THE USE OF SMART SENSORS FOR TESTS OF LOADED CONCRETE PILES

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Abstract - *A lot of geotechnical engineering problems can be analysed in situ with tests of horizontal and vertical loaded piles. These are required, for instance, to study the behaviour of piles isolated and in groups. Based on the emergent concept of "smart sensor" a unit was developed that converts the deformation of the concrete pile measured by an LVDT on digital information. This unit is integrated on a local area network supervised by a command unit located at the surface. The communication protocol is based on a master-slave structure supported by dedicated developed commands.*

Keywords – Smart sensor, LVDT, communication protocol, test of loaded concrete pile.

1. LOAD TEST FOR GEOTECHNICAL PURPOSE

The project of concrete piles is a complex task because many of the relevant parameters are not exactly known as the behaviour of each pile depends on the surrounding soil characteristics. This situation can be improved with in situ tests of vertical and/or horizontal loaded piles. This kind of tests consist in applying a force to the head pile and measure: 1) the force applied to the head pile; 2) the head pile displacement; 3) the force distribution along the pile; and 4) the force at the base of the pile. The applied force and the head displacement are measured at the surface, the first using a cell force and the second displacement sensors, like LVDT (Linear Voltage Differential Transducer) or optical rotary sensor. The force, F (N), along the pile is evaluated by measuring the deformation and applying the Hooke's law (1), where A is the cross area of the pile (m^2), E, the Young coefficient (N·m^{-2}) and ε, the deformation (m·m^{-1}).

$$F = A \cdot E \cdot \varepsilon \qquad (1)$$

The force at the base can be measured in the same way, with a measuring point close to the pile base, or by subtracting all the forces measured along the pile to the force applied to the head pile.

1.1 The Old Measuring System at LNEC

The system represented at Fig. 1 was developed at the portuguese National Laboratory of Civil Engineering (LNEC) twenty years ago. The measurement of the pile deformation under test was obtained with strain gauges fixed on the internal wall of a steel tube, installed at the same time as the concrete reinforcement. Signal and power lines flow inside the steel tube until they reach the surface were connected to the data acquisition system and power supply. A computer also responsible to process, visualise and store the data controlled the data acquisition and the force applied to the head pile. Besides deformation, others quantities are important to be known: 1) displacement of the reaction piles; 2) rotation and deformation of the reaction structure; 3) concrete and ambient temperature; 4) pressure on the hydraulic circuit.

Although good results are obtained with this system, it has some drawbacks: 1) a long time is needed to prepare the equipment; 2) the applied instrumentation is lost (not reusable); 3) it is not possible to repair or to change a measuring point after applying the concrete; 4) it is difficult to insert the steel tube inside the pile; 5) the number of measuring points is limited by the available space to make way for conductors inside the tube; 6) disturbance of the normal civil engineering works.

A – hydraulic actuator; B – cell force; C – displacement sensor

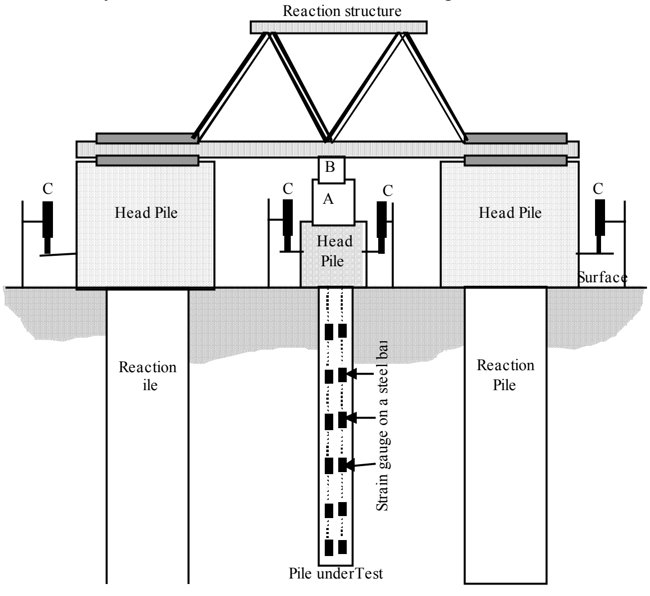

Fig. 1 – A schematic of a vertical load test (not at scale).

1.3 The New Measuring System

To overcome the above referred drawbacks it was decided to develop a new system that allows the instrumentation reusage and minimises the disturbance of civil engineering works. The measuring system is placed in position after the civil engineering works being finished; only the steel tube is installed at the same time as the reinforcement.

The new system is made up of several "units" from now on referred to as "extension units". Each unit evaluates indirectly the extension of the pile using a LVDT (Fig. 2).

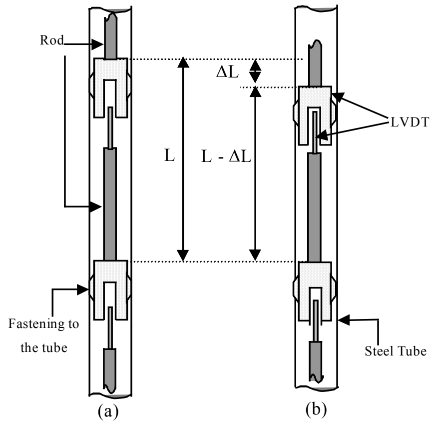

Fig. 2 – Measuring unit: (a) before deformation (b) after deformation.

The average extension $\bar{\varepsilon}$ between two neighbour units is calculated using (2), where ΔL is the length variation measured by the LVDT and L is the length of the rod.

$$\bar{\varepsilon} = \Delta L / L \qquad (2)$$

The distance L between two successive units can be one or two meters long. The maximum extension expected is ±1000µm/m, which means that the maximum value expected to be measured by the LVDT, is ±2mm (LVDTs used have full-scale values of ±2.5mm).

Each extension unit is firmly fixed against the steel tube using a mechanical fastening device, activated through a pneumatic circuit.

Basically, the measuring system is made up of a command unit, a power supply, a valve driver, a microcomputer and several measuring units (Fig. 3). The measuring units are the extensions units, used to measure the pile deformation as previously described, and the surface units, used to measure the force applied to the head pile, the head displacement, the rotation, the temperature and the hydraulic pressure. Each measuring unit is connected to the command unit by a parallel bus that carries data and power supply. The command unit, installed at the surface, rules the bus protocol, data flow and data storage and constitutes the interface between the computer and the test equipment. It also controls the applied force to the head pile, through the valve driver.

This paper describes the implementation of the smart sensors used in the extension units including self-calibration and network facilities and the results achieved so far.

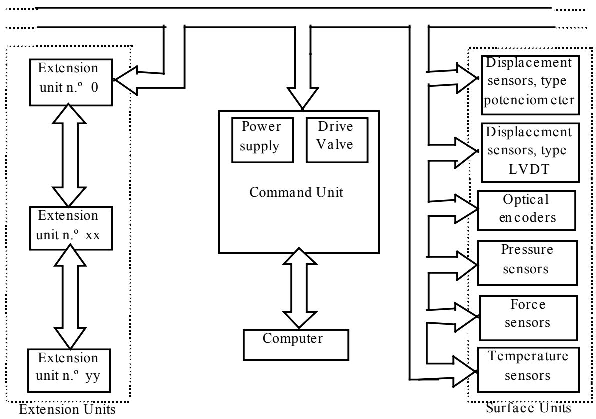

Fig. 3 – Measuring system.

2. EXTENSION UNIT – A SMART SENSOR

The extension unit is a smart sensor (cf. block diagram in Fig. 4) that includes a transducer to transform the deformation into an electrical signal and all the electronic circuitry used to convert the analog signal into digital data and transmit it to the surface. The circuit itself is implemented using SMD (Surface Mounted Devices) components in a 20x110 mm card.

a) The deformation sensor is an LVDT produced by RDP Electronics (D5/100K), and the signal conditioner is AD598JR produced by Analog Devices. The AD598JR includes a low distortion, amplitude-stable sine wave oscillator to drive the primary of the LVDT and an asynchronous demodulator to convert the LVDT output amplitude and phase to position information. A differential amplifier before the Analog to Digital Converter (ADC) reduces its output signal.

b) A microcontroller ADuC824XS controls all activity at the unit: acquisition, protocol communication, error detection, self-test and data processing. Besides, it includes: two ADCs, with 24 and 16 bits; a UART (Universal Asynchronous Receiver Transmitter); a on-chip temperature sensor; three 16 bits timers/counters; 26 I/O lines; 8 kByte FLASH memory for program, 640 Byte FLASH memory for data and 256 Byte of RAM.

c) The interface to the data bus is implemented using a RS485 transceiver (MAX3082CSA).

d) There are three local power supplies at the unit: two for the analog circuits and one for digital circuits.

2.1 Operation

The presence of a microcontroller per smart sensor allows additional features to the sensor:

2.1.1 Self-Test

The self-test is executed: 1) at the beginning of the measuring procedure; 2) when the unit receives a Diagnostic order from the command unit; 3) when a switch in the unit is put on the position ON (local order). This self-test procedure produces information regarding malfunctions that may possibly exist as well as their identification. The tested parameters are:

- Analog and digital microcontroller power supply values;
- Clock signal applied to the microcontroller;
- Voltage reference value;
- Offset and gain compensation for both converters;
- An acquisition for deformation and another for temperature are executed in order to test if there is any malfunction to report (overflow, for example);
- Calibration table existence for both channels (deformation end temperature);
- The values of deformation and temperature previously acquired are now processed with the calibration table and it is investigated if there is any malfunction to report.
- Excitation signal for LVDT (frequency and voltage);

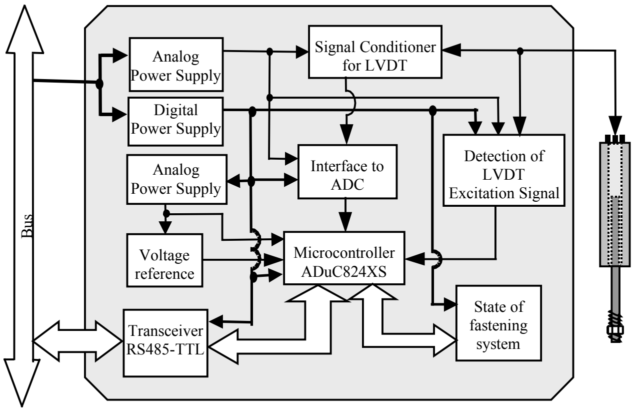

Fig. 4 - Diagram block of an extension unit.

The test results are saved in two 16-bit variables at the microcontroller RAM within the unit and may be sent at any time to the command unit. Each bit reports a test result. In case of malfunction, and to expedite the debug task, this information may also be watched locally through a sequence of LED pulses.

2.1.2 Calibration Table

For each channel, there is one calibration table that can be built or update at any time and that is required if data is to be processed locally. The maximum number of points is respectively: 101 for the deformation channel and 51 for the temperature. Each calibration point at the table uses two bytes for the reference and two bytes for the measured voltage. At the calibration table it is also saved the date, calibration temperature and the operator identification (one byte).

2.1.3 Data Processing

The data processing uses the acquired data and the calibration tables to convert it, through linear interpolation, into mm or ºC. The microcontroller starts by finding the section where the data value, W, is stored and finally computes the value V using (3).

$$V = \frac{\left[\left(Y_{n+1} - Y_n\right)\cdot\left(W - X_n\right)\right]}{\left(X_{n+1} - X_n\right)} + Y_n \qquad (3)$$

with $X_n < W \le X_{n+1}$

and $Y_n = \text{Table}(X_n),\ \ Y_{n+1} = \text{Table}(X_{n+1})$

The mathematical operation is executed in binary format (integer type) and fixed point. All operators X_n, X_{n+1}, Y_n, Y_{n+1} and W are 16 bits long; V is 32 bits long but the two most significant bytes at normal conditions are null. To avoid eventual overflow situations an error control is executed at the end of all partial operations.

2.1.5 Programming In-Circuit

The smart sensor has its address and identification saved at the program memory (flash memory) to ensure that they are not modified by accident. To change them it is necessary to reprogram the microcontroller.

3. NETWORK

The LAN (Local Area Network) implemented is based on the RS485 standard. The main reasons for this choice were: cost; simplicity of the LAN itself as well as of the interface to the microcontroller; baud rate; line length; number of units; and complete control over the protocol communication.

The LAN implements three layers of OSI (Open Systems Interconnected) reference model: physical, data link and application.

3.1 Physical Medium

At the physical layer, the network satisfies the RS485 specifications (maximum number of units that can be connected to the bus, as well as the maximum distance).

The bus uses a cable with twisted conductors, two for power and two for data. The section of the conductors and the voltage supply are dimensioned to guarantee a voltage between $14.75V_{DC}$ and $20V_{DC}$ at the entry of all units connected to the bus.

3.2 Communication Protocol

The protocol implemented follows the model master/slave, with the command unit as master and the measuring units as slaves. The command unit controls the bus and is the only device that has full access to it. All the measuring units (at the surface and at the extensions units) interact with the protocol the same way: at a certain time only one is allowed to accede to the bus. The command unit identifies each measuring unit by its unique bus address. Besides, all units have embedded an identification tag (ID) reporting the sensor type, and the serial and version numbers.

The communication is half-duplex serial with a baud rate of 19200 baud; each character transmitted is formed with a start bit, eight data bits, even parity and a stop bit.

The communication is initiated by the command unit that sends a *message* (command) to the measuring unit, which is then allowed to send back the *response* (message). The *message* and *response* format is shown in Fig. 5.

(A)

Byte 0	Byte 1	Byte 2	Byte 3	Bytes 4 … n
Start message	Number of Bytes Message	Address	Command (option)	Data (option)

(B)

Byte 0	Byte 1	Byte 2	Bytes 3 … n
Start response	Number of Bytes Response	Address	Data (option)

Fig. 5 – (a) *Message* and (b) *Response* format.

As we can see the message and response format are quite similar. The byte *start message* and the byte *start response* are the same and equal to code 80H; it is used to synchronise all units with the reception. The byte *number of bytes message/response* represents the number of bytes that message/response transports and is for synchronism too. The address byte used by the message is used to select the measuring unit; this byte, at the response, serves to confirm its origin. The first three bytes must always exist either at the message or at the response; the others bytes can exist or not, but if a message has data bytes it must have a command byte too.

When the measuring unit receives a message it must always send a response, except when the message is addressed to all units connected to the bus (broadcast message). The broadcast messages are used to synchronise a task at all units and to reduce the data flow in the network.

Between the message end and the response start there must be a minimum pause of 0.5ms with no more than 2ms.

3.2.1 Messages

The change of information between command unit and the measuring units is supported by a group of messages:

- *Presence* - to detect if one measuring unit is connected to the bus and responding correctly;
- *Identification* - to get the unit identification;
- *Acquisition* (*) - to order an acquisition. It is necessary to give the analog channel identification and the number of samples;
- *Programmable Acquisition* (*) - to order a time sequence of acquisitions; similar to the previous; in addition it is necessary to send the time between acquisitions;
- *Send Data* - to receive the most recent data acquisition from the measuring unit;
- *Diagnostic* (*) – to order a self-test;
- *Send Diagnostic* - to receive the tests results from the measuring unit after sending a message diagnostic;
- *Start Calibration* - to start the calibration task;
- *Save Point* - to calibrate a point and save it on the calibration table. It is necessary to give the calibration point number and the reference value;
- *End Calibration* - to end the calibration task;
- *Clean Table* - to eliminate the calibration table of one analog channel;
- *Send Table* - to receive the calibration table of one analog channel, that is saved at the unit;
- *Status* - to get information about the state of the measuring unit: mainly information about errors, acquisition progress and state of the microcontroller.

The messages marked with (*) may be sent in broadcast mode; in this case the address is the code 26H and there isn't any response. The message *status* has maximum priority, which means that is the only one that can stop the execution of a microcontroller task. For all the others messages the processing is conditioned to the "non busy" state of the microcontroller.

3.3 Detection of Transmission Errors

The detection of transmissions errors takes place at both the command and measuring units and happens at the physical and data link layers. At the physical layer the errors are detected by a parity bit. At the data link layer the detection is extended to the message/response format and is based on the following rules:

- The message/response first byte must be the character 80H;
- The message second byte must be a value between 1 and 6; the response second byte must be a value between 1 and 61 and must be related to the last message sent;
- The message third byte must be the address of a measuring unit connected to the bus or the character 26H; the response third byte must be the unit address;
- The message fourth byte, if exist, must represent a known command;
- The message second byte must be in accordance with the command message;
- The time between the end of reception of one character (stop bit) and the beginning of reception of the next one (start bit) must be less than 0.25ms.

3.4 Network Architecture

The architecture adopted for the LAN is presented in Fig. 6. As we can see the bus is divided into small buses, isolated at the power and data lines. DC-DC converters make the isolation of power lines while the data lines are isolated by a RS485 transceiver. The advantages of this distribution are: 1) it is easier to localise and isolate eventual problems on measuring units and/or on the bus; 2) current and voltage drop on each small bus is less than with just one; 3) easy to install; 4) easy to expand the system, which depends only in the I/O CPU (Central Processing Unit) capacity. Besides the higher number of measuring units that is possible to connect to each small bus (there are 255 possible address), to maintain the drop voltage along the cable at acceptable values this number must be such that the total current on each small bus stays below 2A.

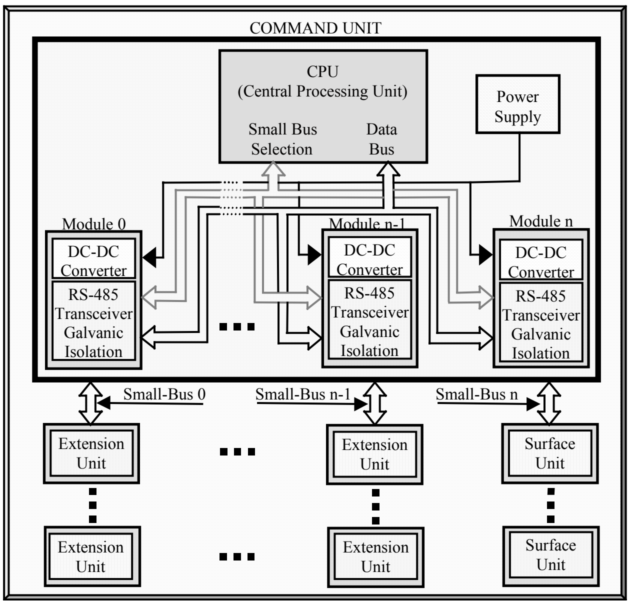

Fig 6 – Network Architecture.

The communication between the CPU and a measuring unit comprises three steps: 1) CPU selects the right small bus; 2) it sends the message 3) it waits for the response. After having received the response, the CPU can address another small bus.

4. TESTS AND RESULTS

Tests were performed to evaluate communication protocol and measuring performance.

For the communication protocol test, a PC running a dedicated program simulates the command unit. The communication was done using the serial port RS232 and the electrical signals were converted to RS485 using a MAX3162CAI component. The RTS (Request To Send) line controls the data transfer. This test was successful for the three extension units used.

For the measuring test, although we had made use of two units, for graph simplicity we will show the results of just one. Fig. 7 shows the calibration curve. The curve shows some non-linearity because the sum of voltages at both secondaries of the LVDT doesn't keep constant for all the range - a condition required by the signal conditioner used. The results presented at Fig. 8 were obtained by comparisons of the data processed within the smart sensor and processed in the computer and the output values of a position calibrator. As we can see, the error accuracy is less than ±0.5μm. Another test was performed to evaluate how the temperature affects the system; results are showed in Fig. 9. This test was done with all measuring units inside a box, subjected to the variation of ambient temperature and repeated at three LVDT positions; each position was recorded for several hours (roughly 70 hours).

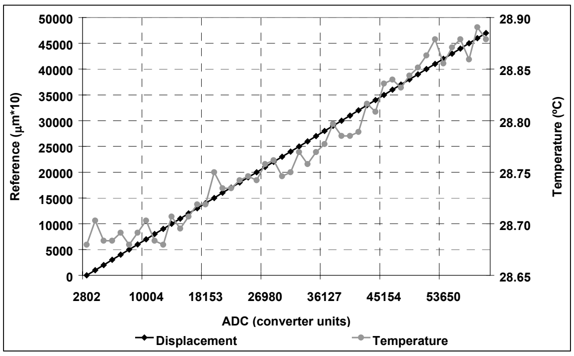

Fig. 7 – Curve calibration of an extension unit.

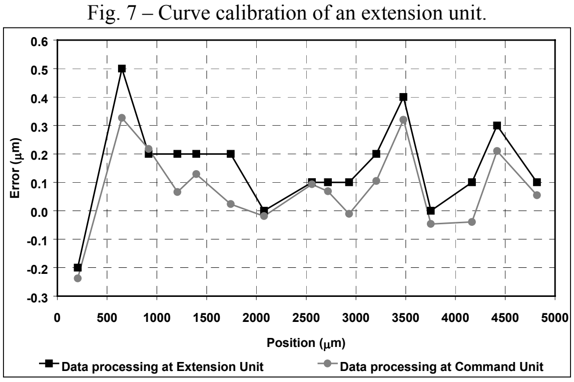

Fig. 8 – Accuracy test of an extension unit.

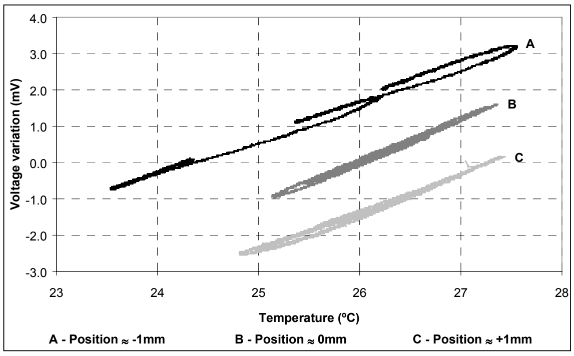

Fig. 9 – Temperature effect on the signal stability.

5. CONCLUSIONS

Taking advantage of the characteristics of modern electronic components, a new smart sensor to measure pile deformation was developed. Each measurement unit implements a self test able to detect and localize an eventual malfunction, stores a calibration table and acquires the temperature measurement for data processing. All data is available in a data bus and a network protocol, based on a master/slave structure, is responsible for the communication between each measurement unit and the command unit. Besides, the system is removable which means that it can be reused and is easy to install inside of the pile.

The tests showed that the smart sensor satisfies the accuracy better than the required, with an error less than ±0.5μm. Besides, the measurement units showed very good stability and repeatability. However, the system is quite sensitive to temperature variations. The almost constant temperature in the pile reduces this drawback.

6. ACKNOWLEDGMENTS

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