Bending of Piles Determined by Inclinometer Measurements[1]

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This paper deals with the bending of slender precast concrete piles which are driven in segments 10 to 14 m in length and spliced in the field by means of rigid steel couplings. The requirements of the Swedish Building Code for allowable bending of these piles are reviewed and the method of inspecting the bending is described. The inspection is performed by lowering a slope inclinometer through a pipe, which is cast centrically in the pile and attached to special couplings by which access all through the pile is obtained.

By the inclinometer the inclination and the direction of the inclination is measured. The results are used for determining the location of the pile in the ground and the bending of the pile. Mathematical expressions for this are derived.

In Swedish practice, when judging a pile, the bending of the pile segments is treated separately from the bending of the pile over the pile splices, as the latter involves the question of squareness of the joint couplings in casting. The bending of a segment is judged in terms of change of inclination per metre of pile and of bending radius over the length of the segment. A typical example is given on how to present and evaluate the measuring results.

Cet article traite de la courbure des pieux de béton préfabriqués de grande longueur, foncés par sections de 10 à 14 mètres de longueur et couplés au moyen de joints rigides. Les exigences du code du bâtiment suédois concernant la courbure maximum admissible de ces pieux sont revues et une description des méthodes de contrôle de la courbure est donnée. Le contrôle est réalisé au moyen d'un inclinomètre descendu dans un tube axial coulé avec le pieu et muni de joints spéciaux assurant sa continuité sur toute la longueur du pieu.

A l'aide de l'inclinomètre on mesure la grandeur et la direction de l'inclinaison. Des résultats obtenus, on peut déduire la position du pieu dans le sol et sa courbure. On présente ici les expressions mathématiques nécessaires et les erreurs de mesures affectant l'interprétation.

Dans la pratique suédoise, lors de l'évaluation de la qualité d'un pieu on considère séparément la courbure en section courante de pieu de la courbure au niveau des joints, cette dernière étant reliée au problème de perpendicularité des joints au bétonnage. La courbure en section courante est analysée en terme de variation de l'inclinaison par mètre linéaire de pieu et du rayon de courbure sur la longueur du segment de pieu. On donne un exemple type de présentation et d'interprétation des résultats de mesure.

Introduction

A pile, vertical or battered, should always be straight. However, the word "straight" is an absolute word and means that no bending or deviation, however small, can be allowed. For engineering purposes a more liberal meaning of the word has to be defined. The question is therefore: "How straight is a straight pile or rather, when is a pile bent and when too much?" It should be evident that definitions based upon the out-of-verticality or out-of-plumb are unsatisfactory, especially if they refer to the part of the pile that is above ground. The bending allowance is dependant of factors such as the length of pile in the ground, the working load, the type of soil, the type of pile, etc. To some extent the bending allowance is also dependent of the factors which govern the actual bending; the squareness of the splices, the quality of the pile installation work, the slope of the bedrock, the pile spacing, the presence of boulders etc.

Measurements of pile bending have been performed in Sweden since 1960 with the aid a slope inclinometer. In the following an account will be given of the inclinometer and of the bending criteria which are being used.

The content of this paper refers mainly to driven slender precast concrete piles, which are the most common piles in Sweden. Out of 4 200 000 m of piles which were installed in 1970, 66% consist of precast concrete, 29% are timber piles and 5% of steel piles (Swedish Pile Commission 1971). Cast-*in-situ* piles and caissons are used only to a limited extent.

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The Piling System

The pile consists mainly of 10 to 14 m long segments, which are spliced in the field with rigid steel couplings. The splices are equally strong as the pile or stronger. When, for instance, inclinometer measurements are required, a steel pipe, diameter 42 mm, is cast concentrically in the pile. Thus, when using special steel couplings equipped with a concentric hole, a continuous hole is obtained from the pile head to the pile tip. This center hole is used for plumbing inspection of the pile and for lowering a slope inclinometer through the pile.

The Slope Inclinometer

The slope inclinometer which is used for measurements of pile bending and deviation is as train gauge device which was developed by the Swedish Geotechnical Institute (Kallstenius and Bergau 1961). At each reading the depth of the measuring point, the inclination of the pile and the horizontal direction of the inclination is recorded. The inclinometer equipment consists of the following main parts: (*1*) measuring body (See Fig. 1), (*2*) extension pipes, (*3*) measuring bridge, and (*4*) calibration unit

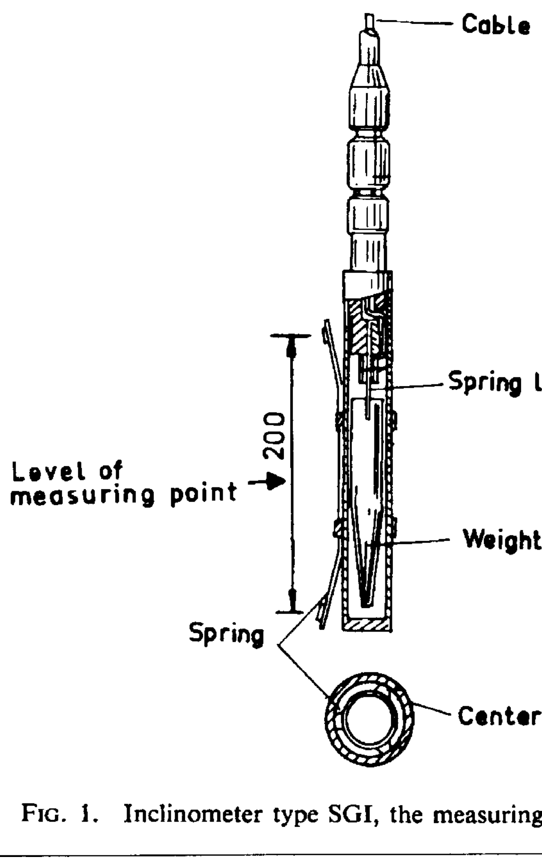


FIG. 1. Inclinometer type SGI, the measuring body.

The measuring body, which is in fact the inclinometer gauge, consists in short of a weight on a spring leaf. The spring leaf is equipped with strain gauges connected to a separate electric measuring bridge by cables. When the inclinometer is inclined and turned the strain gauges will pick up the varying strain which is imposed on the spring leaf by the weight. The maximum strain will occur when the plane of the spring leaf is perpendicular to the inclination plane of the pile. The normally occuring errors due to temperature sensitivity and creep in the strain gauges are eliminated by calibrating the inclinometer inclination to the difference between the two readings which are obtained by turning the inclinometer 180° in the inclination plane of the center pipe.

The inclinometer is lowered into the center pipe by means of extension pipes which are spliced by torsion stiff joints, free to bend in all directions. The measuring body can the efore follow the curvature of the center pipe while at the same time its turning from a certain horizontal direction always is known. The turning of the inclinometer is recorded by a precision levelling instrument mounted on a protractor.

Mathematical Formulas

From each measuring point the inclination (v) and the horisontal direction of the inclination (β) are obtained. The coordinates (x, y, z) of the measuring points are calculated by the following formulas (See Fig. 2 and 3).

$$[1a] \qquad x_n = \sum_{i=1}^{n} L_i \sin v_i \cos \beta_i$$

$$[1b] \qquad y_n = \sum_{i=1}^{n} L_i \sin v_i \sin \beta_i$$

$$[1c] \qquad z_n = \sum_{i=1}^{n} L_i \cos v_i$$

where L_i is the slope distance between the measuring points i and i–1.

The deviation from the vertical line through the pile head is calculated by

$$[1d] \qquad r_n = \sqrt{x_n^2 + y_n^2}$$

When judging the bending of a pile the bending radius is used, which is calculated by

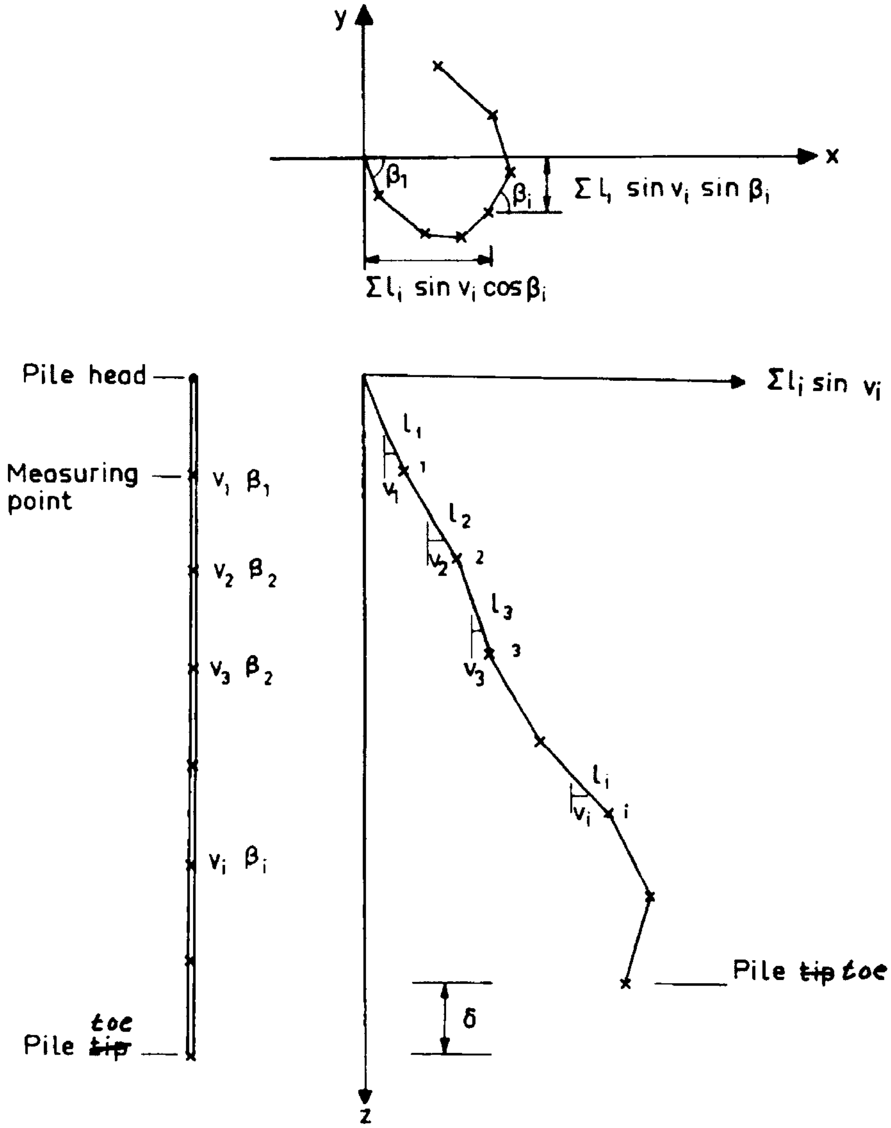


FIG. 2. Calculation of the location of the pile in the ground. ν = inclination, β = horizontal direction of inclination, δ = apparent pile shortening, L = slope length of pile between measuring points.

[2a] $$R = \frac{L}{\Delta \nu} \cdot \frac{180}{\pi} = \frac{L}{\Delta \alpha}$$

If the pile bends in a helical curve, the expression for the bending radius becomes

[2b] $$R = \frac{L}{\theta} \cdot \frac{180}{\pi}$$

where

[2c] $$\cos \theta = \cos \nu_i \cos \nu_{i+1} + \sin \nu_i \sin \nu_{i+1} \cos \left| \beta_i - \beta_{i+1} \right|$$

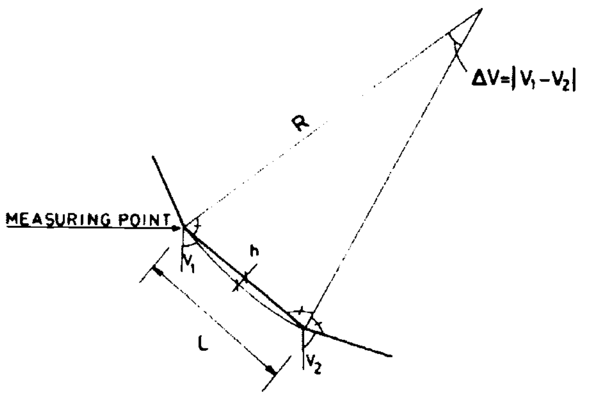
Also, the pitch or height of arc (h) may be of interest

[3] $$h = \frac{L \Delta \alpha}{8} = \frac{L^2}{8R}$$

The complete calculation according to the equations is very time consuming. An automatic computation of the measuring data is therefore advisable. As the formulas are simple, a programmable table calculator is adequate enough and will provide complete results in a few minutes. If the calculator is provided with a printer and a xy-plotter the results will simultaneously be obtained in a final form.

Measuring Accuracy

The measuringaccuracy depends of the accuracyof determiningthe angles ν and β. The error of the length of the extension pipes is small and will influence the results only to a negligible degree.



$$\Delta V = |V_1 - V_2|$$

$$\Delta\alpha = \Delta V \cdot \frac{\pi}{180}$$

$$R = \frac{L}{\Delta\alpha}$$

$$h = \frac{L\Delta\alpha}{8} = \frac{L^2}{8R}$$

FIG. 3. Formulas for the bending radius and the pitch of arc.

The inclination v is determined within 0.01° and the horizontal angle β within 1°. The sensitivity of the instrument corresponds to a lateral movement in the direction of inclination of 0.2 mm in 1 m.

Bending of Piles

Literature References

The mechanics of bending of precast concrete piles was for the first time in Sweden studied by means of inclinometer measurements in an investigation in southwestern Sweden 1960 (Swedish Pile Commission 1964). This investigation showed that piles driven in soft clay may bend and deviate from verticality or intended direction. However, it was also shown that this could be avoided by certain measures such as for example:

(1) Using straight pile segments,
(2) Having splices equally strong with the pile,
(3) Turning the segments 180° at each splicing *vis-à-vis* each other. (In casting of the segments the upper part of the pile gets a lower elastic modulus than the lower part, which difference may cause the pile to bend),
(4) Ensuring that the hammer strikes concentrically and parallel with the length of the piles,
(5) In the case of piles driven to sloping bedrock the pile tip may slide along the rock surface. This is avoided by providing the piles with a rock tip and by using a driving procedure similar to the one Bjerrum (1957) has described for steel piles.

Other investigations have verified the importance of these simple rules and that even very long piles, up to 100 m, can be driven straight (Pejrud 1965; and Hellström 1968).

In the investigation of 1960 a bent 60 m long pile was load tested over a period of 15 months. The pile had a minimum bending radius of 177 m calculated over 10 m length. The average bending radius was 220 m. During 12 months a constant load of 125 t equal to about 210 kg/cm^2 (3000 psi) was applied to the pile head. By inclinometer measurement it was shown that no change of bending occurred during the entire long-term loading test.

Bending of concrete piles has also been studied in the laboratory, for example Fellenius (1964) and Pejrud (1965). For pile sections of normal size, *i.e.* 500–900 cm^2, bending failure is obtained at a bending radius of about 50 m as measured over 1.0 m distance. Crack widths larger than 0.2–0.3 mm (0.01 in.) appear at a bending corresponding to a radius of 100 m, at which bending about 50% of the bending strength of the pile section is employed.

Hanna (1968) investigated long H-piles and found that very small bending radii (170 to 190 ft or about 60 m) occurred, inducing stresses in the pile section well exceeding the normally accepted values. (For comparison, as reported by Bjerrum (1957), the Norweigian authorities reject steel piles with a smaller bending radius than 400 m (1200 ft)). At points the yield strength of the piles was exceeded. Consequently, the bending increased during a subsequent load test, indicating that long-term settlements of the piles would occur. Due to the brittle nature of the concrete section, precast concrete piles would not normally be driven to such excessive bending without failure in driving would occur.

Further references can be found in Hanna (1968).

Allowable Bending Prior to Driving

In this and the following two paragraphs the Swedish rules for judgement of bending of precast concrete piles will be cited.

The Swedish Building Code (1967) stipulates the following maximum deviation of pile segments prior to driving. The deviation of the pile center line from a straight line between two points of at least 5 m distance from each other should be maximum 0.2% of the distance. The largest allowable deviation for pile segments which are shorter than 5 m is 10 mm. This maximum deviation can be expressed in terms of bending radius with $h = 0.002\ L$ incerted in Equation 3.

$$R = 62.5\ L \quad [4]$$

For example, a 12 m pile segment can prior to driving consequently be allowed to have a deviation from a straight line corresponding to a bending radius of 750 m. However, measurements indicate that piles normally show much smaller deviation prior to driving. The stipulation of the Building Code is mainly a rule for judging pile segments which have been bent during transport and handling.

Also, the Swedish Building Code stipulates requirements for the squareness of the steel couplings. The largest allowable value for out-of-square of a coupling is 1:150, *i.e.* per splice the out-of-square may be 1:75 = 0.8°. This value can be incerted in Equation 2, taking the length equal to 1 m, 0.5 m above and 0.5 m below the splice, thus

$$R = \frac{L}{\Delta\alpha} = \frac{1}{1/75} = 75 \text{ m}$$

If the length is 2.0 m, 1.0 m above and 1.0 m below the splice the radius becomes R = 150 m. A too large out-of-squareness can cause the pile to break during driving or cause excessive bending of the pile.

Allowable Bending after Driving

For accurate judging of pile bending an inclinometer measurement must be undertaken. When judging the result of the measurement the bending of the pile splice should be separated from that of the pile.

The allowable bending may differ from case and cannot be generally stated. However, the study should intend to check that the interaction of the steel couplings and the pile is sound. A large bending over the splice indicates that the steel coupling may be weak or that the casting of the couplings into the pile has been unsatisfactory. Especially, a small change of inclination between the steel couplings in combination with a large bending will be a sign of this.

Also, the bending of the pile segment should be studied. First, there should be no sudden changes of inclination, so called dog legs, as these are a sign of severe damage in a precast pile and thus they can considerably weaken a pile. The question of dog legs is studied in terms of change of inclination per metre of pile. Then, the bending of the pile segment is studied in terms of the bending radius over a longer length of the segment. Naturally, the bending of the segment could also be studied in terms of change of inclination over the length. However, it is more practical to use the bending radius for this study and thus separate the two approaches from each other.

While the Code has specified requirements for allowable pile bending prior to driving no specification is given for allowable bending after driving. This is partly due to that accurate measurement of pile bending is not a very common inspection measure and partly due to that general values of allowable bending cannot be given. Individual consideration must especially be taken to the characteristics of the soil around the pile. For example the buckling length of a pile in soft clay is approximately equal to the length of a pile segment, whereas the buckling length in stiff soil can be much shorter.

The bending of a pile should be judged over a length equal to the buckling length and the allowable bending can therefore neither be generally stated as to length nor to a certain bending radius. The allowable limits should further consider the deformation characteristics of the pile itself. For example, for the same loading stress in a pile a more slender pile can be allowed a larger bending than can a pile of a larger diameter.

Furthermore, the allowable bending must be related to the intended working load on the pile and the sensitivity of the superstructure to small uneven settlements. A bent pile is driven to a lesser end-bearing capacity as a larger part of the driving energy has been used for the "spring" of the pile as compared to a straight pile. The bent pile will also show larger deformation between head and tip under load. Also, for instance

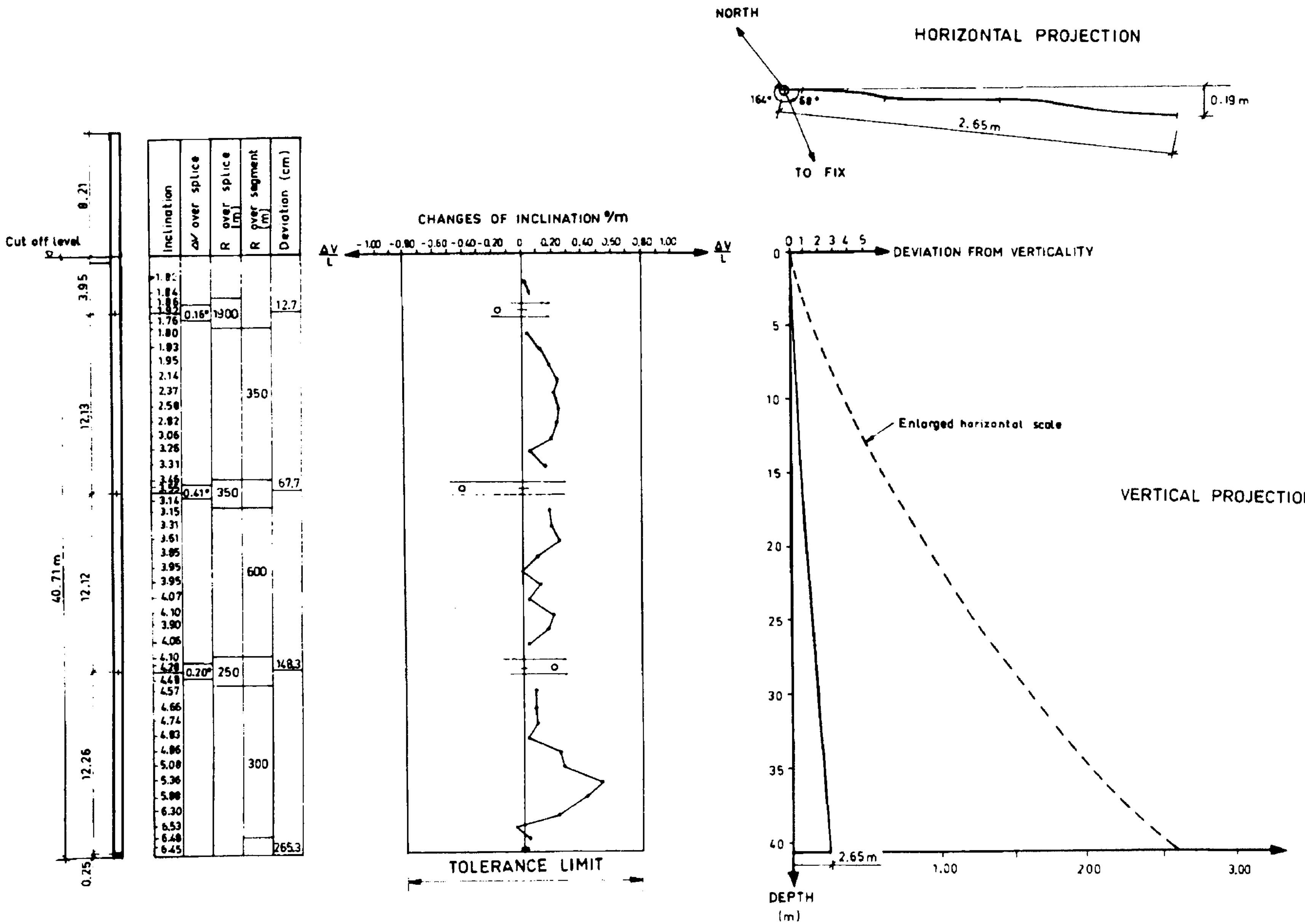


FIG. 4. Example of presentation of inclinometer measurement data.

if negative skin friction comes into the picture, the end-bearing resistance of a bent pile may be reduced or even destroyed.

Example for Long End-Bearing Piles in Soft Clay

Even if generally valid requirements cannot be proposed some common rules can be suggested for certain areas and conditions. For example, the following rules have been found to be valid for long (40 to 120 m) end-bearing piles intended for at least 60 t load (100 kg/cm2) which are driven into the soft sensitive clays (water content 60 to 100% and undrained shear strength 1 to 3 t/m2) that cover large areas in Sweden.

All piles should be provided with a center pipe. Then every fifth to tenth pile is inspected by means of inclinometer measurement. The change of inclination over the pile splices as measured over a distance of 1.0 m should be less than 0.8°. The bending over the splices in terms of bending radius as measured over 2.0 m distance should be larger than 100 m. A dog leg in a pile segment is defined as giving a change of inclination of 0.8° over 1.0 m distance. The bending of the pile segment as measured over minimum 10 m distance, 1.0 m below the upper splice, and 1.0 m above the lower, should be larger than 300 to 400 m. If the pile cannot meet these requirements the allowable working loads will be reduced or, in severe cases, the pile have to be replaced. Every replacement pile must then also be measured.

Fig. 4 shows the results of inclinometer measurements of a precast concrete pile with 30 cm diameter. The pile was driven through about 2 m of backfill containing boulders and through about 35 m of soft material below which the tip penetrated about 3 m into layers of sand- and mudstone.

As shown in Fig. 4, the inclination changes and the bendings over the splices are well within the requirements. Also, the inclination changes ($\Delta y/L$) of the pile segments are within the tolerance limits. The bending radius of 350 m over the upper pile segment lies near the limit and is considered more serious than the smaller radius of 300 m over the bottom segment which occurs at a considerable depth where the lateral support is good.

Due to the boulders in the backfill the pile was not driven absolutely vertical as intended. Therefore, it is already from the beginning inclined by almost 2°, which with depth increases to 6.5° at the pile tip. The inclination occurs in practically one plane, *i.e.* no screwing effect is encountered. Had this been the case, two vertical projections of the pile would have been shown in the diagram.

The pile bending is accepted after the applied requirements. A load test was later performed to a load of 300 t without pile failure was obtained.

Conclusions

The inclinometer, which has been described in this paper, was originally intended for research purposes. Inclinometer measuring of piles is a costly inspection method and can become a delaying factor in an ordinary piling job and it is thus normally used only for inspection of test piles, which are driven prior to the actual contract piles. However, the higher degree of safety which is achieved by inspection of the bending of the contract piles may be worth the cost of inspection if one as a result can increase the loading of the piles, *i.e.* decrease the number of piles.

When using the inclinometer for bending inspection one has to define the allowable bending limits in consideration to the soil conditions, the intended load, the type of pile etc and present the results accordingly. In this paper one inclinometer device is described and the requirements for one type of pile driven in a certain type of soil is presented as an example of one approach to the problem of judging the allowable bending of piles.

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