at the B.E.S.T. site. It is the intention of the Conference Organizers to make available all data from the B.E.S.T. site investigations and pile tests in digital format at the conference web platform for use in future investigations, in cooperation with ISSMGE TC 212.

Volume 3 includes a description of the test piles and the loading test programme. The predictions as well as a presentation of test results will be published in a Volume 3 after the conference.

3rd Bolivian International Conference on Deep Foundations

Conference Program

April 27th 2017

8:00-	Registration
8:30-8:45	OPENING SESSION Official opening of conference
8:45-9:45	SESSION 1 **Paul Mayne** (United States of America) Recent developments and applications in geotechnical field Investigations - Session Chairman: Jorge Alva (Perú)
9:45 -10:15	COFFEE BREAK
10:15-11:15	SESSION 2 – “**Bengt H. Fellenius Lecture”** **Frank Rausche** (United States of America). Dynamic Loading Tests: A State of the Art of Preventing and Detecting Deep Foundation Failures Session Chairman: Bengt H. Fellenius
11:15-12:15	Presentation of Invited Papers 1 and 2 **Carlos Santamarina** (Argentina): Casos interesantes de interacción suelo-estructura (Interesting cases of soil-structure interaction). **Tomás Murillo** (Spain): Diseño y ejecución de pilotes con celda de inyección en punta. Aplicación en ríos amazónicos (Design and execution of piles with pile toe injection. Application in Amazonian rivers). Session Chairman: Paulo Albuquerque (Brazil)
12:15-12:45	Opening and overview of Exhibition
12:45-14:00	LUNCH BREAK AND DIGITAL POSTER SESSION
14:00-15:00	Presentation of Invited Papers 3 and 4 **Alan Lutenegger** (United States of America): Recent development in helical piles. **Carlos Medeiros** (Brazil): Energy measurement for CFA piles capacity estimation. Session Chairman: Morgan Nesmith (United States of America)
15:00-16:00	SESSION 3. **Bengt Fellenius** (Canada): Discussion on best practice for performing static loading tests. Examples of test results and relevance to design. Session Chairman: Luciano Decourt (Brazil)

16:00-16:30	COFFEE BREAK
16:30-17:30	SESSION 4 **Joram Amir** (Israel): Testing pile integrity - past present and future. Session Chairman: Victor Hugo Alvarez (Bolivia)
17:30-18:30	SESSION 5 – “**K. Rainer Massarsch Lecture”** **Oscar Vardé** (Argentina): Subway stations retaining walls: Case histories in soft and hard soils. Session Chairman: K. Rainer Massarsch (Sweden)

April 28th 2017

8:30-9:30	SESSION 6. **Dan Brown** (United States of America): State of art and state of practice in deep foundations. Session Chairman: Oscar Vardé (Argentina).
9:30-10:30	COFFEE BREAK
10:30-11:30	SESSION 7. **Alessandro Mandolini** (Italy): Design options for piled rafts **-** An overview. Session Chairman: Juan Carlos Rojas V (Bolivia)
11:30-12:30	Presentation of Invited Papers 5 and 6 **Mónica Prezzi** (United States of America): Effects of installation processes on axial pile capacity **Mario Terceros Arce** (Bolivia): Practical application of new expansion devices for pile improvement in sandy soils. Session Chairman: Walter Paniagua (Mexico)
12:30-14:30	LUNCH BREAK AND DIGITAL POSTER SESSION
14:30-15:30	SESSION 8. **Franz Werner Gerresen** (Germany): Conventional methods and recent developments in retaining walls. Session Chairman: Carlos Medeiros (Brazil)
15:30-16:30	SESSION 9. **K. Rainer Massarsch** (Sweden): Recent developments in vibratory driving and soil compaction. Session Chairman: Bengt H. Fellenius (Canada).
16:30-17:00	COFFEE BREAK

17:00-18:00	SESSION 10. **Jarbas Milititsky** (Brazil): Deep foundations pathologies. Session Chairman: Renato Cunha (Brazil)
20:00	Gala Dinner

April 29th 2017

8:30-9:00	B.E.S.T. Presentation. Alesandro Mandolini (Italy), Chairman of TC212 Bengt H. Fellenius (Canada), Mario Terceros (Bolivia), Paulo Albuquerque (Brazil) and Peter K. Robertson (Canada). Session Chairman: Roger Frank (France), ISSMGE President
9:00-10:15	**Session 1 – Soil Investigation Results. - Memorial Session in Honour of Prof. Silvano Marchetti** SCPT: Peter Robertson (Canada) SDMT: Diego Marchetti (Italy) SPT-T and DPSH: Luciano Decourt (Brazil) PMT: Roger Frank (France) GEOPHYSICS: K. Rainer Massarsch (Sweden) Session Chairman: Paul Mayne (United States of America)
10:15-10:35	COFFEE BREAK
10:35-12:05	**SESSION 2: Pile Installation and Instrumentation** EB and Toe Box: Mario Terceros A. (Bolivia) FDP CFA and Drilled Piles: Morgan Nesmith (United States of America) Micropiles: Mario A. Terceros H. (Bolivia) Helical Piles: Alan Lutenegger (United States of America) Session Chairman: Oscar Vardé (Argentina)
12:05-14:00	LUNCH BREAK AND DIGITAL POSTER SESSION
14:00-16:00	**SESSION 3: Experimental Results and Predictions** Prediction Outcomes: Bengt H. Fellenius (Canada) Pile Group and Piled Raft: Alessandro Mandolini (Italy) Single Piles: Luciano Decourt (Brazil) Session Chairman: Dan Brown (United States of America)
16:00-17:00	**Mario Terceros Banzer Lecture** **Luciano Decourt**, (Brazil):Fifty years designing foundations. A retrospective Session Chairman: Mario Terceros B (Bolivia)
17:00-17:20	CLOSING SESSION

Electrical Resistance Strain Gages in Instrumentation of Deep Foundations

Albuquerque, P.J.R.⁽¹⁾

⁽¹⁾ University of Campinas - Unicamp, Campinas, São Paulo, Brazil <pjra@fec.unicamp.br>

ABSTRACT. The purpose of this paper is to describe some instrumentation techniques for steel piles and for cast-in-place piles by means of strain gages. A brief history of strain gages is presented as well as the theoretical principles that the technique involves, showing the types of connections used in pile instrumentation, indicating the advantages and disadvantages of the use of each type. Determining the load distribution of a pile is the key objective of instrumentation. Therefore, three ways are proposed to analyze the stress data collected. Also procedures for instrumentation and installation of sensors in depth are presented. Instrumentation via strain gage is a reliable technique commonly used in all areas of knowledge. However, it is necessary to adapt the parameters one wishes to obtain to the technique to be used.

1. INTRODUCTION

The use of instrumentation to get parameters of the behavior of geotechnical structures is very frequent nowadays in works such as: dams, slopes, foundations, containments, etc. For each type of work and purpose of the data to be collected and analyzed, a different type of instrumentation is used. According to Dunnicliff (1993), there are two general categories of measuring instruments. The first category covers instruments used for in-situ determination of existing conditions of rock and soil, such as resistance, compressibility, and permeability to be used in projects for which purpose cone tests, vane tests, pressuremeter, etc, are used. The second category is used for monitoring changing conditions during the construction phase and operation, such as water pressure, total stresses, displacements, loads, and deformations.

Over the last decades, instrumentation equipment manufacturers have developed a variety of materials and instruments for geotechnical monitoring. However, it is important to point out that users must be aware of the desired parameters and of the techniques involved in each type of instrument to get reliable and accurate information.

Several types of instruments may be used. In general, the most commonly used are based on change of strain, employing vibrating wire gages, electrical resistance gages, and optical fiber gages. Foundation engineering is constantly trying to learn about the behavior of deep foundations in terms of load transfer. To this end, among the aforementioned techniques, strain gages are used.

This article is a study that aims to describe the technique of instrumentation of deep foundations with the use of strain gages. The article will include both a theoretical approach and practical experience.

2. ELECTRICAL RESISTANCE STRAIN GAGES

Electrical extensometers, also called strain gages, are not recent tools. In the 1930's, Edward Simmons (California Institute of Technology, Pasadena, CA, USA) and Arthur Ruge (Massachusetts Institute of Technology Cambridge, MA, USA) working separately, were the first engineers to use metal wires glued to the surface of a specimen to measure strain. The strain gages included measuring the change of electrical resistance between with two terminals, mounted on a support, having the purpose as an insulator.

Electrical extensometers are sensitive instruments that transform tiny strains in equivalent variations of their electrical resistance. Using electrical extensometers is a means to measure and record the phenomenon of strain as an electrical quantity. When an element is submitted to a determined stress, the ensuing strain is transformed into an electrical signal that is captured, decoded, and then translated into a numerical value.

There are several types of extensometers: inductance and capacitance extensometers, and also piezoelectric extensometers. These showed later to be less successful as resistance extensometers, however, they contributed considerably to the development of measurement of strains.

Current electrical resistance extensometers are wire extensometers and blade extensometers, comprising an electricity conductive metal with large sensitivity to strain. Different from carbon extensometers, these are not sensitive to variations in temperature and humidity. Electrical-type extensometers are used to measure strain in different structures, such as bridges, machines, locomotives, ships etc.

Awareness of internal stress is of great importance, since it is through stress that structures are sized. The stress *vs*. strain characteristic of structural materials, such as steel, is sufficiently well understood nowadays for most practical applications.

Strain depends on the stress applied and the limitations of the specimen. The characteristics of the specimen material are resistance threshold, proportionality threshold, and yield point.

Strains caused by the action of loads or other external influences or by own weight, can be measured with extensometers, same as distortion, which is an angular variation, although with a certain complexity in comparison to measurement of linear strain. As most calculations are based on stress, it is necessary to transform the effect of strains so they can be measured as stress. The total strain in any direction comprises three portions: strain caused by variation in temperature; strain due to Poisson effect, and primary strain which is stress in the direction of the imposed load.

As the device is glued to the surface and the part deforms, the value of its electrical resistance changes proportionally; then the key problem here is humidity. However, gluing and sealing techniques protect these sensors against humidity and protects against zero drift.

Sensitivity to temperature variations is one of the most important factors to be considered when using strain gages due to two key factors: the difference in elongation among the part, the grid support and the grid itself, and the variation in resistivity depending on temperature.

Results may vary as the temperature changes while strains are measured. The change in temperature influences the material's linear expansion and that of the extensometer wire, besides the specific resistance of the wire, as shown in Eq. (1) which will serve both for free expansion of the extensometer and for the material:

$$\Delta L = L_0 \alpha \Delta t \tag{1}$$

where:

ΔL = variation in length both of the extensometer wire and of the specimen
L_0 = initial length
α = material expansion coefficient, or resistivity coefficient
Δt = variation in temperature

To minimize the effects of temperature variation regarding of environment, different types of assemblies of strain gages can be used in resistive bridges, such as: 3-cable assembly (1/4 bridge), 2-cable assembly (half bridge), and full bridge.

The strain measured by the extensometer must be the same as the strain experienced by the element studied. The imposed strain is proportional to the change of the measured change of resistance via a gage factor as indicated in Eq. 2.

$$\varepsilon = \frac{\Delta L}{L} = \frac{\Delta R/R}{K} \qquad (2)$$

where: ε = total strain
ΔL = variation in length
L = initial length
ΔR = variation in resistance
R = resistance
K = strain gage-factor, which ranges from 1 to 200 (commonest value is 2.0),
R = 60 – 10,000 Ω, (commonest value is 120 Ω or 350 Ω).

The variance of resistance caused by a change of strain is determined by a Wheatstone bridge. A device having four resistors connected two by two in parallel as shown in Figure 1.

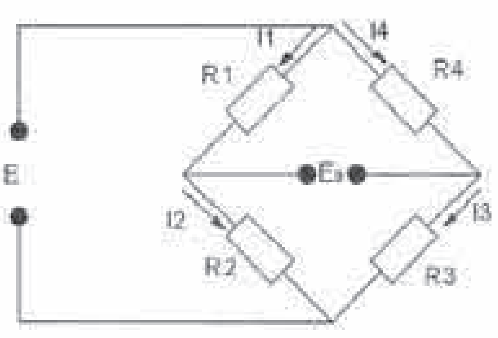

Fig. 1. Wheatstone bridge.

Using Eq. 2 and the principle of the Wheatstone bridge, we get to the generic Eq. 3:

$$\frac{\Delta R}{R} = K\,(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \qquad (3)$$

where: ε_1 = strain due gage one
ε_2 = strain due gage two
ε_3 = strain due gage three
ε_3 = strain due gage four

Being:

$$\varepsilon_i = \varepsilon_t + \varepsilon_f + \varepsilon_n \qquad (4)$$

Where: ε_t = strain due to temperature
ε_f = strain due to bending
ε_f = strain due to normal stress

Among the characteristics of electrical resistance strain gages are high measuring accuracy, excellent dynamic response, and excellent linearity; they can be used immersed in water or in corrosive gas atmospheres provided that the suitable treatment is made; remote measurements can be made, etc. Because of such characteristics, this sensor has many applications in experimental studies.

2.1 Types of circuits

Several types of circuits can be used in various areas. The type to be used will depend on the property that one desires to obtain (momentum, resistance, torsion etc). Figures 2, 3 and 4 shows the most commonly used types of circuits.

A) Half-bridge circuit with one active branch (Eq. 5):

$$\Delta Vd = \frac{VK}{4}(\varepsilon_1) = \frac{VK}{4}(\varepsilon_t + \varepsilon_f + \varepsilon_n) \qquad (5)$$

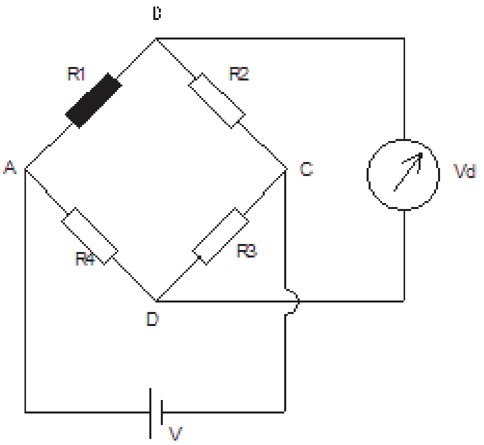

Fig. 2. ¼ bridge with one active branch.

- ¼ bridge with 2 wires: In this type of connection, the strain gage signal could be affected by variations in resistance of the cable because of temperature and change in length. Depending on the cable length, the instrument will not be able to balance the bridge. Calibration will be incorrect: the more incorrect, the greater the cable resistance. The advantage of this type of connection is the use of a smaller number of cables. The application of this connection is indicated for places with controlled temperature, short cables with a large diameter, and short-term tests. For this type of circuit, absence of bending and temperature change are required.

- ¼ bridge with 3 wires: The bridge balance is independent of cable length, but the cable must have constant length and cross section; also the wires must be twisted with each other. When the installation gets irradiation heat and the three cables are exposed, they must have the same color, because the objects that absorb more colors within the spectrum create more heat, if the wires have different colors they can affect the bridge balance. It must be pointed out that the variation in cable resistance as a function of temperature does not impact the measurements. The triple wires can cross places with high thermal variation without impacting the measurements. This type of connection is very commonly used in cases of long cables and large temperature variations along its length. It is indicated for long-term tests. In this type of connection, the effect of temperature is eliminated but the effect of bending is not.

B) Half-bridge circuit with two active branches (Eq. 6).

$$\Delta Vd = \frac{VK}{4}(\varepsilon_1 - \varepsilon_2) = \frac{VK}{4}(2\varepsilon_f) \tag{6}$$

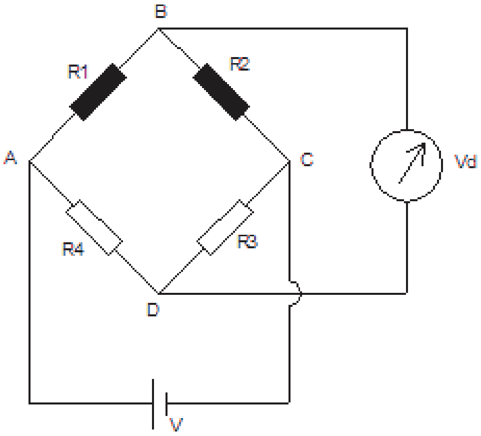

Fig. 3. ½ Bridge with two active branches (adjacent arms).

This type of connection is suitable to situations of long-term tests with large thermal variation. In this type of connection, the effect of temperatures and axial strength is eliminated. The readings of strains will be due to bending only. The signal is amplified two times.

C) Full-bridge circuit with four active branches (Eq. 7).

$$\Delta Vd = \frac{VK}{4}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) = \frac{VK}{4}\varepsilon_n 2(1+\nu) \tag{7}$$

where: ν = Poisson ratio

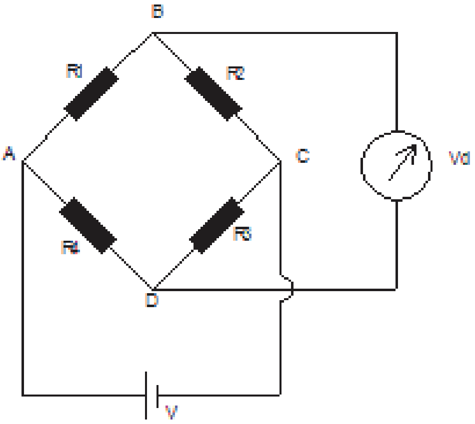

Fig. 4. Full bridge with 4 active branches.

- This type of connection is the most suitable one to be used in situations of long-term tests with large thermal variation of strain gages where it is necessary to eliminate the bending effect. In this type of connection, the temperature effect is also eliminated.

2.2 Principles of analysis

The following examples will clarify how to apply the technique where a full bridge connection with four active extensometers was used, so effects of temperature and bending strains were eliminated and only strains from normal resistance were obtained.

The operational principle is simple: strain (ε) was measured for a pile element with a cross section area, A, due to an applied increase of load was measured. Using Hooke's Law, we get Eq. 8.

$$P = AE_c\varepsilon \tag{8}$$

where: P = load in the cross section
A = area of the pile cross section
E_p = pile modulus
ε = strain measured

By placing gages at selected depths in the pile, we obtain load at various depths and the load distribution. Using Hooke's Law, we get the Young modulus in the pile's reference section and, from that value on, the loads at each instrumented level are obtained. The slope of the load versus strain diagram shown in Figure 5 is the pile axial stiffness, E_pA. N.B., the stiffness is obtained without input of the pile cross section, which is a variable for cast-in-place piles.

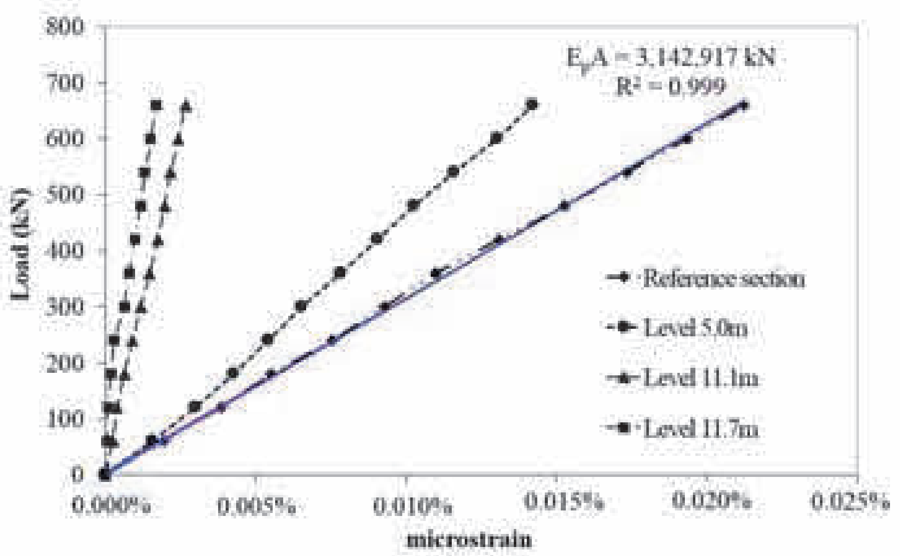

Fig. 5. Load *vs*. microstrain graph.

For the example of Fig. 5 in which product E_pA is equal to 3,142,917 kN, the effective diameter of the pile (bored with mechanical auger) was 0.44 m in average ($A = 0.152\ m^2$). This way, the Young modulus is about 20.7 GPa.

Another way to analyze the instrumentation data is given by Fellenius (2016), using the method of tangent modulus as indicated in Eq. 9.

$$M_t = \left(\frac{d\sigma}{d\varepsilon}\right) = a\varepsilon + b \tag{9}$$

By integrating Eq. 9, we get to Eq. (10)

$$\sigma = \left(\frac{a}{2}\right)\varepsilon^2 + b\varepsilon \tag{10}$$

Eq. 11 shows the basic equation to calculate stress

$$\sigma = E_s.\varepsilon \tag{11}$$

Equaling Eqs. 10 and 11, we get Eq. 12.

$$E_s. = 0{,}5a\varepsilon + b \tag{12}$$

where: M_t = tangent modulus of composite pile material
E_s = secant modulus of composite pile material
σ = stress of the pile cross section
a = slope of the tangent modulus line
ε = measured strain
b = ordinate intercept of the tangent modulus line

Figure 6 shows an example of application of the tangent modulus. The data used to get this figure were the same as those used in Fig. 5.

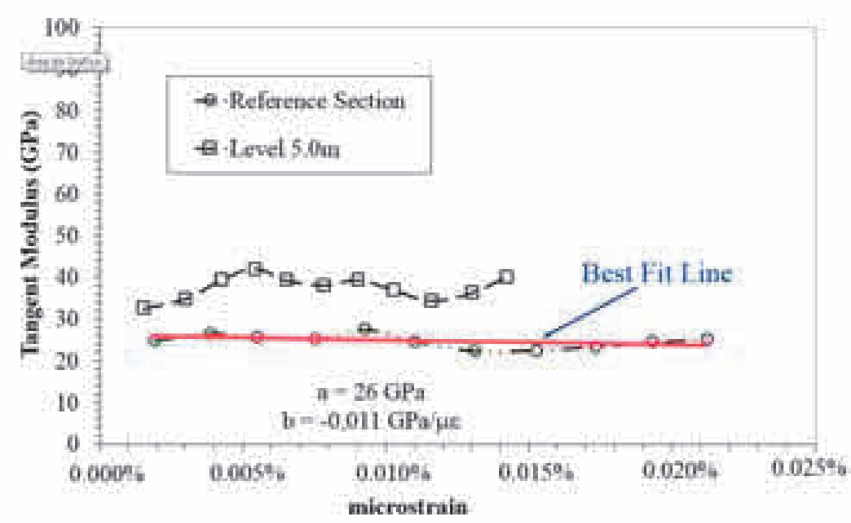

Fig. 6. Tangent Modulus *vs.* microstrain graph

From the results shown in Fig. 6, a constant modulus of the order of 24.8 GPa (average) was obtained.

As the strain gage level lies close to the pile, it is possible for determining both secant and tangent modulus. The Fig. 7 shows that the tangent plot a bit of scatter, and the secant modulus is less sensitive to such variations with a smoother curve, even though requires a well-established zero level (Fellenius, 2016).

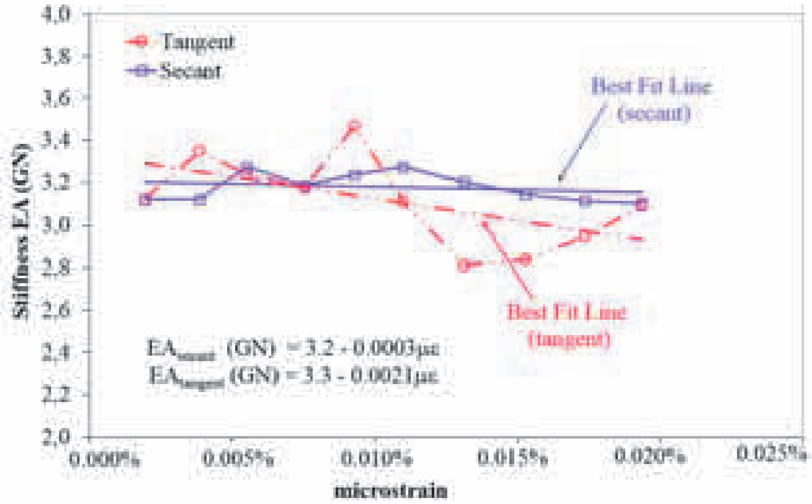

Fig. 7. Comparison between stiffness determined from tangent and secant modulus approaches

The analysis of the strain records produced the load distributions shown in Figure 8.

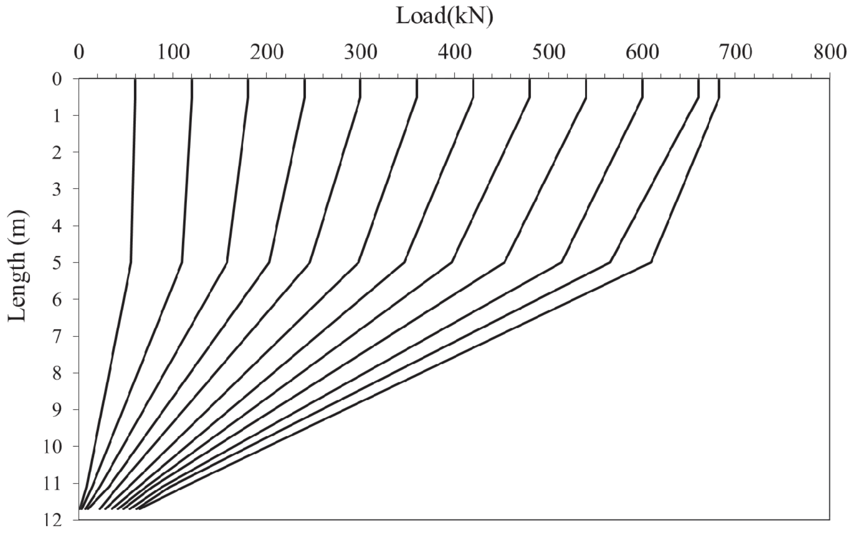

Fig. 8. Load transfer in depth (Albuquerque et al. 2011).

3. INSTRUMENTATION APPLIED TO PILE FOUNDATIONS

The experience is vast in the use of instrumentation via strain gages in pile foundations. In general this technique involves instrumenting a steel bar that may or not be part of the pile cage in the case of pre-cast or cast-in-place piles. For steel piles, the instrumentation must be made directly on the metal profile. Below is a simplified presentation of the instrumentation processes.

3.1 Concrete Piles

As a general rule, the technique of installing instrumented bars inside the pile is used for this type of piles, the difference being the executive procedure of the pile. In general, the instrumentation is carried out with construction steel bars with 12.7 mm or 19.0 mm diameter, depending on the diameter of the cross section of the pile. It is not appropriate using large cross section steel bars in piles with small cross section, because the installation process can be arduous.

The manufacturing sequence of full-bridge bars is shown below. When preparing the bars, it is important to know at what levels the bars will be placed so as to have appropriate cable lengths. The cables to be used have 4 paths (full bridge connection), and must have a minimum cross section area of 0.5 mm^2 and an outer protective coating (PVC) and an inner protective lining with twisted tin copper (Figures 9 - 14).


Fig. 9. Preparing the steel bar surface

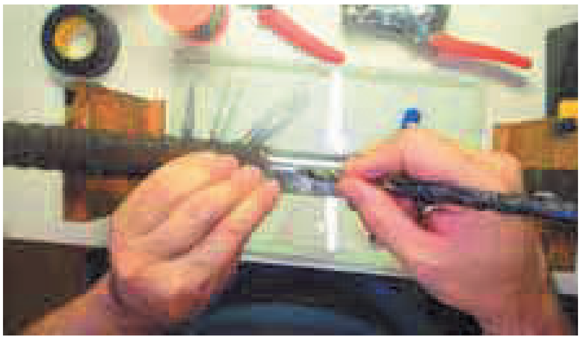
Fig. 10. Marking the place to glue the strain gage


Fig. 11. Gluing the strain gage


Fig 12. Wheatstone bridge connection


Fig 13. Checking the bar on a tensile testing press


Fig 14. Instrumented bar guide

Once the instrumentation steps are over, the procedures for field installation start. In cases of piles where the concreting is executed after insertion of the reinforcing cage, it is possible to fasten the instrumentation on the cage (Fig. 15). Details of the installation technique have been presented by Freitas Neto (2013), Polido et al. (2014), and Garcia (2015).

Fig. 15. Fastening the instrumented bar in the pile reinforcing cage

Gages can be installed in continuous auger flight piles or full displacement piles by inserting a steel tube (smooth or corrugated; with external diameter of approximately 50 mm). For continuous auger flight piles and full displacement piles, the tube is inserted before the pile is drilled. Figure 16 shows the tube to be placed into the shaft of the continuous flight auger pile. Figure 17 shows the tube extending above the pile head after completed installation (Albuquerque 2001).

Fig. 16. Tube being placed in the pile

Fig 17. Tube after the pile is constructed

After the pile is completed, the instrumented bars are installed at the predetermined levels inside the tube and the tube is grouted. The 500 mm bars are connected and placed inside a galvanized tube in a predefined position to form a continuous bar. To make it possible to splice the bars, a threading system of the ends is used with coupling of sleeves of the same material (Fig 18). After placing the bars inside the tube, it is filled with cement slurry with water / cement factor equal to 0.5. Fig 19 shows the finished process.


Fig 18. Bar splicing


Fig 19. Finished installation

Once the bar installation is completed, the step of forming and casting of the pile cap starts. Fig. 20 shows the details. We can see the black side tube used as exit for the instrumentations cables. Fig. 21 shows the cables coming out on the side of the pile crowning block at the time of the loading test.


Fig. 20. Preparing the crowning block.


Fig. 21. Completed block

3.2 Steel piles

For this steel piles, the instrumentation must be carried out on site by gluing the strain gages to the pile section (Albuquerque and Melo 2014; Albuquerque et al. 2016). These spots must be arranged so as to supply information from different depths as required.

The sensors are directly adhered (by cyanocrylate) to the core, after treating the surface with a degreasing product. Strain gages are guarded against humidity and mechanical shocks by means of a silicone resin, adhesive tape, and electrical guarding resin, besides epoxy resins and metal fishplates in the section made of metal profiles.

The metal profile must be installed in several steps:

- ✓ Welding of metal fishplates at the joint between the base and the core of the metal profile in order to provide protection against mechanical shock when the metal profile is driven (figure 22) and cables are passed through;

- ✓ Cleaning and treating the surface of the metal profile to be fastened to the extensometer later on;

- ✓ Fastening the sensors (Figure 23) and applying resin to protect strain gages from humidity and mechanical shock;

- ✓ Closing the instrumentation levels between the metal fishplates with epoxy resin for protection against mechanical shock when driving the piles;

- ✓ Fastening electrical cables, which are connected to the strain gages along the instrumentation levels of the metal segment in the upper part of the metal profile.

- ✓ Lifting and driving the metal profile must be performed with utmost care so as not to break the cables.

Fig 22. Guarding fishplates.

Fig 23. Strain gage fastened to the surface

While the pile is being driven, it is possible to get the strains resulting from each instrumented level. To do so, a data acquisition system must be used to collect data with a minimum frequency of 10 Hz. Fig. 24 shows the variation in strain obtained for each blow of the hydraulic hammer at the level of the pile head when the pile driving is completed.

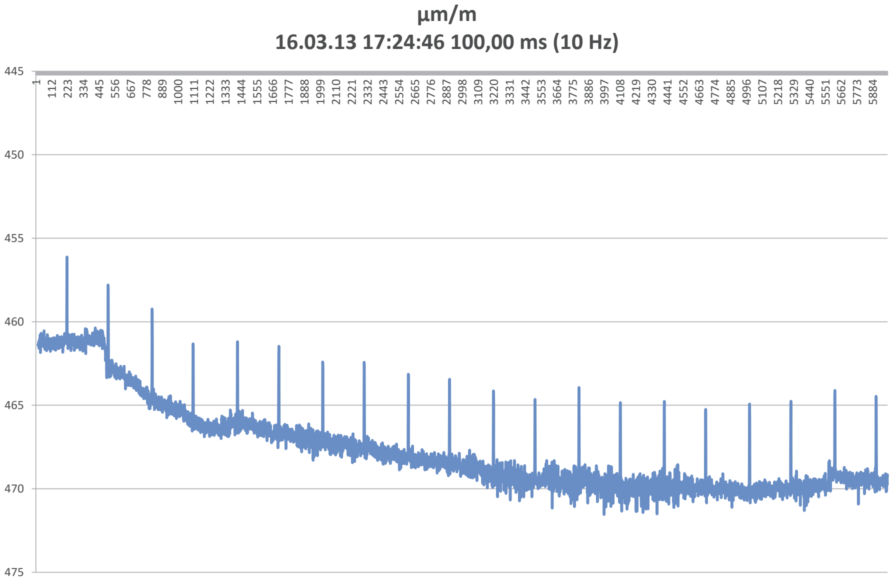

Fig. 24. Strain of each blow of the hydraulic hammer.

With this type of piles, the strains are obtained during and after driving. The value of residual load can be obtained prior to the execution of the slow maintained load test.

4. FINAL CONSIDERATIONS

- The instrumentation technique via strain gages is widely used from medicine through engineering, which proves that the technique is reliable. However, lack of theoretical and practical knowledge may lead to unreliable results;
- Using strain gages to get strains and loads in deep foundations is a reliable technique that can be applied to practically all types of piles;
- It is important to stress that the type of connection to be used (full bridge, ½ bridge or ¼ bridge) must be carefully considered so as to get highly reliable data;
- The instrumentation in cast-in-place piles or pre-cast piles (steel or concrete) is more effective when the bars have been previously instrumented at the laboratory, and are installed on site. In the case of continuous flight auger piles or another similar type of concreting, a different installation technique should be used;
- In the case of steel piles, direct instrumentation in the profile proved to be appropriate; however the procedure must be carried out on site and very carefully since preparation of the surface, cleaning and gluing the sensors are key considerations for success. Another factor that requires attention is during pile driving, since cables may get damaged and jeopardize the entire process.

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