Efficiency analysis of hydraulic Junttan pile driving hammer

Analyse d'efficacité du marteau Junttan hydraulique pour enfoncer les pieux

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ABSTRACT: The main results of hydraulic hammer study held in Hong Kong in 1994 are presented. The tests included stress wave measurements of four different hydraulic hammers and one open ended diesel hammer at three different sites by using two different types of piles. Stress wave measurements were analyzed by CAPWAP-program and static load tests were performed. All hydraulic hammers were provided by manufacturers' own kinetic energy measurement equipment which enables the determination of driving system efficiencies. According to measurements the hydraulic hammers were much more efficient than the dieselhammer. In addition differences between various hydraulic hammers can be found. Stress wave measurements for Junttan HHK-9A-hammers were further analyzed with GRLWEAP-program and by using an analytical approach. A simple dynamic piling formula is suggested from the results.

1 INTRODUCTION

In 1994 Hong Kong Construction Associated, Ltd. arranged a Hydraulic Hammer Study in Hong Kong. The aim of the test was to establish the efficiences of various hydraulic hammers and to develop a simple pile driving formula for these hammers. The performance of dieselhammers are well established in Hong Kong, but an application method for the use of hydraulic hammers is lacking.

The working system of a typical hydraulic hammer differs from that of a dieselhammer and the transmitted energy to the pile is quite independent of the pile behaviour. With the dieselhammer the dropheight of the ram depends on the soil resistance acting on the pile. In hard driving the ram rises high and the transmitted energy to the pile is thus comparable with the potential energy of ram provided that the cushions behaves in a similiar manners as with lower strokes. In easy driving the hammer does not neccessary even start, because the combustion may not be initiated.

Manufacturer's rated energies for their hammers are valuable data for driveability studies and for the choice of hammer to the pile driving operation. The rated energy is often the maximum potential energy of ram, but it may also be maximum kinetic energy of ram before impact. The latter comes into question primarly with double-action hydraulic hammers where the motion of the ram can not always be visually seen. For driveablity studies and also for dynamic pile driving formulas the kinetic energy of the ram is needed. Although there are conituously updated recommendations available for different hammer models' efficiences in the well known GRLWEAP-program (GRL 1994), the knowledge and the application of these efficiences have not neccessarily reached all the people involved in driven piling.

The aim of this paper is to present the main results of the hydraulic hammer study held in Hong Kong. The original results were presented by Maunsell Geotechnical Services Ltd. (1994) in their testing report. Test results were further analyzed especially for Junttan HHK-9A hammer by using GRLWEAP-program and an analytical approach developed by Deeks (1992). A new dynamic pile driving formula for hydraulic hammers was also developed from the test results of the tests.

2 DEFINITATIONS

There are three different efficiency concepts which govern pile driving hammers.

Hammer efficiency (HE) is defined as the proportion of the kinetic energy of the ram before impact and the potential energy of the ram at the top of it's stroke.

$$HE = \frac{KE}{PE} \tag{1}$$

KE is the kinetic energy of a ram
PE is the potential energy of a ram

The kinetic energy of a ram can be measured by hammer manufacturer's energy measuring device or by means of Hammer Performance Analyzer (HPA). The use of the latter has been described for example by Likins and Rausche (1988).

Application of impulse-momentum consideration to the stress wave measurements may also lead to good estimations of maximum impact velocity of ram (PDI 1993).

$$MF0 = \int_0^{t1} F(t)dt$$
$$MW0 = \int_0^{t2} F\downarrow(t)dt \tag{2}$$

and

$$MF0 = MW0 = M_{ram}\, v_{ram} \tag{3}$$

where

- $F(t)$ is the measured force from the top of the pile
- $F\downarrow(t)$ is the downward travelling wave
- $t1$ is the time of zero velocity
- $t2$ is the time of zero downward travelling wave
- M_{ram} is the mass of ram
- v_{ram} is the velocity of ram before impact

From equation (3) the impact velocity of ram can be solved and thus the kinetic energy of ram (KE).

Driving System Efficiency (DSE) is defined as the proportion of the maximum energy transferred to the pile (EMX) and the kinetic energy of the ram

$$DSE = \frac{EMX}{KE} \tag{4}$$

Maximum energy transferred to the pile can be determined from the stress wave measurements

$$EMX = \int_0^{t1} F(t)v(t)dt \tag{5}$$

$v(t)$ is the measured velocity from the top of the pile

Overall Transfer Efficiency (OTE) is defined as

$$OTE = \frac{EMX}{PE} = HE \cdot DSE \qquad (6)$$

For open end diesel hammers only the ram stroke and thereby the potential energy of ram can be calculated from the Saximeter equation (PDI 1993)

$$h[m] = 1,22 \cdot \left(\frac{60}{BPM}\right) - 0,1 \qquad (7)$$

BPM is the blows per minute

According to litterature review (PDI (1993), Broms&Lim (1988), Cheng&Ahmad (1988), Wu et al. (1985) and Yao et al. (1988)) the overall transfer efficiences of diesel hammers are approximately 30-40% for timber and concerete piles and 40-50% for steel piles. The energy transferred to the pile for diesel hammers can be as low as 20% of the hammer's potential energy (Broms&Lim 1988).

3 HYDRAULIC HAMMER STUDY IN HONG KONG

3.1 *Test procedure*

The tests were done at three different sites by using two different types of piles. The tests were open for any hydraulic hammer manufacturer provided he answered for the cost of the testing. The manufacturers were informed that the piles would be commonly used pile types in Hong Kong and aimed also to be driven with Delmag D62-22 diesel hammer. The tests were arranged January to March in 1994.

The test procedure at each site was as follows:

1. A site was selected according to site investigations such that ground conditions were similiar in the whole testing area.
2. At first one reference pile was driven with Delmag D62-22 diesel hammer. The set criterion was originally aimed to establish by the Hiley type dynamic pile driving formula or by the PDA-measurements with CASE-method for the ultimate bearing capacity that is typical for the pile type. The latter method was used in practice because Hiley's formula with used hammer efficiency of 90% for diesel hammer gave unrealistic values when comparing to CASE-method RMX-capacity. The penetration where the capacity demand was reached for diesel hammer was determined to be the reference level. At this level elastic comperession and permanent set of the reference pile was recorded with pencil and paper.
3. Next were four test piles driven each one by a different hydraulic hammer approximately to reference level by using same transmitted energy to pile as with diesel hammer. Permanent set, elastic compression of soil and pile and kinetic energy of ram were recorded. The distance between test piles was 3 to 4 meters.
4. After a proper waiting period restrike tests were performed for all test piles with PDA-measurements, set and temporary compression recordings and kinetic energy readings.
5. CAPWAP-analyses were performed for PDA-data of all piles both end of drive and restrike records.
6. Static load testing was carried to the four test piles and to the reference pile if neccessary. The type of testing was proof load test with safety factor of two.

3.2 *Description of hammers*

The selection hammer size was made by each manufacturer on the basis of information given in advance.

Four different hydraulic hammer manufacturers took part into the tests: Junttan from Finland, Menck from Germany, IHC from Netherlands and Nippon Sharyo from Japan. In Table 1 are presented the hammer models which took part in tests.

Table 1. Properties of different hammer models

Model	Total mass [kg]	Mass of ram [kg]	Rated energy [kNm]
Delmag D62-22	12000	6200	224
Junttan HHK-9A	12500	9000	106
Menck MHF5-12	15500	12000	130
IHC SC150	17500	10900	140
Nippon Sharyo NH100	22500	10000	141

IHC SC150 and Nippon Sharyo NH100 are both double-acting hammers whereas Junttan HHK-9A and Menck MHF5-12 are single-acting hammers although in both hammers the ram is moderately accelerated.

The choice of hammer and pile cushions is made by each manufacturer and the intention was that they would use their standard cushions.

3.3 *Description of the test sites and pile types*

The three test sites together with average pile penetrations are presented in Table 2 and typical Standard Penetration Test SPT "N-values" in Figure 1. Sites 2 and 3 were chosen on same building site to reduce the costs of the tests.

3.4 *Test results*

Major test results are collected in Table 3. Equation (4) can be used for hydraulic hammers to calculate the corresponding kinetic energy of ram (KE) and equation (6) for diesel hammer to calculate the maximum potential energy of ram.

In Table 3 C_p+C_q is the temporary elastic compression of pile and soil, which has been measured by paper and pencil near the top of the pile. R_u is ultimate static resistance of the pile determined by CAPWAP-analysis. The results of static loading tests and CASE-method are not presented here because half of the piles didn't reach the ultimate static resistance during static loading tests and CASE-method is always more or less subjective method without calibration of J_C by static loading tests or CAPWAP-analysis.

Only Menck's hammer included instrumentation which could measure the actual stroke and thus the potential energy. It is not known by the author whether the instrumention takes into consideration the oil pressure acting on the ram during moderate acceleration. In theory the work done during acceleration should be added to the potential energy as suggested by Poskitt (1991).

As far as efficiencies between diesel hammer and the different hydraulic hammer models are concerned, the test results clearly show that the overall transfer efficinecies of hydraulic hammers are much larger than the diesel hammer and that the measured

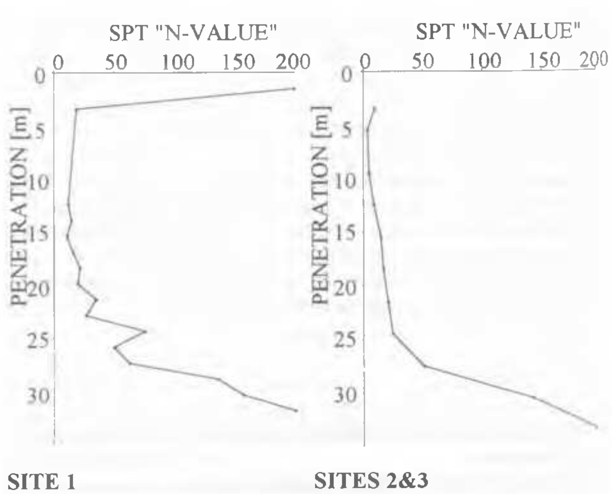

Figure 1. Typical SPT "N-Values" from the test sites.

Table 2. Description of test sites and pile types

Site	1	2	3
Location	Swimming Pool Complex beside Hammer Hill road	Tin Shui Wai Area 13, Phase 2	Tin Shui Wai Area 13, Phase 2
Ground conditions	Rubble fill over weathered granite, over granite rock	Sand fill over soft pond deposit, over alluvial silt/clay, over weathered siltstone	Sand fill over soft pond deposit, over alluvial silt/clay, over weathered siltstone
Pile type	ϕ500 mm t=100 mm DAIDO concrete pile	ϕ500 mm t=100 mm DAIDO concrete pile	305x305x180 steel H-pile ($A=229{,}3\ cm^2$)
Nominal ultimate resistance [kN]	4600	4600	4800
Penetration [m]	28	23	30

Table 3. Major test results of the hydraulic hammer study held in Hong Kong in 1994

Pile ID	Type	Set/Blow [mm]		C_p+C_q [mm]		EMX [kJ]		R_u [kN]		HE [%]		DSE [%]		OTE [%]	
		EOD	BOR	EOD	BOR	EOD	BOR	EOD	BOR	EOD	BOR	EOD	BOR	EOD	BOR
HH/D62/2	DAIDO	3.4	1.3	18	16	60	61	3055	4655	-	-	-	-	39	35
HH/MHF120/1	DAIDO	2.1	0.35	25	24	85.3	84.9	3895	4650	95	97	84	85	80	82
HH/NH100/2	DAIDO	1.6	0.4	21	26	79.3	75.5	3800	4600	-	-	74	70	-	-
HH/HHK9A/1	DAIDO	0.9	0.05	22	22	76	76.3	3788	4630	-	-	89	88	-	-
HH/SC150/2	DAIDO	0.95	0	22	22	70	58.4	3394	4726	-	-	78	68	-	-
TSW/D62/1	DAIDO	7	2.8	17	14	77.5	67.2	3358	4753	-	-	-	-	39	36
TSW/MHF120/1	DAIDO	5.4	2.7	19	21	85.3	72.6	3425	4049	93	94	84	70	77	66
TSW/NH100/1	DAIDO	8	2.3	16	14	79	71.6	3253	3915	-	-	81	72	-	-
TSW/HHK9A/1	DAIDO	6.5	2.2	15	17	81.4	77.5	3812	4855	-	-	91	87	-	-
TSW/SC150/1	DAIDO	5.5	2.2	16	18	81	80.9	3550	4737	-	-	89	88	-	-
TSW/D62/2	H-PILE	5.8	2.4	19	21	87.3	83.4	4854	4644	-	-	-	-	44	43
TSW/MHF120/2	H-PILE	2.1	1.3	24	26	108.9	96.1	4936	3195	92	92	96	87	88	80
TSW/NH100/2	H-PILE	4	1.7	24	26	96.6	97.1	4491	5605	-	-	73	73	-	-
TSW/HHK9A/2	H-PILE	7	3.9	23	22	103	98.1	4212	4350	-	-	97	96	-	-
TSW/SC150/2	H-PILE	7.1	2	24	22	100.1	93.2	4525	5933	-	-	93	93	-	-

EOD is End Of Driving
BOR is Beginning Of Restrike

Table 4. Average driving system efficiences for different hydraulic hammers.

Hammer model	Driving System Efficiency [%]	
	DAIDO-piles	H-piles
Junttan HHK-9A	89	97
IHC SC-150	81	93
Menck MHF5-12	81	92
Nippon Sharyo NH100	74	73

efficiencies of the diesel hammer are close to those values presented in literature. It can also be concluded from the measurement's of the Menck's hammer, that friction losses during the drop of well maintained hydraulic hammers are very small.

The test results showed clear differences between the driving system efficiences of different hydraulic hammers. The average DSE-values for the different hydraulic hammers are presented in Table 4. It can be concluded that the greater the DSE-value, the better the helmet mass in proportion to the ram mass and the properties of cushion have been chosen to pile's impedance.

The original testing report prepared by Maunsell (1994) suggested a new dynamic pile driving formula which can be used in connection with hydraulic hammers. The formula is not discussed here, but another very simple formula can be easily derived from the measurements done for hydraulic hammers.

By assuming that the form of the formula is

$$R_{u,dyn} = K \cdot \frac{KE}{s + \frac{1}{2}(C_p + C_q)} \qquad (8)$$

where

K is the factor, which takes into consideration all energy losses in cushions and dynamic energy losses in pile and soil.

s is the permanent set per blow

and by comparing equation (8) to Table's 3 corresponding CAPWAP-capacities with DAIDO-piles (16 cases: 4 hammers, 2 sites and 2 tests (EOD and BOR)) and with H-piles (8 cases: 4 hammers, 1 site and 2 tests (EOD and BOR)), a reasonably good correlation is obtained, when K=0,5 and K=0,6 are chosen for DAIDO-piles and H-piles respectively.

This will yield an average ratio of $R_{u,dyn}/R_{u,CAPWAP}$ to 0,97 with a standard deviation of 0,17 when whole test data is taken into consideration.

Paikowsky's (1994) energy approach is similiar in shape to equation (8). However, in his formula KE is replaced with EMX and C_p+C_q with DMX-SET, where DMX is the maximum displacement of the pile head and SET is the permanent set. Determination of EMX and DMX needs however use of Pile Driving Analyzer.

It should be understood that equation (8) is only valid for similiar hammers and soil conditions as they were in the tests.

4 ANALYSIS OF STRESS WAVE MEASUREMENTS FOR JUNTTAN HHK-9A HAMMER

GRLWEAP-program's hammer library includes information of various Junttan hammers. However, the present information is limited only to ram dimensions and hammer assembly. No information is given hammer cushion properties or helmet weights. It is expected, that this information is included in the GRLWEAP 1.997-1 version.

By using measured ram velocity, actual hammer cushion dimensions and weight of helmet it is possible with GRLWEAP-program to compare simulated pile top curves to measured ones.

In Figure 2 is PDA-measurements compared with the GRLWEAP simulation. The soil parameters in simulation are obtained from the CAPWAP-analysis. It should be noted, that the pile cushion is not modelled because signal is measured from the H-pile. By using E=2500 MPa and CoR=0,9 for the Monocast MC 901 hammer cushion reasonably good compatability is achived between curves. The measured maximum pile top velocity was 5,57 m/s and the enthru energy 103 kNm, whereas GRLWEAP-simulation gives 5,54 m/s and 98 kNm respectively.

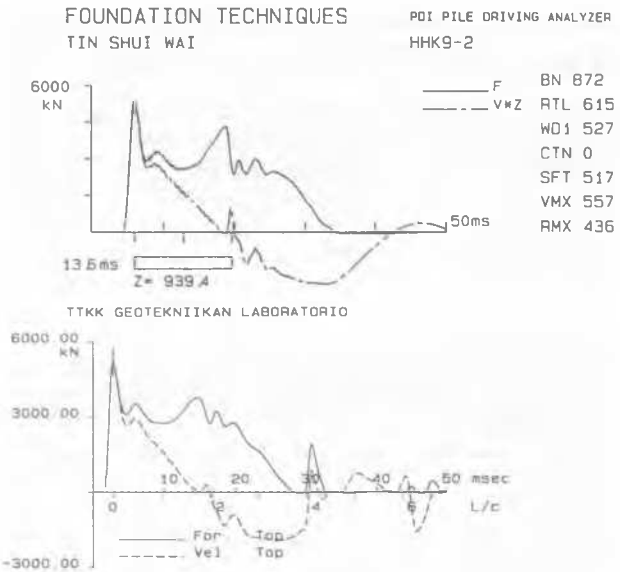

Figure 2. Comparision of measured and simulated pile top force and velocity times impedance.

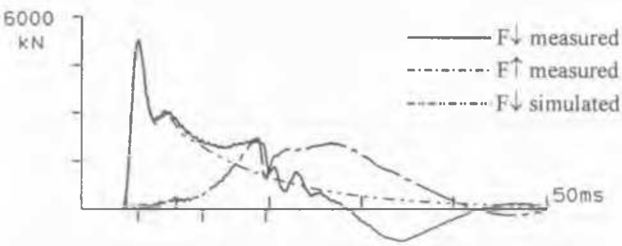

Figure 3. Comparision of downward travelling waves between analytical approach presented by Deeks (1992) and measured curves

The deviations between measured and simulated curves can be explained as to have been caused by different soil models. The GRLWEAP-analysis has only used the Smith-1-type damping model, while results of the CAPWAP-analysis include also Smith-2-type damping, which yields a dampened behaviour of pile top velocity.

Deeks (1992) has developed a rather complicated closed form analytical solution for the modelling of ram impact to pile. In his model lumped ram and anvil are separated by a parallel connected linear spring and dashpot, which are representing the hammer cushion. The pile is modelled as a dashpot of impedance Z=EA/c, where EA is cross-sectional rigidity of the pile and c is the 1-dimensional wave speed in the pile.

The formulas developed by Deeks are not presented here, but an application of matching test data is shown.

In Figure 3 the comparision between measured downward travelling wave and simulated downward travelling wave is presented. It should be noted that the signal is same as in figure 2 and represents a typical signal for pile TSW/HHK9A/2 EOD. By using actual ram and anvil masses 9000 kg and 900 kg respectively, actual ram velocity before impact 4,85 m/s, actual hammer cushion dimensions (D=600 mm, t=200 mm) and by supposing that elastic modulus of hammer cushion is 2500 MPa and damping constant of the hammer cushion is 35% of the impedance of the pile, the downward travelling wave caused to pile can be expressed with equation

$$F(t) = 4277 \cdot e^{-96 \cdot t} \cdot \left(1 - e^{-572 \cdot t} \cdot \frac{\cos(1945 \cdot t - 0,0974)}{0,9953}\right) \qquad \textbf{(9)}$$

where force is in kN and time is in seconds.

According to Figure 3 simulated and measured downward travelling waves are nearly identical before 14 ms. After this the measured downward travelling wave includes also effects of skin resistance, which are not taken into consideration in analytical approach.

Calculated enthru energy to the pile by using equation (9) is approximately 96% of the modelled kinetic energy. This corresponds very well to actual measurements.

5 CONCLUSIONS

According the test results done in Hong Kong the overall transfer efficiency of the diesel hammer was on an average 37% for DAIDO-piles and 44% for H-piles. These values correspond well to values presented in literature.

Differences between driving system efficiences of various hydraulic hammers can be found. The best DSE-value had Junttan HHK-9A hammer with both DAIDO- and H-piles.

A simple pile driving formula for hydraulic hammers was presented, which correlates quite well with CAPWAP-capacities. However, the use of such formulas is not suggested unless their validity is not calibrated via static loading tests or CAPWAP-analyses.

Stress wave measurements for Junttan HHK-9A hammer were further analyzed by GRLWEAP-program and analytical approach. By comparing measured curves with simulated curves were parameters for hammer cushion backcalculated.

6 ACKNOWLEDGMENTS

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