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Publication date:
1999

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Rasmussen, J. L., & Feld, T. (1999). *Pile Driving Fatigue Damage. A Case Story*. Geotechnical Engineering Group. AAU Geotechnical Engineering Papers : Foundation Engineering Paper Vol. R 9903 No. 14

AAU Geotechnical Engineering Papers

ISSN 1398-6465 R 9903

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June 1999

Foundation Engineering Paper No 14

GEOTECHNICAL ENGINEERING GROUP
AALBORG UNIVERSITY DENMARK

Rasmussen, J.L., Feld, T. (1999). Pile Driving Fatigue Damage. A Case Story.

AAU Geotechnical Engineering Papers, ISSN 1398-6465 R9903.

Foundation Engineering Paper No 14

The paper has been published in *Proc. XII Eur. Conf. Soil Mech. Geotechn. Eng.* 7-10 June 1999, Vol. 2, pp. 577-582.

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Pile Driving Fatigue Damage, A Case Story
Dégâts de Fatigue en Battage de Pieu, un exposé d'un cas concret

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Keywords: Driveability, Fatigue, Pile, Concrete Pile, Hammer, Recommendations.

ABSTRACT: Concrete piles were driven by a hydraulic hammer for a new heavy loaded building at a refuse disposal plant, located in Copenhagen, Denmark. Some of the piles got fatigue damage during driving. The fatigue damage was due to the fact that the piles were driven with too much energy, and the falling height was too high compared to the total number of blows. The investigation concluded that it was necessary to decrease the falling height of the hammer with increasing total number of blows, or reduce the falling height with increasing driving resistance. Finally recommendations are given for the falling heights of the hammer compared to the total number of blows in order to avoid fatigue damage on concrete piles.
RÉSUMÉ: Des pieux en béton étaitent battus par un mouton hydraulique pour un nouveau bâtiment fortement chargé à une usine d'incinération, située à Copenhague, Danemark. Quelques-uns des pieux ont eu des dégâts de fatigue en cours du battage. Les dégâts de fatigue résultaient du fait que les pieux étaient battus avec trop d'énergie, et l'hauteur de chute était trop élévée en comparaison du nombre total de coups. L'examen a conclu qu'il était necessaire de réduire l'hauteur de chute du mouton avec un nombre total de coups augmentant, ou réduire l'hauteur de chute avec une résistance de battage augmentant. Enfin des recommendations ont été données pour les hauteurs de chute comparées au nombre total de coups pour qu'on n'ait pas de dégâts de fatigue aux pieux en béton

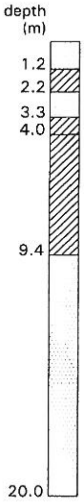
1 INTRODUCTION

The foundation of a new heavy building consisted of a piled foundation with 0.4×0.4 m^2 reinforced concrete piles. The piles were driven with a hydraulic 60 kN hammer. Some of the piles got refusal before the target penetration. These piles were driven with a stroke up to 1.0 m. These too high falling heights compared to the total number of blows resulted in pile driving fatigue damage on the piles.
A driveability study on a 0.4×0.4 m^2 concrete pile was carried out using the GRLWEAP program. This commercial driveability program calculates the stress gab in the individual pile element for each blow, the stresses form the input to the fatigue analysis, carried out as described by NS 3473 Code.
A computer program developed by RAMBØLL was designed to carry out the calculation of the fatigue damage ratio for different pile elements with given stress histories.

2 DRIVEABILITY STUDY

2.1 *Soil Condition*

The characteristic soil parameters used in the study are depicted in Figure 1. The upper sand layer (0 - 1.2 m) is fill and the clay and sand layers down to 4 m below the ground level are post glacially deposits. The clay layer from 4 to 9.4 m below ground level is glacial clay till, while the pile tips is placed in a glacial sand layer below 9.4 m.



DESIGN PARAMETERS

Soil type	γ' (kN/m³)	φ (deg)	c_u (kPa)	E (MPa)	ϵ_{50} (%)	t_c (kPa)	t_t (kPa)	q (MPa)
SAND	18.00	35.0		6.5		5.0	5.0	0.4
CLAY	20.00		125.0	50.0	0.2	44.3	44.3	1.1
SAND	18.00	35.0		14.2		23.8	23.8	1.7
CLAY	20.00		165.0	66.0	0.2	66.2	66.2	1.5
CLAY	10.00		165.0	66.0	0.2	73.2	73.2	1.5
SAND	9.00	38.0		39.7		92.0	92.0	8.7

γ' : Submerged unit weight
φ : Angle of internal friction
c_u : Undrained shear strength
E : Modulus of elasticity
ϵ_{50} : Strain which occurs at one-half of the maximum stress in laboratory undrained compression test
t_c : Unit skin friction, compression
t_t : Unit skin friction, tension
q : Unit tip resistance, compression

SCOUR: Local scour: 0.0 m
Glocal scour: 0.0 m
Scour angle: 0.0 deg

Figure 1. Characteristic Soil Parameters.

The driveability study was carried out using the computer program GRLWEAP. In the analysis the soil parameters in Figure 1 and following dynamic parameters were used:

Table 1 Dynamic Parameters used in Driveability Study

Dynamic Parameters		
Quake		2.5 mm
Damping clay	side	0.65 s/m
Damping clay	side	0.65 s/m
	tip	0.50 s/m
Damping sand	side	0.16 s/m
	tip	0.50 s/m

It was assumed that the dynamic skin friction is equal to the static skin friction times an empirical e-factor taken as 0.7 as an expected value for a hydraulic hammer. The result of the driveability study is given in Figure 2.
The predicted driving resistance was in accordance with the observed driving resistance.

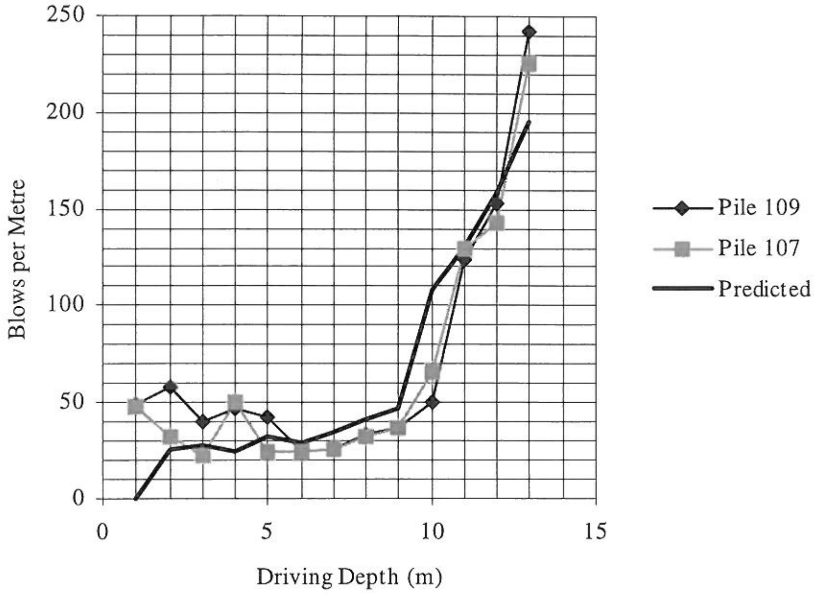


Figure 2. Observed and Predicted Driving Resistance.

2.2 *Pile Data*

The piles were 0.4 × 0.4 m^2 prestressed concrete piles with a length of 18 m. The piles were coated on the upper 4 m in order to limit the down drag from the upper post glacial layers.

2.3 *Pile Driving Equipment*

The piles were driven with a 60 kN hydraulic Junttan hammer. The stroke of the hammer during the driving varied from 0.20 m in the beginning to 1.0 m at the last 2.5 m of the driving of pile no 107, and from 0.2 m to 0.80 -1.0 m at the last 5 m for pile 109.

3 PILE DRIVING FATIGUE ANALYSIS

The pile driving induced partial fatigue damage was calculated using the following procedure: Each pile was divided into a number of elements during the driveability analysis. Output from the computer program, GRLWEAP can be ordered to specify maximum and minimum stress for each element at each depth analyzed, following the stress gap was calculated from these stresses.
For each element the fatigue damage was calculated in accordance with Palmgren-Miner's equation for each driving depth as:

$$\eta = \sum_{i=1}^{i=n} \frac{n_i}{N_i}$$

where η = the partial damage; n_i = number of blows for a given stress gab; and N_i = the number of blows for fatigue damage.
N can be calculated in accordance with the following equation proposed by Aas-Jacobsen (1970). When this equation is unity, fatigue damage will occur.

$$\left(\frac{\sigma_{max}}{f_c}\right) + 0.064 \cdot \left(1 - \frac{\sigma_{min}}{\sigma_{max}}\right) \cdot \log N = 1$$

where σ_{max} = the maximum compression stress; σ_{min} = the maximum tension stress; f_c = the concrete reference stress, taken as 15.6 MPa; and N = number of blows.
In Table 2 the partial fatigue damage is given. At a driving depth of 15 meter the fatigue damage was greater than 1.0. The fatigue damage on the pile is illustrated on Figure 3.

Table 2 Partial Fatigue Damage.

Driving Depth (m)	Blows per meter	Stress Gab (MPa)	Fatigue Damage
7	26	9.9	2.2×10^{-8}
8	28	14.7	1.8×10^{-5}
9	24	14.7	3.3×10^{-5}
10	32	14.7	5.6×10^{-5}
11	29	18.5	3.9×10^{-3}
12	35	18.5	8.3×10^{-3}
13	41	18.5	1.3×10^{-2}
14	47	18.5	1.9×10^{-2}
15	108	21.8	1.3
16	131	21.7	2.6

The interval between the crushed zones is measured to approximated 0.30 m as expected the pile width divided by √2.

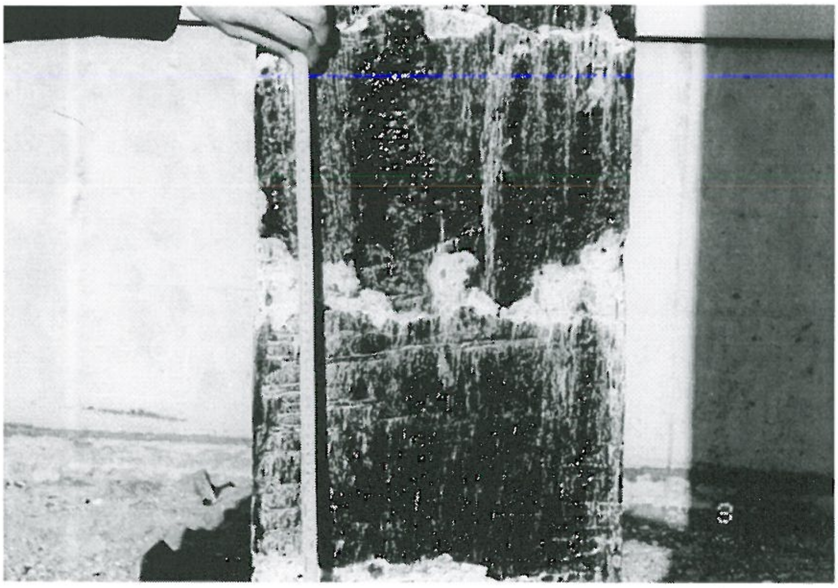


Figure 3. Fatigue Damage on the Pile

4 RECOMMENDATIONS

Based upon the results from the driveability study the stresses in the pile can be assessed for different stroke values. With the given stroke and the stresses the number of blows can be calculated in order to get the fatigue damage 1.0. In Figure 4 the total number of blows are given compared to the stroke. It can be seen that for the actual pile the stoke should be limited to 0.5 m in order to avoid fatigue damage in the actual concrete piles.

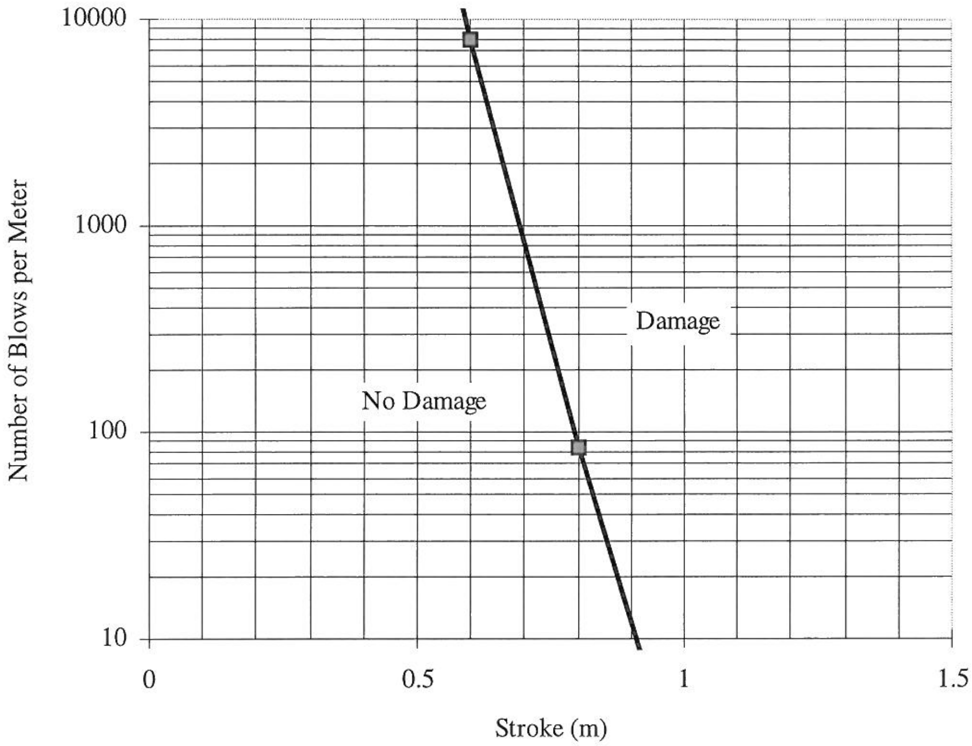


Figure 4. Total Number of Blows versus Stroke

In Figure 5 the results of the driveability study for stroke up to 1.0 m and for maximum stroke 0.5 m are given. If the stroke of the hammer had been limited to 0.5 m the piles could have been driven to target penetration without fatigue damage.

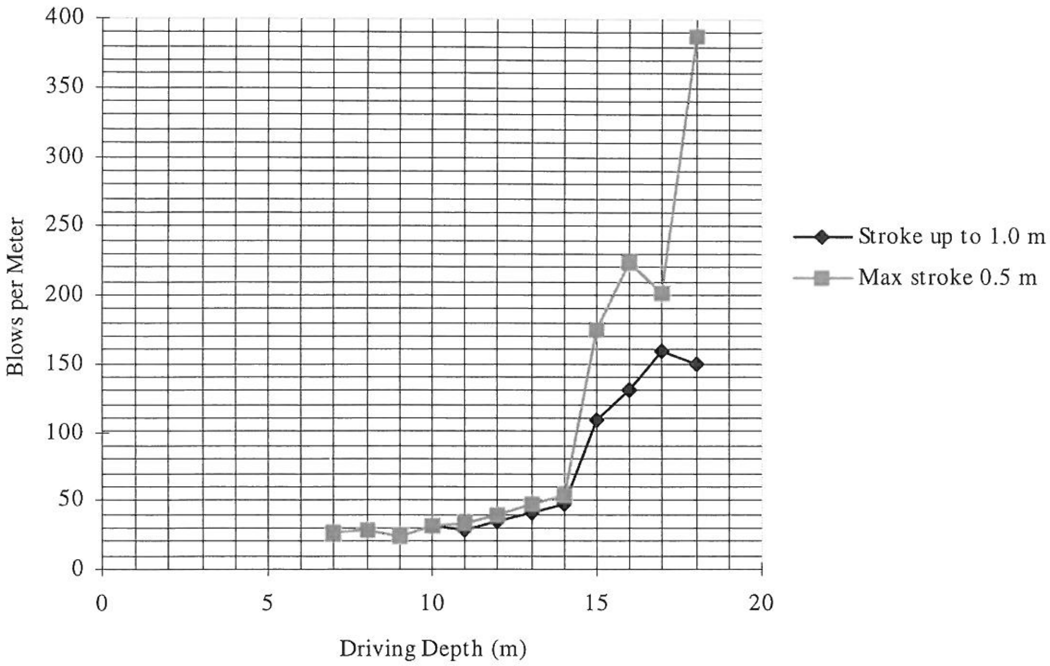


Figure 5. Expected driving Resistance for max. Stroke 1.0 m and Limit Stroke 0.5 m.

Generally it is recommended for concrete piles to limit the stroke of hammers to 0.5 or 0.6 m in order to avoid pile driving fatigue damage.

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