DETERMINATION
OF
PILE DISPLACEMENTS
BY
INCLINOMETER MEASUREMENTS

IN

PARTIAL

FULFILLMENT OF THE

REQUIREMENTS FOR

CE 689

Submitted by: John A. Mundell

Submitted to: R. D. Holtz

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Introduction

Pile displacements and pile bending have been measured with the aid of the inclinometer for more than twenty-five years. In this time span, the results of such practice have been used to (1) predict the adequacy of pile supported foundations and retaining structures, (2) determine the effects of such factors as pile driving technique, pile splice construction, and pile-soil interaction on the load carrying capacity of steel, concrete, and composite section piles, (3) help interpret load and deformation characteristics observed during pile load tests, and (4) provide data so that new theories for predicting load carrying capacity of piles in situ can be developed.

Up until the use of the inclinometer, there had really been no way to rationally estimate the actual stresses and bending moments developed in the pile due to the bending action created during pile installation. With the gathering of the first field displacement data by Tschebotarioff in 1956, stress and moment distributions both in the pile and acting on the pile began to be studied extensively.

This paper will present a summary of the work that has been done with pile deflection measurements using the inclinometer. Measurement techniques and the reduction and interpretation of inclinometer field data will be discussed. Acceptance criteria and tolerance limits used in the Scandinavian countries for pile bending evaluation will be outlined to show what types of design standards are in use, especially where inclinometer measurements are an accepted part of practice. Finally, the control of factors governing pile bending using the inclinometer will be briefly examined as well as the use of the gathered deflection data to aid in the interpretation of pile load tests.

Pile Bending Studies Using the Inclinometer

One of the earliest reported applications of the use of the inclinometer for bending moment determination in sheet pile walls was done by Tschebotarioff and Ward (1957). Displacement measurements on five selected bulkheads were taken using the Wiegmann inclinometer and used to calculate the bending moments in the steel sheet piling by the methods outlined in Wiegmann (1953, 1954). Similar work by Bailly et al (1969), Thompson and Maitich (1961), and Kyle and Kapp (1957) followed. Figures 1 and 2 show the Wiegmann slope differential instrument and the measuring system used by Kyle and Kapp in their investigation of bulkhead deflections. Figure 3 shows the Wilson Slope Indicator used by Thompson and Maitich in their work.

The bending of composite piles approximately 40 meters in length observed using slope inclinometer measurements was reported by Parsons and Wilson (1954). The piles consisted of a 0.27 m diameter steel tube in the lower part and a 0.35 m diameter corrugated shell in the upper part. A minimum of 63 piles were bent to some extent, with some tip displacements measured up to 2 m from their intended positions. Johnson (1962) reported deflections of the pile tip as large as 10% of the pile length for long composite piles (27m) driven into sand.

Bjerrum (1957) observed the possibility of long steel H -piles buckling during driving installation. Work by Glick (1948), Gibson (1954), and Walter (1951) concentrated on the study of the effects of pile

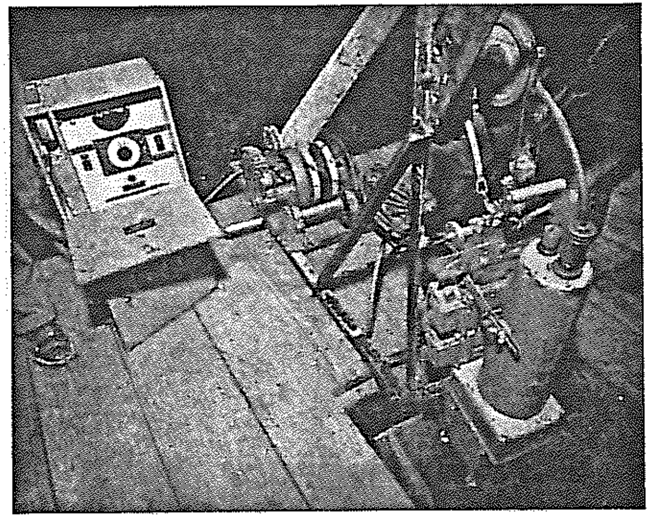


Figure 1. The Weigmann Slope Differential instrument used in making deflection measurements on bulkheads for Kyle and Kapp (1957)

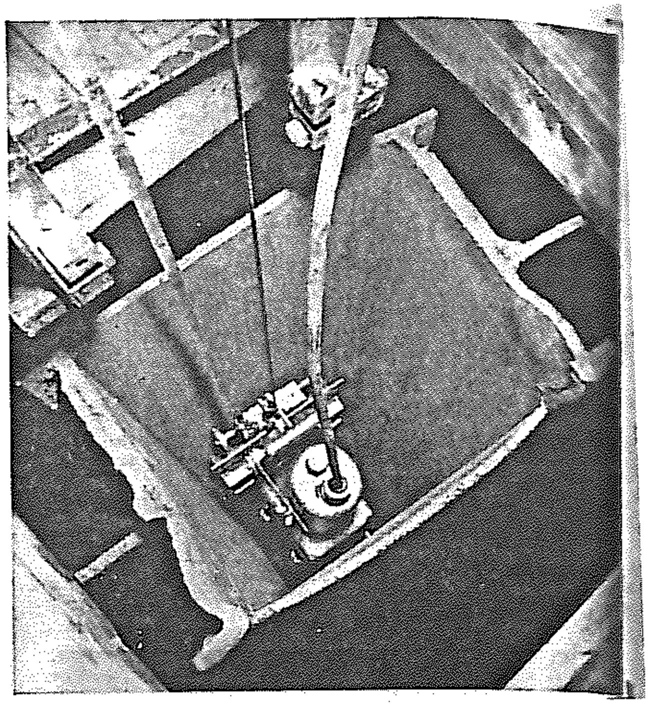


Figure 2. The Slope Differential instrument running down a special box pile. (Kyle and Kapp (1957))

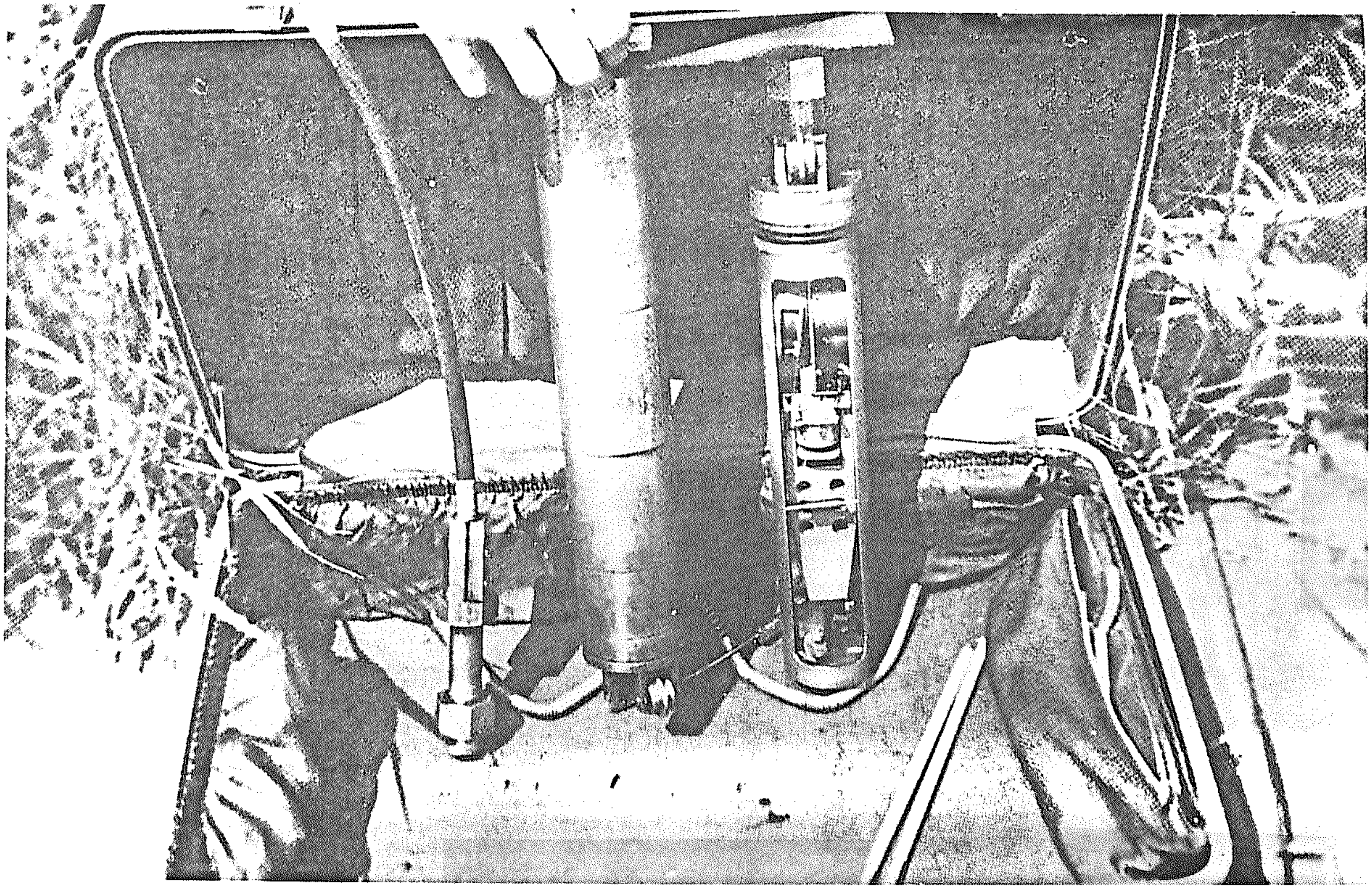


Figure 3. The Wilson Slope Indicator used by Thompson and Maitich (1961).

imperfections on the induced stresses during loading and the piles reduced ultimate buckling capacity. Following Bjerrum's work, Hanna (1968) used a Wilson Slope indicator to measure deflections of 44 m long H-piles driven through firm clays into bedrock. He found through these studies that very small bending radii (170 to 190 ft or about 60 m) could induce stresses in the pile section well exceeding the accepted standard values. It was noted that bending increased during load testing because the yield stress had been surpassed, thus indicating that long-term settlements of the pile would occur. Pile shortening due to bending was observed to have a great effect on the final founding elevation of the pile tip.

End bearing precast concrete pile bending was first studied in an investigation in southwestern Sweden in 1960 (Swedish Pile Commission 1964) using the S.G.I. slope inclinometer. The results showed the extent of pile bending observed in 60 m long piles driven through soft clays into bedrock. Certain procedures were recommended for minimizing the deviations from the vertical direction which occurred during the driving process. Similar studies by Pejrud (1965) and Hellström (1968) confirmed the observations made in the earlier studies. Laboratory tests run on model piles by Fellenius (1964) and Pejrud (1965) investigated the influence of pile diameter on the bending radius at failure and the ensuing reduction in bending strength due to cracking of the piles.

The recent work of Fellenius (1972) has provided a comprehensive review of Scandinavian practice. The results of the major reported cases of pile bending measurements are summarized in Table 1 taken from CHAN AND Hanna (1979). Hanna draws the following conclusions from these and other studies:

1. Pile bending or deviation during driving does occur in practice and is not restricted to a particular soil type, pile system, or pile length, although pile splices and imperfections are important.
2. The method of pile driving is believed to be important and factors such as obstructions in the ground, change in soil properties, and the presence of adjacent piles and nearby excavations have been singled out as possible causes of bending.
3. Little data is available on the response of bent piles to applied loads.

Measuring Procedure and Data Interpretation

It is outside the scope of this paper to discuss in detail the wide variety of slope inclinometers in use, and the different techniques needed to gather deflection data for each one. Instead, two different general methods for obtaining pile deflection data will be discussed, and the interpretation of the gathered data described. These methods were chosen because they are the most widely used and differ in the specific way in which the deflections are calculated.

The "Swedish" Method

In the "Swedish" method, the inclinometer is lowered into the center pipe (i.e. a precast hole usually made in the center of a precast pile, or welded to the side of the pile, see Figure 4 and 5a) by means of a series of pipes spliced by torsion stiff joints free to bend in all directions. The measuring body is then able to follow the curvature

Table 1. Summary of Reported Pile Bending Measurements (after Hanna, 1979).

Deviation of base, x (m)	Pile length, L (m)	x/L (%)	L/d*	Pile and soil details	Source
1.37	18.0	7.6	55	End bearing composite† pile, through silt to schist bedrock	Parsons and Wilson (1954)
3.04	27.4	11.1	75	Friction composite pile, in sand	Johnson (1962)
3.19	25.9	12.3	78	End bearing composite pile, through silt to dense sand	Mohr (1963)
11.0	60.0	18.3	218	End bearing precast concrete pile, through soft clay to bedrock	National Swedish Council for Building Research (1964)
1.85	24.6	7.5	69	Friction steel H-pile, through stiff clay and dense sand to hard clay	Worth *et al.* (1966)
2.16	42.6	5.1	120	End bearing steel H-pile, through soft to stiff clay, to shale bedrock	Hanna (1968)
2.65	40.0	6.6	133	End bearing precast concrete pile, through soft clay to mudstone bedrock	Fellenius (1972)
1.06	12.0	8.8	47	End bearing steel H-pile, through soft to firm clay, to limestone bedrock	Kim and Brungraber (1974)

*d = diameter or width of pile.
†Steel pipe filled with concrete after driving.

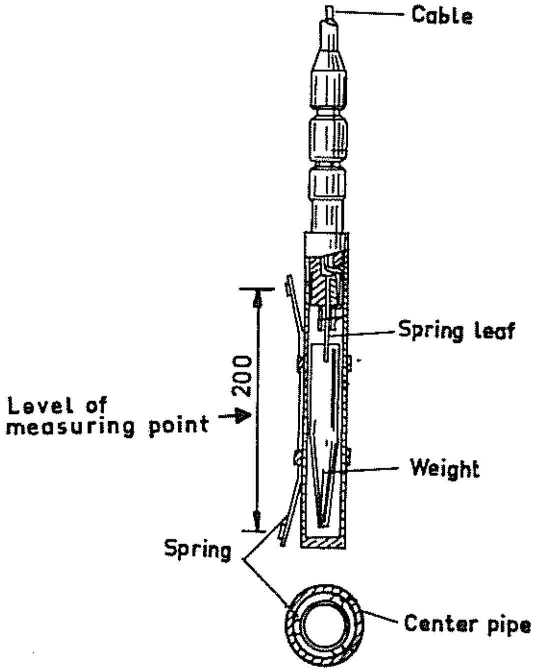


Figure 4. The measuring body of the SGI inclinometer, showing the precast hole for lowering instrument into the pile (Fellenius 1972)

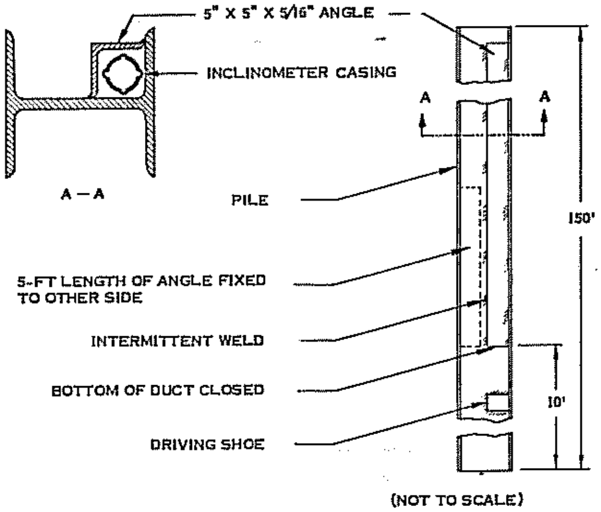


Figure 5. Detail of a welded inclinometer duct for steel H-section piles (Hanna 1968).

of the center pipe and record its horizontal direction by means of a precision levelling instrument mounted on a protractor, as shown in Figure 5b and 6. Thus, at each measuring depth, the instrument may be rotated until the maximum inclination and its horizontal orientation are determined. Measurements are generally taken every 1.0 m (3.3 ft). Near the segment ends, the locations of the measuring points are adjusted so that they are at even 1.0 m distance from the splice. Two additional measurements are taken 0.5 m above and below the splice.

For each measuring point along the pile depth profile, the inclination (v) and the horizontal direction of the inclination (β) are obtained. The coordinates (x,y,z) of the measuring points in space can be calculated by the following formulas:

$$X_n = \sum_{i=1}^{n} L_i \sin v_i \cos\beta_i$$

$$Y_n = \sum_{i=1}^{n} L_i \sin v_i \sin\beta_i$$

$$Z_n = \sum_{i=1}^{n} L_i \cos v_i$$

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

The distance from the vertical line through the pile head (r_n) is:

$$r_n = \sqrt{X_n^2 + Y_n^2}$$

The bending radius (R) is:

$$R = \frac{L}{\Delta v} \cdot \frac{180}{\pi} = \frac{L}{\Delta\alpha}$$

For a helical curve:

$$R = \frac{L \cdot 180}{\theta \cdot \pi}$$

Where: $\cos\theta = \cos v_i \cos v_{i+1} + \sin v_i \sin_{i+1} \cos\left|\beta_i - \beta_{i+1}\right|$

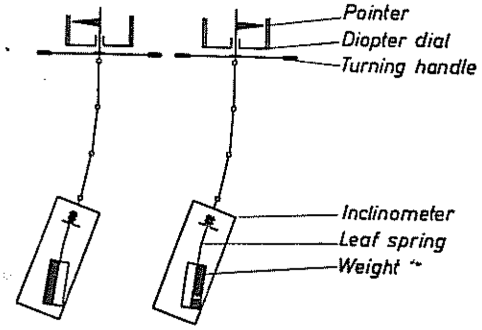


Figure 5.b Measuring position of the inclinometer.
(Kallstenius and Bergau, 1961)

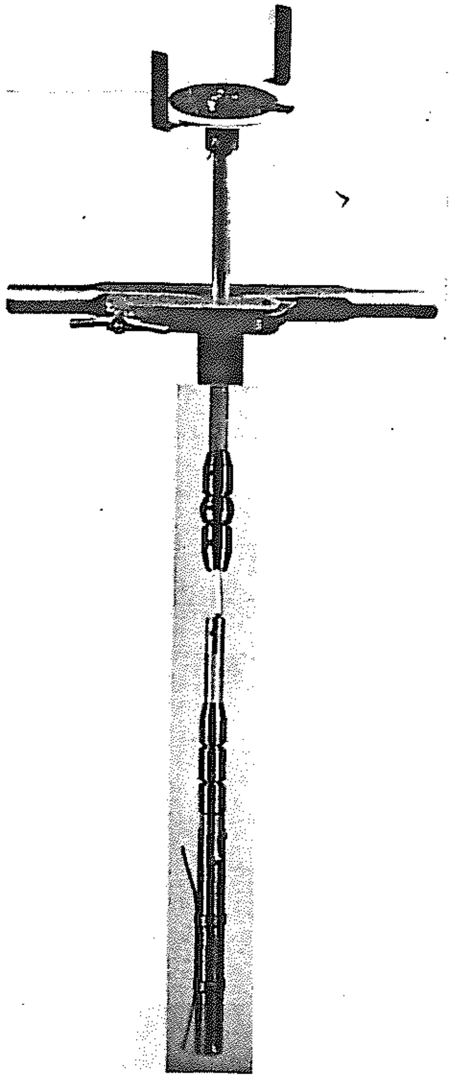


Figure 6. SGI inclinometer mounted on the swivel protractor setup. (Kallstenius and Bergau, 1961)

The pitch or height of arc (h) can be calculated by:

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

Refer to Figures 7 and 8 for a graphical representation of the formulas given above.

The "U.S." Method

In the "U.S." Method, the casing into which the inclinometer is lowered to take readings contains two sets of grooves oriented perpendicular to each other. These act to guide the inclinometer down through the casing, and thus, deflection readings may only be taken in these two directions (usually oriented or labeled as North-South, East-West). The maximum deflection and its horizontal orientation are taken as the resultant of the two readings at any given depth.

For each measuring point along the pile depth profile, the inclination (v) in two perpendicular directions may be obtained. The (x,z) and (y,z) coordinates of the measuring points in space can then be calculated by the following formulas:

$$X_n = \sum_{i=1}^{n} L_i \sin v_{i_x}$$

$$Y_n = \sum_{i=1}^{n} L_i \sin v_{i_y}$$

$$Z_n = \sum_{i=1}^{n} L_i \cos_i$$

where L_i is the slope distance between measuring points i and i-1. The distance from the vertical line through the pile head, the bending radius, and the pitch are calculated using the resultant determined from the two perpendicular directions.

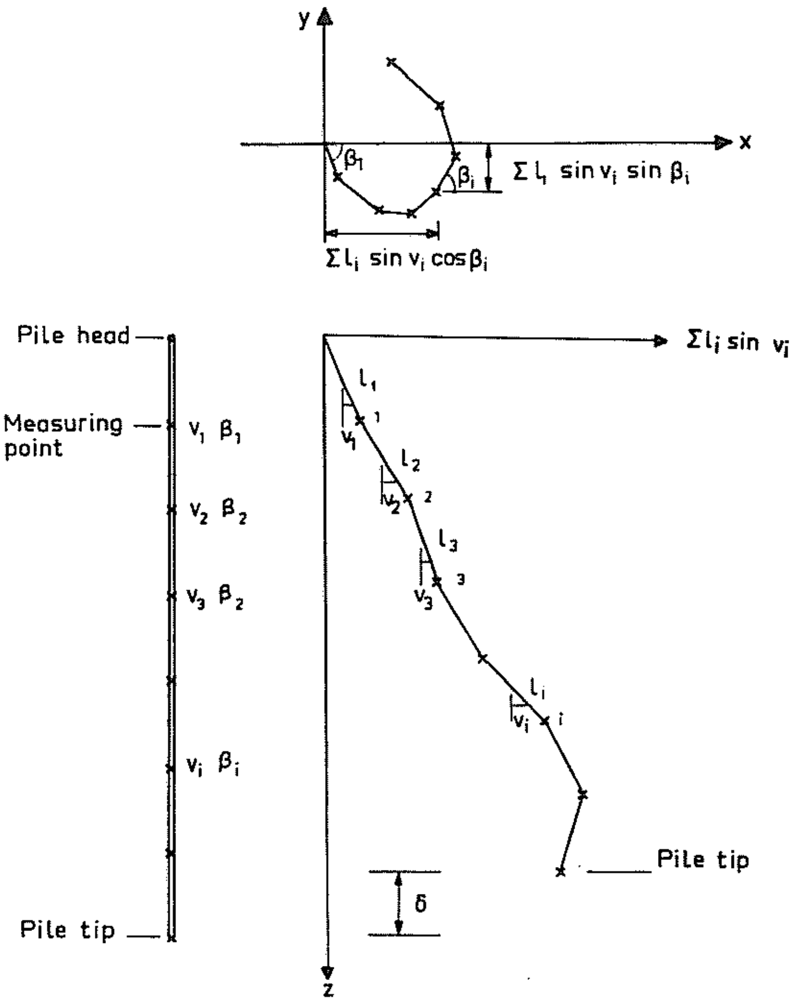
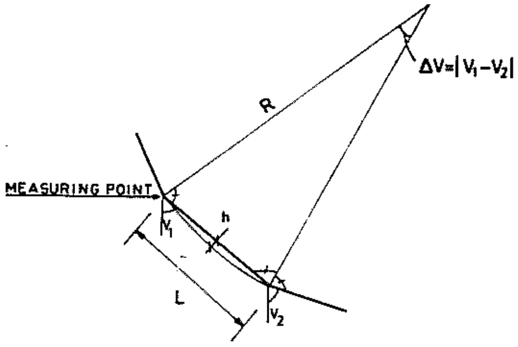


Figure 7. Calculation of the location of the pile in the ground. v = inclination, β = horizontal direction of inclination, δ = apparent pile shortening, L = slope length of pile between measuring points. (Fellenius 1972)



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

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

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

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

Figure 8. Formulas for the bending radius and the pitch of the arc. (Fellenius 1972).

Figures 9 and 10 show the results of the studies down by Hanna (1968) on steel H-sections. Measured deflection components, pile bearing vs. depth, and driven pile position have been determined using calculations similar to those shown above. Position of piles after driving are shown in Figure 11 for precast concrete piles, as determined by Pejrud (1965).

Evaluation of Pile Bending

There have been many attempts to define acceptable criteria for the rejection of a pile that is bent after driving. Hollow steel piles have been rejected if a light that has been lowered into the pile cannot be seen along the entire length (Hanna 1970, Hjeldness 1980). Non-acceptance of this same pile type has occurred if a specified length of steel rod cannot be lowered to the bottom of the pile.

[illegible]

Standard practice in Norway and Sweden has been to specify the straightness of pile segments before pile driving, and then to place a limit on the minimum radius of bending a pile can have after driving (Bjerrum 1957, Hellman 1967, Swedish Building Code 1968). Because the evaluation of pile bending from inclinometer measurements has been performed in the Scandinavian countries since 1959, code requirements providing acceptance criteria and tolerance limits have been established to guide the standard practice. No equivalent U.S. practice exists at this time, because of the limited use of inclinometer measurements in pile evaluation. It is for this reason that the following discussion is based almost exclusively on Scandinavian practice for precast concrete piles.

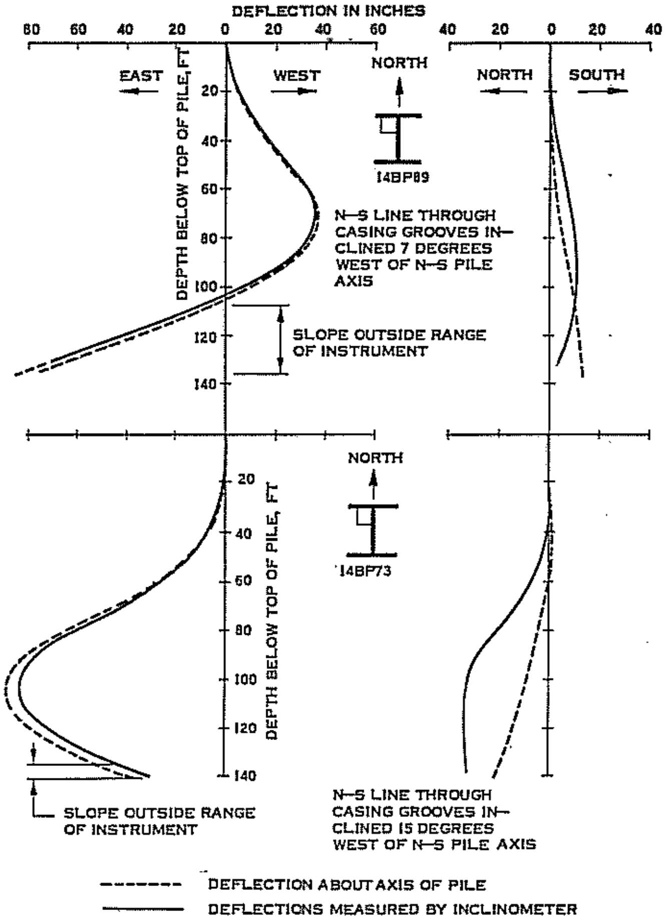


Figure 9a. Measured deflection components of steel H-section piles (Hanna 1968)

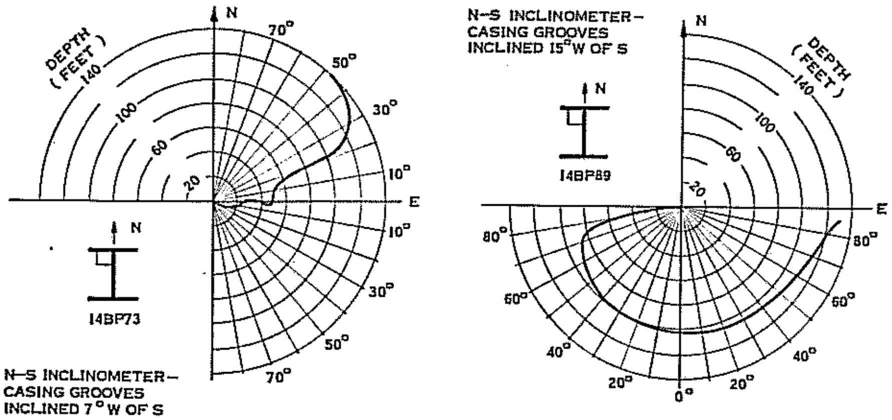


Figure 9b. Bearing of pile vs. depth relationship for driven steel H-section piles (Hanna 1968).

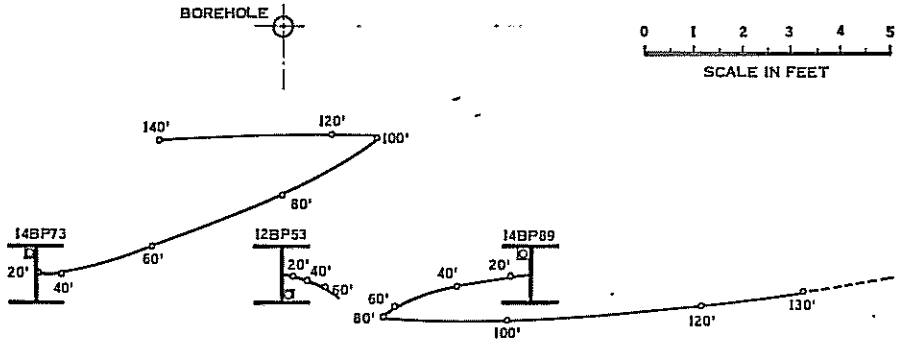


Figure 10. Driven position of steel H-section piles (Hanna 1968).

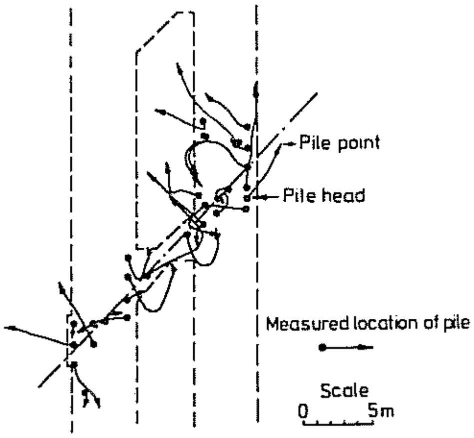


Figure 11. Measured positions of pile top and toe of precast concrete piles for a railway bridge abutment (after Pejrud 1965).

Pile Bending Criteria: Sweden

The evaluation of pile bending is based on the idea that the yielding of the concrete or steel piles may occur in the zones of minimum curvature (radius). Therefore, the method for determining the adequacy of a pile is to calculate the bending radii of the pile under investigation along its entire length using the inclinometer deflection measurements, and then compare these values with those that have been accepted as the standard tolerance limits. If the pile's minimum radius is greater than the allowable minimum radius, then the pile is regarded as satisfactory.

Allowable Bending Before Driving

Maximum Deviation of Pile Segments:

The 1968 Swedish Building Code allows for a maximum deviation of the pile centerline, expressed in terms of bending radius with $h = 0.002L$, of: $R = 62.5\ L$. For example, a 10 m long pile segment can be allowed a deviation from the pile centerline corresponding to a bending radius of 625 m. This code requirement limits the bending that may be allowed to occur during handling and transportation of the piles.

Squareness of the Steel Couplings:

Noncompliance with this code specification increases the likelihood that the pile will break or experience excessive bending between splices during driving. The maximum allowable out-of-square coupling value per splice is $1{:}75 = 0.8^\circ$. Using this value in equation 3, and taking a length, L, equal to 1 m, 0.5m above and 0.5m below the splice, the minimum allowable bending radius can be calculated as: $R = L/\Delta\alpha = 1/(1/75) = 75\text{m}$.

Allowable Bending After Driving

The evaluation of pile bending after driving should be separated into bending over the splices verses bending over the pile segments. Because of their inherent differences structurally, bending requirements for each of these sections have been adapted to properly determine the adequacy of each one.

In general, specified allowable bending requirements are not available for different pile types and sizes in different soil conditions subjected to different working loads by structures of different sensitivities to settlement. Realistically, all of these factors must be considered to sufficiently evaluate the deflection measurements from the inclinometer. The Scandinavian practice is based on the use of relatively slender precast concrete piles, with a maximum diameter of 10 to 12 inches and a maximum pile segment length of 12m (40 ft). A more slender pile can be allowed a larger bending than can a pile of a larger diameter because of differences in deformation characteristics. In the case of a longer pile segment, the tolerance limit values of bending radii should be increased, and for shorter segment lengths, they should be decreased.

The Swedish Code requirements which follow are not considered conservative by all authorities in Scandinavia. Some apply stricter requirements. None are less strict.

The Splice

Large occurrence of bending over the splices may indicate that either the coupling is defective or the casting of the coupling into the pile is unsatisfactory. The bending over the pile splices is evaluated by determining both the change of inclination and the bending radius over the splice. The maximum change of inclination over the splice between the points 0.5m above and 0.5m below the splice, is 0.75° /m (0.23° /ft). This corresponds to an out-of-squareness tolerance of 1:150 of each pile segment end, or a 1:75 per splice. Values greater than this are defined as "dog-legs" in the pile.

The minimum bending radius over the splice, between the points 1.0m above and 1.0m below the splice, is 100m (330 ft).

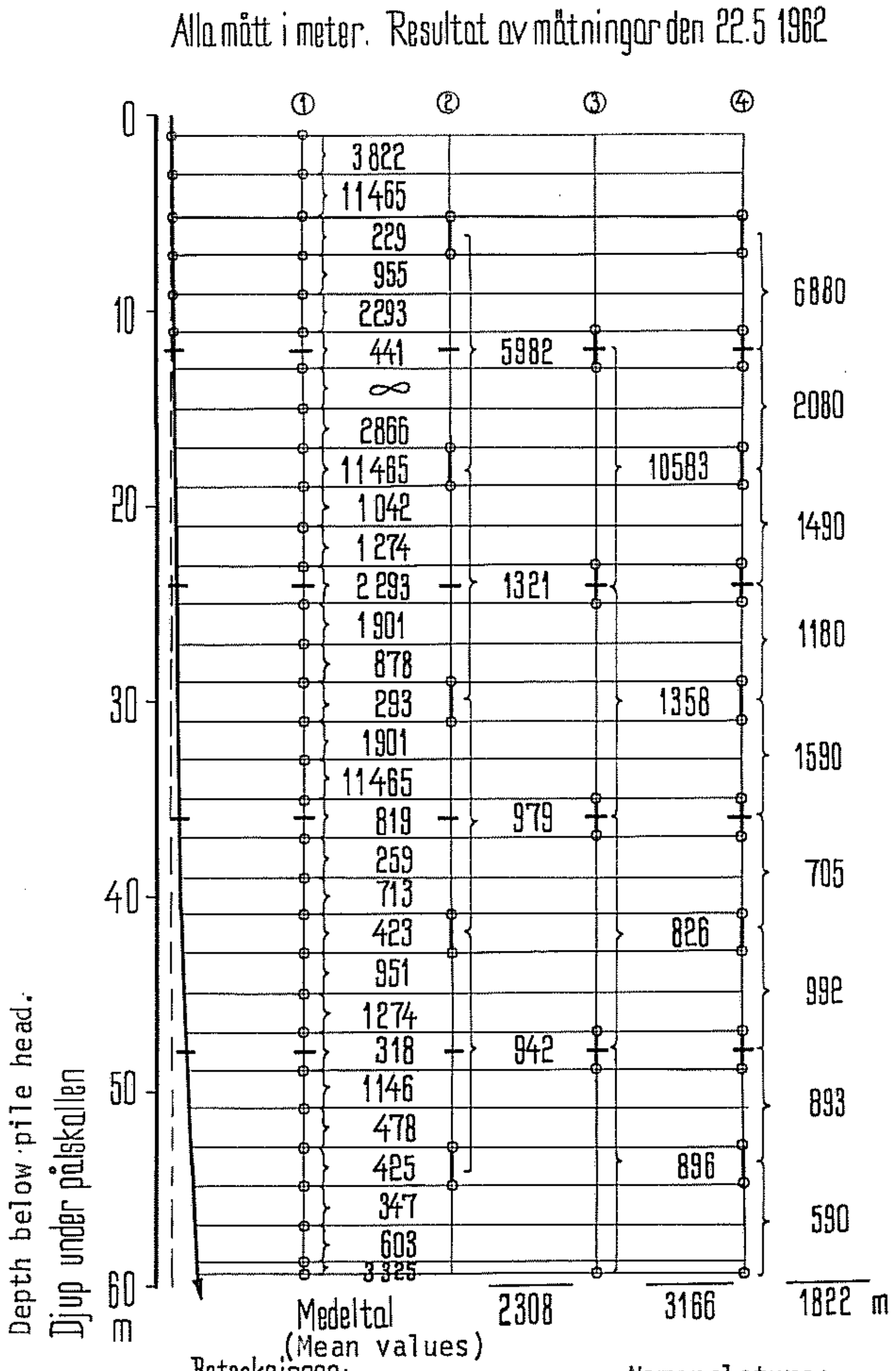
The Pile Segment

The maximum change of inclination over the pile segment to check for dog-legs as measured every 1.0m is 0.7° /m (0.23 /ft), relating directly to a bending radius of 75m (250 ft). Laboratory studies by Fellenius (1964) showed that ultimate bending failure for 10 to 12 inch diameter piles could occur at 0.7° to 1.2° /m bending change, or a bending radius of 80 to 50 m (250 to 150 ft).

The maximum bending radius over the pile segment of 10m (measured 1.0m below the upper end and 1.0m above the lower end) is 300 to 400m (1000 to 1300 ft). The lower limit is applied to stiff soils, or in the lower part of the pile, and the higher limit to soft soils, or in the upper portion of the pile.

Figure 12 shows the results of inclinometer measurements and the resulting calculated bending radii evaluated along the concrete piles tested at Gubberö, Gothenburg (1964). It can be noticed that bending radii were calculated across pile segments and across pile splices.

All measurements in meters. Results of Measurements May 5, 1962.



Beteckningar:	Nomenclature:
+ Pålskarv	Pile joint
ϕ Måtpunkt	Measuring point
Medelvärdet av lutningsvinklarna i dessa mätpunkter har använts	Mean value of the slope angles in these Measuring points.
Krökningsradien har beräknats mellan dessa punkter	Curvature radii have been calculated between these points.

Figure 12. Inclinometer measurements and calculated bending radii for precast concrete piles tested at Gubberö, Gothenburg Sweden (1964)

Figure 13 shows the results of inclinometer measurements performed on a 12-inch hexagonal precast concrete reference pile driven with Herkules splices and shoe, through dense bouldery soil. (Fellenius, 1980). A summary of the measurement interpretation shown in Table 2 reveals that the pile complied satisfactorily with the code requirements, demonstrating the degree of straightness that can be achieved when the factors governing pile bending are controlled (see pg.22).

Table 2 Inclinometer Measurements of a reference 12-inch Hexagonal Precast Concrete Pile (Keehi Report, Fellenius 1980)

Change in Inclination °/m		Change of Direction of Inclination (°)	Bending Radii meters	
Nonhelical	Helical		over splice	over segment
0.10	0.13	5	820	1500
0.09	0.25	10	730	760
0.16	0.16	0	890	1200
Allow. Limit 0.75			100	300-400

Pile tip Deviation from a straight line starting from pile head. = 0.46m (1.5 ft) or 1.2%

Control of Factors Governing Pile Bending

By using the inclinometer to measure pile deflection and, therefore, pile bending in situ, many of the factors governing pile bending

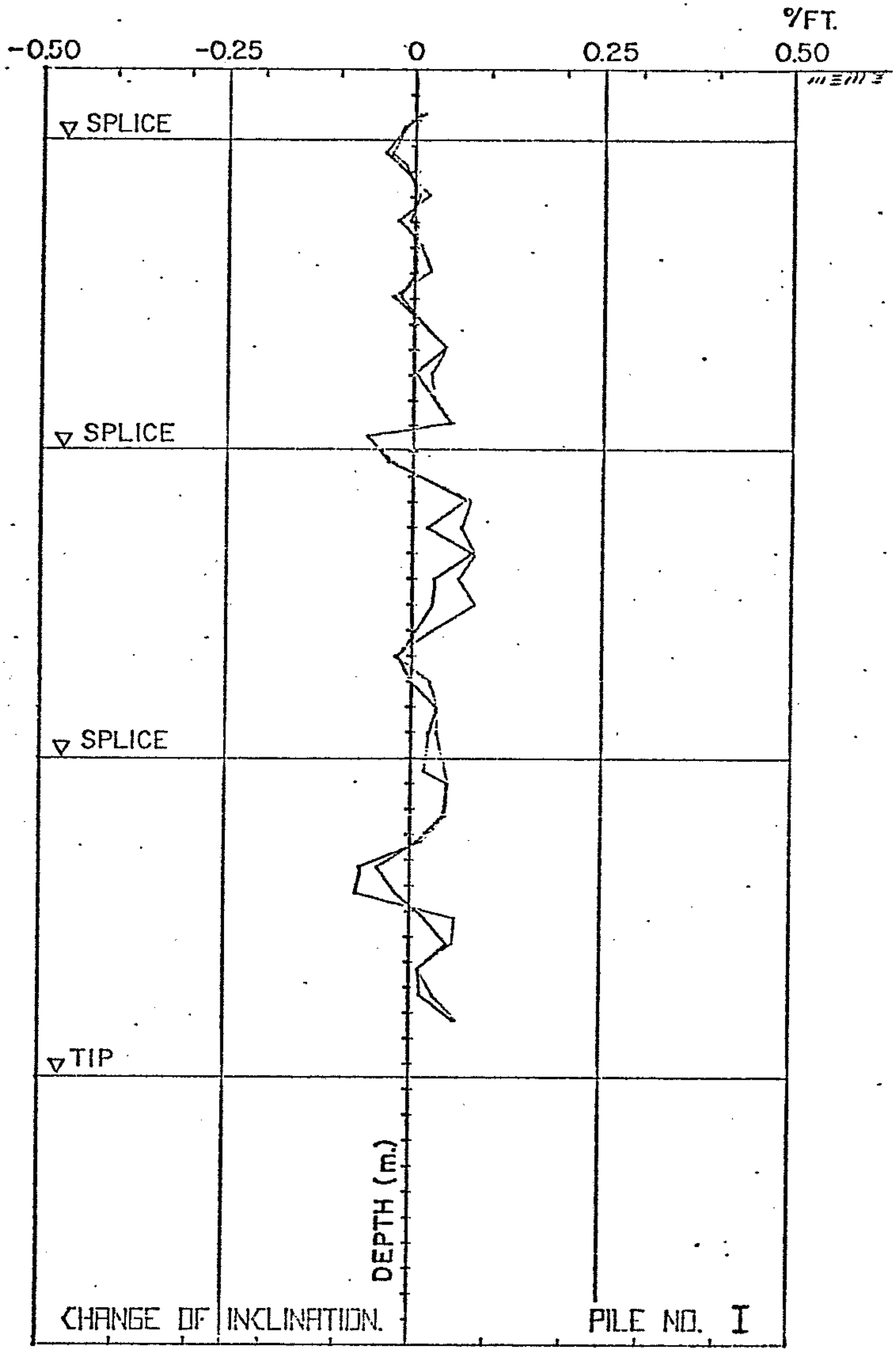


Figure 13. Change of inclination ΔV/ΔL and Δθ/ΔL °/ft for a 12-inch hexagonal concrete reference pile with Herkules splices. (Fellenius, Keehi Report, 1980).

have been evaluated for various pile driving programs (Swedish Pile Commission 1964, Bjerrum 1957, Fellenius 1964). By varying these independent pile-pile driving variables, the effect on the dependent variable of pile bending can be measured with proper inclinometer instrumentation. These factors and their effects on pile bending are as follows:

1. Symmetry and Straightness of the Pile Segments

   This is to insure an even stress distribution over the pile cross section and to the soil. The more symmetric and straighter the pile, the less bending that occurs.

2. Shape of the Pile Tip

   The more pointed, symmetrical, and square the pile tip is, the less bending is likely to occur because of the reduction of soil bending forces (eg. boulder obstructions, sloping bedrock surface).

3. Bending Stiffness Relative to the Pile Diameter

   As bending stiffness increases with a constant diameter, the pile's resistance to dynamic bending forces applied by the soil increases, thus decreasing bending.

4. Positioning of Pile Segments to be Spliced with Respect to Driven Pile Segment

   Rotating the segments 180° at each splicing in precast concrete piles decreases bending. During casting of the segments, the upper section of the pile segments develops a lower elastic modulus than the lower part. This difference, when spliced together, can increase the potential for pile bending.

5. Strength of Pile Splice with Respect to the Pile Segment

   Splices designed with full moment capacity considerations are able to resist bending forces at very low angular deviations of the pile segments, thus reducing bending.

6. Alignment of Driving Hammer with The Pile

   The more concentric and parallel the alignment, the greater the potential for less bending of the pile segments.

7. Hammer Impact during Driving

   Excessive tension in the pile along with bending tensile forces increase the potential for greater pile bending.

8. Difficulty of Pile Driving Conditions

   Potential for bending increases with the number of hard obstacles or changes in soil conditions. Reduction of bending for steel piles may occur if pre-augering is done through the rough driving conditions (Hanna 1968).

With the aid of the inclinometer, the above factors may accurately be accessed for any specific situation, and the most efficient combination of pile driving characteristics then used to reduce pile bending to a minimum.

Interpretation of Load Tests: General

Because the degree of pile bending or misalignment may be determined using the inclinometer, subsequent load testing performed on such "instrumented" piles may be interpretted with respect to these measurements.

Because of bending, the tip of the pile may be located at a higher elevation than the location given by the straight pile intial assumption (refer again to Figure 7). Because of such apparent shortening (Hanna 1968 observed as much as 30 inches for steel H-sections), driving to the predetermined elevation and "set" does not guarantee that such a pile is adequately founded. Thus, load testing results which may give misleading deformation and bearing characteristics of a soil or rock stratum can be re-evaluated in light of the inclinometer observations.

If excessive bending has been measured in the pile suggesting possible localized yielding at certain locations along the pile, then load test results which produce large deformations at relatively low loads can be looked at in view of pile-damage concepts.

Without the use of the deflection measurements from inclinometer readings, load tests on bent piles cannot be evaluated adequately. With such measurements, all available information can be used to make proper decisions concerning the adequacy of the driven piles.

Conclusions

The use of the inclinometer for measuring pile displacements has been shown effective in determining the adequacy of pile foundations. By interpreting these measurements for various pile types and sizes, pile installation procedures, and soil-rock conditions, the primary factors governing pile bending have been identified, and can thus be controlled to some extent. Allowable bending stresses, as measured by minimum bending radii, have been established in Scandinavian practice, but have yet to be agreed upon by different pile authorities.

For any pile bending inspection program using the inclinometer, the allowable bending criteria must be established based on:

Pile Characteristics

-pile type, pile length, pile segment length, pile stiffness with respect to length (length vs. diameter), squareness and strength of splices.

Soil Characteristics

-sloping bedrock, presence of boulders or other obstacles, changes in soil conditions

Structure Characteristics

-working loads, sensitivity to settlements, pile spacing

Because of the high cost of instrumenting piles, inclinometer measurements are normally done on test piles only, but may be used on actual contract piles if load capacities can be increased and a sufficient savings realized.

The combination of pile load testing with the use of inclinometer measurements can provide valuable information concerning the effects of the observed pile bending on the load and deformation characteristics of the pile. More research must still be done on the stresses and bending moments developed in piles during the driving process. The possible use of strain gages and load cells along with actual deflection measurements could ultimately prove to be the method that will yield the most accurate results concerning what is actually happening to the pile during the driving process.

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