Development of an improved load cell for construction work

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ABSTRACT: This paper aims to inform of the development and long-term field uses of new improved methods of monitoring load (strain) within the construction industry to redress the lack of information on full scale soil/structure interaction. The aim of the authors has been to provide cost effectively the means of obtaining the quality of loading data needed to calibrate the most sophisticated design methods as well as allowing a more radical look at economic and safe design. However, they are aware of the need to monitor other parameters along side the load not always possible in a commercial contract) so that the information can be put to its best use.

1 INTRODUCTION

With the need to make the most of building space within our cities there is an ever-increasing need to accurately predict the outcome of changing soil/structure interaction. The soil under an existing City such as London will undoubtedly be carrying existing structures, such as underground rail tunnels, major utility ring mains for water and sewerage as well as adjacent buildings. Changes in the loading of adjacent soil, whether by an increase or decrease in load transfer will have an effect on the already existing structures. As yet the resulting movement associated with any change in load cannot be confidently predicted, because of the limited information on the in-situ stiffness of soil with time and load.

Since the mid 1970s significant improvements in electronics transformed computers and consequently the availability of computer based design packages for the construction industry. Determining the parameters that controlled the interaction of structures within the founding soils, however, can not be found in a computer. For the design of Civil Engineering structures the most common way of deriving the necessary parameters is by back analysing the data from a few well documented projects, or by extrapolating the necessary data from tests on small diameter piles (<= 1 m diameter), or from (disturbed) soil samples tested in a laboratory. The information on soil properties obtained by such means will not provide alone the quality of data needed to match the associated risks of building close to an already existing major facility such as a mass transit system. Monitoring the effect of interactions between full-scale structures, long term could provide the additional quality and reassurances needed for future development, but at present such information is still extremely limited and very often not fully or properly recorded and reported.

2 TRADITIONAL METHODS OF MONITORING LOAD

Traditionally load cells consist of a strain-gauged element, or elements fitted between a top and bottom loading surface. When calibrated changes in load can be determined from the change in strain within the element or elements. The two most commonly used sensors to monitor strain are Electrical Resistance Strain (ERS) gauges and Vibrating Wire (VW) strain gauges. Other types of sensors are available but are not widely used. Pressure cells are also available but results can be difficult to interpret, especially when attempting to monitor load over large areas, say several square metres.

The main problems with using traditional load cells in construction are as follows:

a. The collapse potential within a traditional load cell is a function of its overall length and how the load is applied to it, ie via its top and bottom loading surface. Typical the collapse would be in excess of 100 mm.
b. The cost of a load cell depends on the amount of engineering involved, the number of strain gauges used and the quantity manufactured. For one off cells made to fit the exact dimensions of the structure, possibly 2 to 3 m in diameter the cost would be high and the cell would not be readily available.
c. Off the shelf load cells are not designed to work under 50 m of water pressure (at the bottom of a pile) in an aggressive environment, and if used would not survive over the time period that load information would be required, ie, 5 to 10 years for soil structure equilibrium.

3 A NEW CONCEPT IN MONITORING LOAD IN CONSTRUCTION

The concept behind monitoring load was to design a series of very stable waterproof tubular sensing elements, initially using ERS gauges, but finally with a single vibrating wire gauge. The units all have standard internal dimensions for the VW gauges but have varying wall thickness to carry different loads so that it is only necessary to carry a few standard sizes to cover a wide variation in load. The units are partially manufactured, i.e. not hardened so the wall thickness can be adjusted for a specific application. The units are only formed into a load cell when cast into the concrete, thus reducing fabrication costs for a cell to a minimum. To key the sensing units into the concrete they are fitted with individual bonding bars top and bottom. Pressure pads are sometimes needed to transfer the load from the concrete through the units at acceptable stress levels. A soft membrane (3 mm thick), fitted across the area over which load is to be monitored and through which only the sensing elements pass forces, all the load from the top mass of concrete through the sensing elements to the concrete below. The sensing elements are also covered with soft membrane. The potential for long-term collapse within the cell is limited to the thickness of the soft membrane, i.e. a maximum of 3 mm. Long term stability of the new cell is achieved by making the sensing element completely watertight and preconditioning the wire used in the VW gauge. The large 3 m diameter load cells discussed later in this document took only a matter of days to assemble and be ready for site. The sensing elements were assembled on a base frame for ease of installation on site.

To fully test the design and the installation of the new technique on a civil engineering site, a 1 m diameter load cell was installed as a base load cell in a 3 m deep pile. The cell section was cast in concrete before being taken to site; it is important not to crush the soft membrane under too much wet weight of concrete. After the pile was fully load tested it was pulled from the ground and the whole pile load tested at the Building Research Establishment in the 10,000 kN grade 'A' load-testing machine. The results of the loading test showed the load cell had a resolution of better than 0.1% full scale, ie, less than 3 kN in 3,000 kN (the capacity of the cell). Many other tests were carried out, including placing cells at the bottom of 50 m deep water filled shafts to prove their water tightness.

4 APPLICATIONS

The technique has been used to investigate various soil structure interaction problems. Most of the work has involved manufacturing load cell and has been carried out under standard commercial contracts with tight installation schedules.

5 THE LONG-TERM LOAD CARRYING CAPACITY OF PILES USED AS SETTLEMENT REDUCERS IN RAFT FOUNDATIONS

Raft foundations are significantly cheaper than piled foundations, but are far more flexible and for large heavy buildings total and differential settlements can be unacceptably high. The use of a limited number of piles in a raft design to reduce both total and differential settlement offers an attractive economic solution. The main design problem is the long-term load reaction of settlement reducing piles, since the supporting soil immediately around the piles is also loaded by the raft and the piles are loaded close to their ultimate capacity. There is therefore a complex problem that can only be confidently resolved by long-term monitoring. Until the development of the new load cell, it was not possible or practical to monitor the behaviour of working piles loaded to their ultimate capacity over the life of a structure, i.e. upwards of 50 years.

Figure 1 – Load cell fitted on pile top

In 1981 one of the settlement reducing piles under the foundation of the new QEII Conference Centre at Westminster (London) was fitted with a new design load cell. Figure 1 shows the top of the pile being prepared with the assistance of the contractor Molem. The concrete at the top was broken back to the correct level to leave an up-stand into the 2 m thick raft. The hardboard shuttering was needed to form a smooth flat surface across the top of the pile onto which the soft membrane could be attached. The top (threaded) section of reinforcing bars that were used to transfer the load into the pile below the soft membrane can be seen. Details of the finished cell with the soft membrane also fitted around the up-stand of the pile are shown in Figure 2. Sixteen 1,250 kN sensing pillars were used to make up the 20,000 kN cell. The tops of the sensing elements can be seen surrounded by hand placed concrete to protect the cable outlets from the vibration poker subsequently used when casting the raft. The reinforcement bars for the heavily reinforced raft were fitted between the top bonding bars. To increase the load transfer from the raft into the top bars additional keypads are attached to the top of the bars, also shown in Figure 2. The results from the cell since 1981 are shown in the Figure 3. The variations in the load on the cell during the early stages of construction were due to uplift forces generated by the soil under the raft. Before the weight of the building load was applied, the pile acting as a soil nail holding down the raft. The cell monitored uplift forces of approximately 1,000 kN over about 2 months of little activity on site as the foundation's contractor moved off site and the building contractor moved on. The pattern of load imposed on the cell clearly indicated bending across the top of the pile, indicating that the raft was bending as it was lifted. Since the completion of the superstructure in 1987 the load reaction from the pile has been relatively constant. There has been a slow drop off in load of about 100 kN over 10 years, possibly due to a reduction in the uplift forces still taking place. The most recent readings show an increase in load, which could be due to changes in the live load from the building. The long-term ability of the pile to offer additional load reaction to the raft has been quantified and has shown the pile to be an effective settlement reducer. Raft pressure cells of the same design were also installed.

Figure 2 – Sensing pillars of the load cell

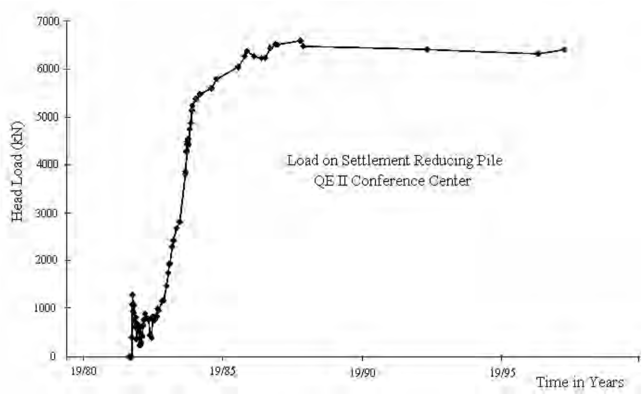

Figure 3 – Changing of the head load with time

5.1 *Shaft loading on large diameter working piles in London Clay*

5.1.1 *1.8m diameter test piles*

Five Acres: A new development in the City of London at Hounditch in 1988 by Stent Foundation involved test loading two 1.8 m diameter bored piles formed under bentonite and founded in the Thanet Sand. The purpose of the tests was to determine if the piles could carry the working load on shaft adhesion alone. To calculate the shaft adhesion the base load was measured with a load cell and subtracted from the head load.

Figure 4 – Base load cell with sensing elements and pressure pad

The two piles with shaft lengths of 40 m were formed through, approximately 4 m of fill, 31 m of London Clay and 5 m of Thanet Sand and were load tested to working load and 1.5 x working load respectively. To reduce the disturbance on the Thanet Sand the piles were formed under benonite. The base load cells were made from nine 4,000 kN sensing units to have capacity 36,000 kN. Figure 4 shows the sensing elements fitted with pressure pads. The cell was later cast in concrete and lowered into the pile bore at the end of the drilling rig's 'Kelly bar', see Figure 5. A screw attachment was cast in the top of the cell to facilitate attachment to the 'Kelly bar', so that the installation only took a few minutes. When at the bottom of the bore the Kelly bar was simply unscrewed, leaving the load cell in place.

Figure 5 – Base load cell cast in concrete

During concreting one of the base load cell monitored 73% of the submerged weight of the first 2 m of concrete poured, (5.6 m^3). At 12 m of poured concrete the percentage weight monitored by the cell fell to about 45%. The cell did not record the full weight of the concrete because the large gravel particles in the mix bridged in the pile bore, reducing the load on the cell. After 1 hour the concrete in the pile started to set and shrinkage during curing further reduced the load at the base. When completed five and a half hours later the load on the cell had dropped to only 2% of the total submerged concrete weight. During pulling the temporary casing at the top of the pile, the load cell responded to the disturbance with the load increasing slightly to 44 kN, i.e. 3% of the submerged concrete weight. The total stress on the soil at the base of the pile was therefore significantly less than before forming the pile. The cell, however, only monitors the net weight - water pressure acts either side of the bottom plate. The final loading on the soil at the base of the pile was only 4% of the weight of soil removed at the end of the installation.

Over the following few days the load at the base of the pile increased due to the active pressure of the soil immediately around the base of the pile. After 14 days the load on the base cell had increased to 311 kN and 40 days later to 330 kN, the uplift pressure decreasing with time.

A second pile also fitted with a load cell behaved similarly to the first during casting of the pile. The stabilised load at the base, however, was only 136 kN at the time of testing. Table 1 summarizes the findings from the cells is given below. The residual load on the cell before and after each of the loading test is also given

Table 1 – Results of the top and base load

Pile	Head load kN	Head movement mm	Base load kN
Pile 1	0		311
Pile 1	15,500	6.6	436
Pile 1	0		336
Pile 1	15,500	7.5	633
Pile 2	0		136
Pile 2.	15,500	9.3	409
Pile 2	23,250	13.98	603
Pile 2	0		281

The average shear stress developed on the shaft of the piles at working load (WL) was about 69 kN/m^2 and at 1.5 x WL was about 103 kN/m^2 for a head settlement of 14 mm. The average shaft settlement would be less because of compression in the pile, about 11 mm. Using published depth profiles for London Clay the average shear strength along the shaft would be around 200 kN/m$^{2.}$ In the total stress method of design the recommended value of alpha is 0.45, which if correct would mean the pile was close to its maximum shaft capacity, however, there is no indication from the build up in load on the base that this was the case, neither from E (Youngs Modulus) back analysed from the load settlement, which are 57,000 and 55,00 MPa respectively for the two values of load given. The settlement for maximum shaft capacity would be about 18 mm, ie, 1% of the pile diameter. The 14 mm of head settlement, with the average shaft settlement because of compression of 11 mm would indicate a much higher value for alpha than the 0.45 commonly used in design.

5.1.2 *2.5m diameter test piles*

A 2.5 m diameter hand dug caisson pile used to support the new development over Charing Cross Station in London was fitted with three shaft load cells. The top section of the pile through the gravel down the top of the London Clay was coated with a 'slip coat' to reduce the load transfer at ground level.

A section through the pile showing the instrumentation is given in Figure 6. Details of the construction of a load cell in the shaft of the large diameter pile is presented in Figure 7. The load cells were installed between the 24th and 31st of March 1988. The bottom section steelwork was cast in the pile and the concrete allowed to cure for 24 hours before the soft membrane was fitted across the pile and around the sensing elements. One metre of concrete was then cast over the cell. Where each of the cells were to be fitted the authors designed soft ring sections 50 mm high to be built into the precast concrete ring sections used to form the piles.

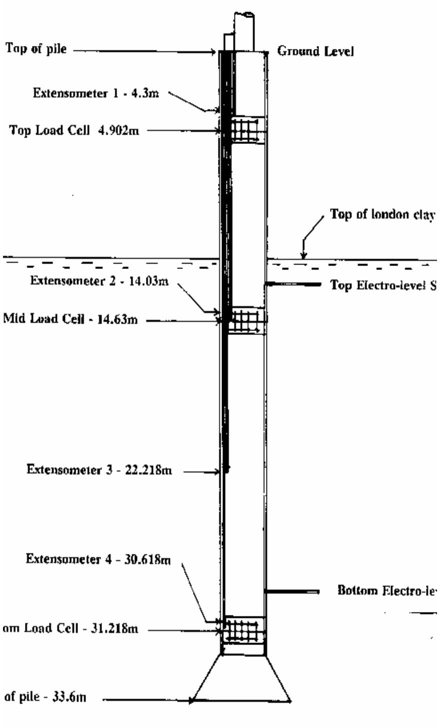

Figure 6 – Lay out of the instrumentation

Table 2 shows a summary of the loads carried at the various levels down the pile.

Table 2 – Load transfer along shaft (KN)

Load Cell	07/1988	12/1988	05/1993	04/1998
Top	- 22.9	382.2	10,639.5	10,923.7
Mid	7.7	792.4	9,627.5	10,005.3
Bottom	-170.0	237.0	4,126.5	5,322.2

Figure 7 – Shaft load cell

The initial negative loads are due to shrinkage of the concrete as it cured. By December 1988 the pile started to carry some construction loads, while in 1993 the full load was applied from the completed building. Changes since 1993 indicate a small increase in load of about 300 kN, that could be easily associated with small adjustments of the way the structure carried the load or possibly variations in the live load from the building.

Currently the top cell is monitoring the expected building load (working load) on the pile. The load cell in the top of the London Clay is recording a similar load indicating that the slip coat applied to the top section of pile is still effective. Load transfer from the shaft of the pile, between the mid and bottom load cell is measured as 4,683 kN, over a surface area of pile of 130 m^2 i.e. an average of about 36 kN/m^2. The 1.8 m piles described earlier indicated that twice this value (about 70 kN/ $m^{2)}$ could be generated at settlements of 7.5 mm or 0.4% of its diameter, suggesting that the settlement of these large hand dug piles is relatively small.

The shaft friction developed on hand dug piles cannot easily be calculated because of limited data on load transfer from such piles. The rotations of the soil relative to a point 3 m from the shaft were monitored using electro-levels. The differential movements monitored over this distance in the top of the London Clay was approximately 2 mm, which using the pile interaction curves given by Cooke et al would indicate a total settlement of 6 mm. If the estimated settlement is correct then the large hand dug piles would have a similar shaft adhesion characteristics to the 1.8 m machine made pile, which at 2% settlement would have similar shaft adhesion to the large hand dug piles.

5.2 *Pile group behaviour*

During the construction of the foundations for the Garigliano road bridge South of Rome (Italy) a major investigation was undertaken to understand the load sharing between piles under a heavily reinforced cap. The project well organised in respect to how and what data to collect has the long-term information from the investigation to used to check the safe performance of the foundations as well as calibrate new computer design methods so that they can more accurately predict future designs. A general view of the bridge is shown in Figure 8.

Figure 8 – General view of the Garigliano Road Bridge

A cross section of the bridge showing proof loading tests, together with a plan view of the pile layout of the central support is shown in Figure9. In order to carry out a comprehensive investigation of load sharing between the piles in one quarter of the foundation, corner, edge and centre piles were fitted with load cells. A selected number in other quarters were instrumented to act as checks on symmetry of the foundation in carrying load.

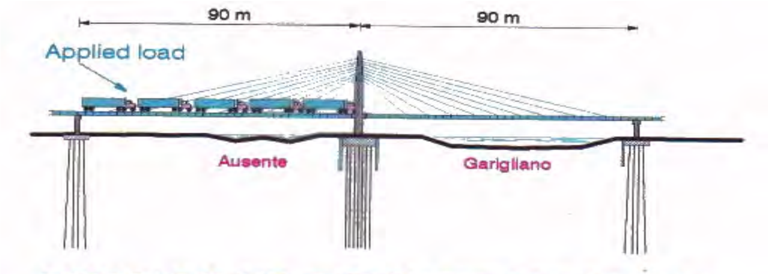

Figure 9 – Lay out of the proof loading test

During construction the loading on the piles was used to assess the safety of the construction sequence. The results showing the final load distribution within the foundation when complete together with the long-term trends in load sharing are shown in the time plot, see Figure 10.

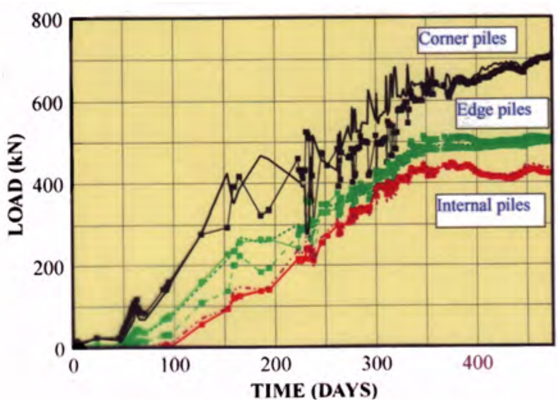

Figure 10 – Loading distribution within the foundation

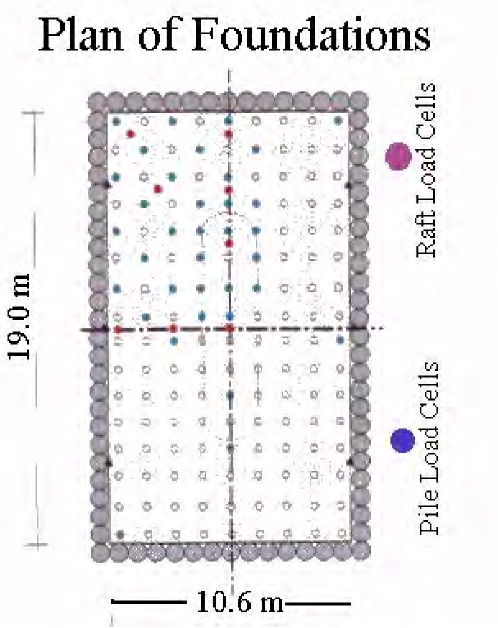

Figure 11 – Lay out of the instrumented piled raft foundation

6 CONCLUDING REMARKS

a. The new design of load cells have been successfully used in working piles, thus providing the best quality data on pile performance.
b. The new design has addressed three fundamental issues:
   - Long-term quality of data.
   - Availability and cost.
   - Safe for use in working piles.
c. While the load cell provides quality data on load transfer into the surrounding soil other important parameters are needed to allow a full interpretation of the information ie, settlement and pore water pressure.
d. Data from the use of the load cells has been used in several theses furthering understanding not only in London Clay, but also in the residual soils in Brazil and the expansive Black Cotton soils in India.

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