NEW PILE FORCE GAUGE FOR ACCURATE MEASUREMENTS OF PILE BEHAVIOR DURING AND FOLLOWING DRIVING

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The paper reports a new pile-force gauge based upon the principle of the vibrating wire. The gauge is intended to be driven down with a precast concrete pile and can be placed at an arbitrarily chosen depth in the pile. The impacts from the pile driving will not impair the gauge. The gauge registers the static loads and bending moments in a pile with an error not exceeding 2% of the linear measuring range. This maximum error includes the drifting of zero point and change of sensitivity with time.

The design of the gauge and laboratory and full-scale tests are reported, and suitable use of the gauge is suggested.

Cet article présente une nouvelle jauge de mesure des efforts appliqués aux pieux; cette jauge est basée sur le principe des mouvements vibratoires de fils métalliques. La jauge est conçue pour être battue avec un pieu en béton préfabriqué et peut être placée à une profondeur arbitraire choisie dans le pieu. Les impacts du battage n'endommagent pas la jauge. La jauge mesure les charges statiques et les moments fléchissants dans un pieu avec une erreur ne dépassant pas 2% de l'étendue linéaire de l'échelle. Cette erreur maximum inclut la déviation du point zéro et les variations de sensibilité avec le temps.

Une description de la jauge est présentée; un compte rendu d'essais en laboratoire et en chantier est également donné; les adaptations possibles de la jauge sont suggérées.

INTRODUCTION

In 1965, A. Johnson & Co. (Canada) Ltd., Montreal, consulted with the Axel Johnson Institute for Industrial Research (AJFO) in Sweden and asked for guidance on problems concerning negative skin friction on piles. AJFO in turn, asked the Swedish Geotechnical Institute for assistance. The three organizations set up a program to carry out full-scale pile tests in the field. It was soon realized that a condition for successfully resolving the problem was to have an accurate force-measuring device. Since this type of measuring equipment did not exist, it had to be developed. This work was undertaken by AJFO, who, after two years of extensive designing and testing, developed a pile-force gauge that satisfied all of the requirements. The actual field test started in June, 1968. The work is being carried out in close cooperation with the Pile Commission of the Royal Swedish Academy of Engineering Sciences. The cost is partly covered by a grant from the Swedish Council for Building Research. This article deals with the design, testing and application of the gauge.

DESIGN AND PRINCIPLE OF THE "PILE-FORCE GAUGE"

In Sweden the measuring of forces in piles was previously based upon the use of the electric strain gauge (IVA Pile Commission, 1964). Outside of Sweden, a system of rods has been used (Bjerrum and Johannessen 1965; Bozozuk and Jarrett 1968). These methods have several disadvantages. The electric strain gauge has an unsatisfactory accuracy due mainly to zero drift, whereas the rods must be installed after the pile driving, and therefore any influence during the pile installation is lost. The accuracy of both systems is limited, because one is not measuring forces, but deformations, which then are transferred into forces by using the modulus of elasticity of the pile material. As mentioned above, it was therefore necessary to develop a special pile-force gauge that would satisfy the following conditions:

(1) The gauge shall, during a long period of time (5–10 years), measure loads up to 150 tons,[1] with a maximum error of 2%.

(2) The gauge shall be able to withstand loads up to 400 tons, without damage.

(3) The gauge shall measure tension loads up to 50 tons.

(4) The gauge shall be able to withstand all stresses during the driving of the pile, i.e. withstand 10 000 blows with impact forces of the order of 150 tons.

(5) The gauge shall measure bending moments in the pile.

(6) It shall be possible to place the gauge at any depth in a pile, and have it function at a surrounding pressure, equivalent to a height of water of 300 ft (91 m).

(7) The gauge shall be adaptable to different types of piles, and adjustable to variable measuring ranges.

Different principles of measuring systems were studied. Two different prototypes were manufactured, one of which was based on the use of load cells with vibrating wires. This design was judged to be the more favorable one.

Measurements with vibrating wire are based upon the principle that a wire under tension will change vibrating frequency with changes in tension. A shortening or lengthening of a steel cylinder, for example, can then be recorded as a change in frequency of a vibrating wire inside the cylinder. The reading of the frequency is transmitted through a magnet, which first activates the wire, when the magnet is subjected to an electrical impulse. The resulting vibrations of the wire induce an alternating current in the magnet. The frequency of the induced current is recorded by an electronic counter.

[1] All "tons" mentioned in this note are metric tons.

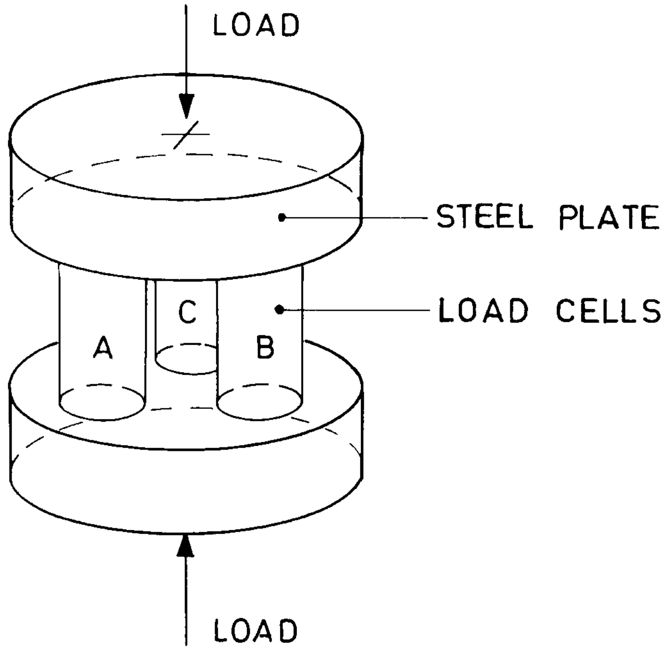

FIG. 1. Basic design of the pile-force gauge.

The mathematical expression for the lowest frequency, as a function of the tension of the wire, is

[1] $$f = \frac{1}{2L}\sqrt{\frac{\sigma \cdot g}{\nu}}$$

where f = the frequency (Hz)
L = the length of the wire (m)
g = 9.806
ν = the density of the wire (kg/m^3)
σ = the tension of the wire (kg/m^2)

The wire is placed in a load cell (steel cylinder) and pretensioned. When the load cell is under zero load the frequency is f_0.

If a load P is applied, the frequency is changed to f_1. The mathematical expression for P, as a function of frequency, is

[2] $$P = \text{const.}\ (f_0^2 - f_1^2)$$

The value of the constant is established through calculations and calibrations.

This principle is used extensively, and has been known for a long time. However, the special feature of the present design is a 'clamping in' of the wire ends, which is not impaired by impact and dynamic loadings, as encountered in a pile-driving operation.

DESIGN OF THE PILE-FORCE GAUGE

The basic design is shown in Fig. 1. Three load cells A, B, and C are placed symmetrically around the center of the gauge, and in between two steel plates.

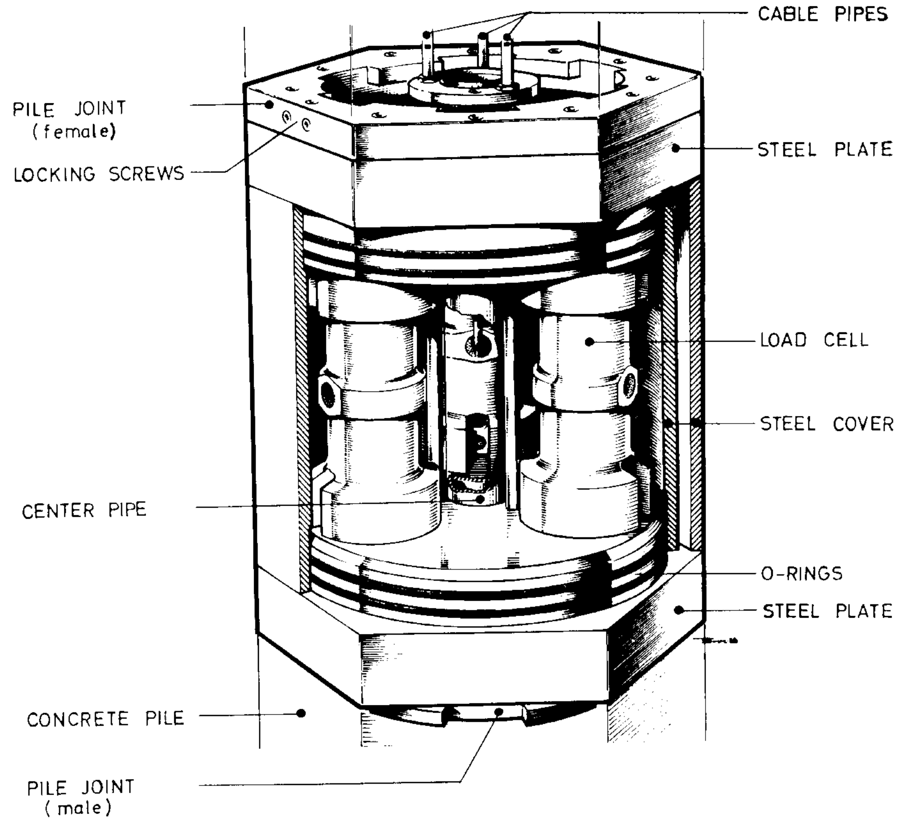

FIG. 2. Cross section of the pile-force gauge.

Pile joints are then mounted onto the plates, and a cover is placed around the gauge. The cross-sectional area and form of the gauge is adjusted to the size and shape of the pile in which the gauge is to be used. The gauge will be placed between two pile joints, and acts in fact as a short pile section.

The load cells in the pile-force gauge are shown in the 'cross section' (Fig. 2). The electric cables from the load cells are assembled through cable pipes, which are cast into the pile. Three cable pipes can be seen in Fig. 2, two of which are coming from other gauges in the pile. The gauge is placed in a pile equipped with a center pipe, which is used for measuring deformations by means of special rods. This center pipe, along with the thick steel plates above and below the load cells, are also shown in Fig. 2. In this case, the pile is a Herkules precast concrete pile of hexagonal cross section.

Figure 3 shows a gauge mounted on a pile equipped with a rock point. This pile, consisting of five sections, was driven down to a total depth of 180 ft (54.9 m) with a 4-ton (metric) drop hammer falling 20 inches (50.8 cm). The total number of blows required for the installation was 6000. After the driving was completed, the gauge was operating perfectly.

EVALUATION OF RECORDED VALUES

The pile-force gauge gives three frequencies, fa, fb, and fc, from which the load P, the bending moment M, and the direction β of the bending moment are

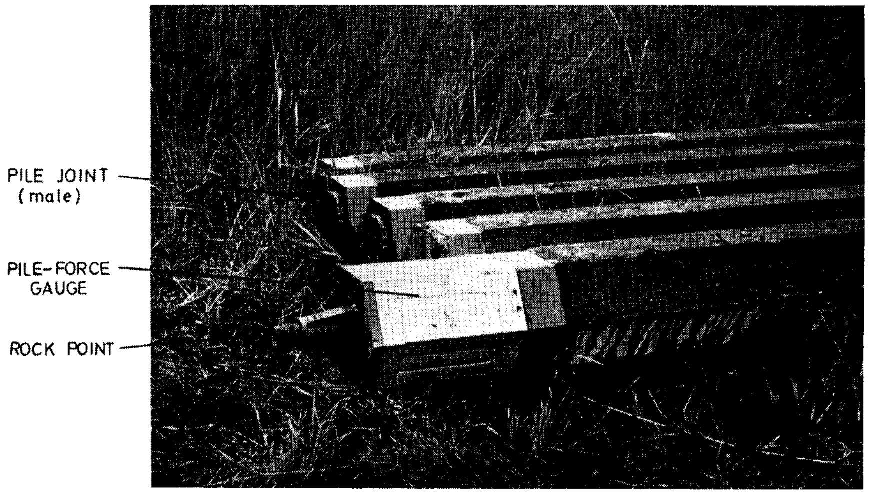

FIG. 3. Pile-force gauge mounted on a pile tip and equipped with a rock point.

evaluated. First, the load in each load cell is calculated from the recorded frequences [eq. 2]. The formula for the load P, as a function of the load in the separate load cells, is then

$$P = P_A + P_B + P_C \quad [3]$$

Then, the moment vectors M_x and M_y at the center are

$$M_y = (P_A + P_C)R\cos 60° - P_B R \quad [4]$$

$$M_x = (P_A - P_C)R\cos 60° \quad [5]$$

and the resulting moment M is

$$M = \sqrt{M_x^2 + M_y^2} \quad [6]$$

Finally, the direction β of the moment is

$$\tan\beta = M_y/M_x \quad [7]$$

The evaluation can be done by hand, but time and money are saved by using a data computer.

CALIBRATION AND ERRORS

Every load cell is first calibrated in a 100-ton hydraulic press. Then the cells are submitted to 20 000 pulsations between 0 and 100 tons, to eliminate tendencies to changes in the system. Following this step a new calibration is carried out. Finally, when the three load cells have been assembled in place, the gauge is calibrated for axial load and bending moment, in a 200-ton hydraulic press.

The accuracy of the readings have been carefully studied, and special interest given to the long-term stability. The annual zero drift has been established at less than 0.8% of the upper limit of the linear range, with the total error being less than 2%.

During the design procedure, a full-scale pile-driving test was performed. A prototype of the gauge was placed on a pile. The pile was driven down through 60 ft (18.3 m) of loose soil to rock, with a 3.5-ton drop hammer falling

20 inches (50.8 cm). After the pile tip was driven into the rock, 10 000 additional blows were given to the pile and the gauge. As a result of this hammering, the investigation that followed showed a zero drift of 0.5% of the upper limit of the linear range, which was 150 tons. The linearity and sensitivity were unchanged.

FIELD TESTS

Seven pile-force gauges are being used in the full-scale test at Gothenburg, Sweden. The gauges have been placed at different depths in two piles driven to a depth of 180 ft (54.9 m). One gauge is right at the tip of the pile (Fig. 3). During the driving, the piles received 6000 blows with a 4.2-ton drop hammer falling 20 inches (50.8 cm). All gauges are operating as planned. The results from this test are being reported by Fellenius and Broms (1969).

The pile-force gauge has clearly demonstrated that it has satisfied beyond expectations all of the conditions originally specified for an accurate force-measuring device.

SUGGESTED USE OF THE GAUGE

A problem encountered during every load test, and worthy of further study, is the actual distribution of skin and tip resistance. For instance, all of the load on an end-bearing pile driven through clay will finally reach the tip of the pile. During a load test, however, a substantial part of the load is taken by skin resistance, and therefore the load–deformation relationship for the pile tip is not known. A gauge placed at the tip of the pile would solve this problem.

A study of the group action behavior of piles could be carried out and results obtained by placing gauges at suitably chosen depths in a few piles in the group. Then the effect on a pile when driving an adjacent pile in the group, the resulting forces in piles upon completion of the driving, the time effects of backfill, negative skin friction, horizontal movements in the soil around the piles, and other related problems could be studied.

Further applications of the pile-force gauge in full-scale tests worthy of special studies include (1) the buckling of long piles in soft clay under long-term testing, (2) the evaluations of bending moments due to lateral forces against piles, etc.

There is an unlimited opportunity to improve pile-load test results and establish pile capacities, with the pile-force gauge, due to its exceptional accuracy, time stability, and ability to separate axial load from bending moment.

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