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# Measurement of wind turbine construction noise at Horns Rev II

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## 1. Executive summary

The construction of the Horns Rev II wind farm is accompanied by a marine mammal monitoring programme. As a part of that study, underwater noise was measured on the installation of pile J2. During pile driving, a maximum peak level of 195 dB and a maximum SEL of 176 dB were observed at 720 m distance from the pile. At 2300 m distance, respective values were 180 dB for the peak level and 164 dB for the SEL (all sound levels re 1 µPa). The spectral maximum of the pile driving noise was in the frequency range 80 – 200 Hz.

# 2. Basic principles

## 2.1 Sound level definitions

In sound engineering, the "strength" of a sound is specified by its *level* in decibels (dB). However, a single dB value is not always a sufficient characterisation. In particular, this is the case for non-continuous sounds like impulses from pile driving blows. Useful quantities are:

- Equivalent continuous sound pressure level ($L_{eq}$)
- Sound exposure level (SEL)
- Peak level ($L_{peak}$)

$L_{eq}$ and SEL can be specified as broadband "single number" values, but also frequency-dependant, e.g. in 3rd octave bands.

### Equivalent continuous sound pressure level, $L_{eq}$

This is a very common quantity in sound engineering. It is also called time-averaged level, or sometimes "RMS level". It is usually abbreviated $L_{eq}$ and is defined as

$$L_{eq} = 10 \log\left(\frac{1}{T}\int_0^T \frac{p(t)^2}{p_0^2}\,dt\right) \qquad (2.1)$$

where p(t) is the sound pressure, $p_0$ the reference pressure of 1 µPa and T the averaging time. As a numerical recipe, equation 2.3 reads *"square observed sound pressure values, average them (i.e. multiply each p² by time step dt, add up all products and divide the sum by T), divide by $p_0^2$ and apply 10 log to obtain result in dB."*

### Sound exposure level, SEL

It is obvious that for non-continuous sound like pile driving strikes, the $L_{eq}$ not only depends on the averaging time and on the intensity of the impulses, but also on the intervals in between them. Hence a better suitable quantity for comparing noise from pile drivers is the sound exposure level or SEL (sometimes abbreviated as $L_E$). It is defined slightly different from the $L_{eq}$:

$$\mathrm{SEL} = 10 \log\left(\frac{1}{T_0}\int_{T1}^{T2} \frac{p(t)^2}{p_0^2}\,dt\right) \qquad (2.2)$$

The averaging start and stop times T1 and T2 are chosen arbitrarily, but in a way that the sound event lays in between T1 and T2, see Figure 2.1. $T_0$ is 1 second. That is, the SEL is the level of a continuous sound with 1 s duration and the same sound energy as the impulse. It equals the "energy level" (in dB re 1 µPa²s) sometimes found in literature. The SEL is more difficult to measure directly than the $L_{eq}$, but there is a simple relationship between the two quantities:

$$\mathrm{SEL} = 10\log\left(10^{L_{eq}/10} - 10^{L_{beq}/10}\right) - 10\log\frac{nT_0}{T} \qquad (2.3)$$

where n is the number of events, e.g. pile strikes, within the observation time T. As above, T0 = 1 s. $L_{beq}$ is the background noise level in between the pile strikes. Applying equation 2.3 to a $L_{eq}$ measurement yields the *average SEL of n events*. If the background noise is negligible with respect to the event noise, equation 2.3 can be simplified to

$$\mathrm{SEL} \approx L_{eq} - 10\log\frac{nT_0}{T} \qquad (2.4)$$

*Note: The SEL function implemented in sound level meters works according to equation 2.4 with a fixed value of n = 1.*

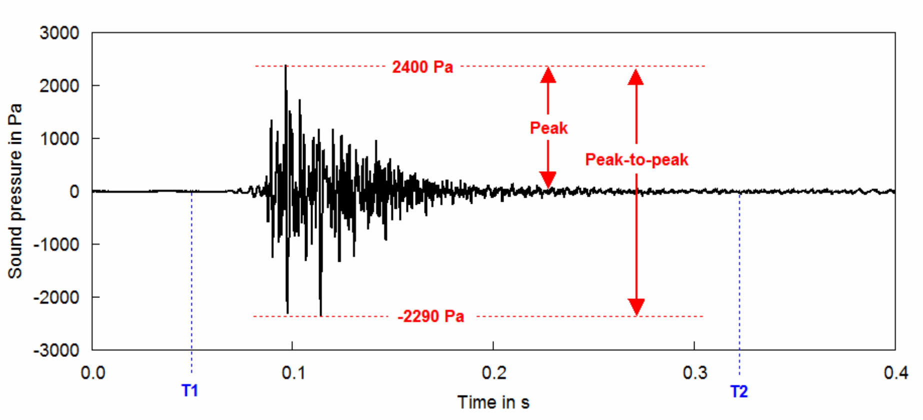


*Fig. 2.1. Typical underwater sound pressure impulse of a pile driving blow, recorded at several 100 metres distance. T1 and T2 are explained in the definition of the sound exposure level, see equation 2.2. The peak level in this example is 20 log(2400/10$^{-6}$) dB = 187.6 dB (the SEL in this example is approx. 162 dB).*

## Cumulative SEL

For evaluating the biological impact of pile driving in terms of a noise dose, it may be reasonable to consider not only the strength of a single strike, but to define the SEL "event" as a series of strikes (up to the whole pile driving process, which may take several thousand strikes). This value is sometimes referred to as "cumulative SEL". If the strikes are all equal, it can be computed from the single-strike SEL according to

$$\mathrm{SEL}_{cum} = \mathrm{SEL}_{single} + 10\log(n) \quad , \qquad (2.5)$$

whereas n is the number of strikes. That is, the $\mathrm{SEL}_{cum}$ increases by 10 dB with every tenfold increase of the number of strikes.

## Peak level

Impulsive sounds can have moderate $L_{eq}$ or SEL values, but very high instantaneous pressure peaks though. A measure for these peaks is the peak level. Contrary to $L_{eq}$ and SEL, there is no averaging:

$$L_{peak} = 20 \log (|p_{peak}| / p_0) \quad , \tag{2.5}$$

where $p_{peak}$ is the highest observed sound pressure (may also be the most negative). An example is shown in Figure 2.1.

*Note: Some authors prefer the peak-to-peak level (see Figure 2.1). At some distance from an underwater sound source, however, after the signal has been reflected several times at the sea bottom and the sea surface, the magnitudes of the positive and negative maximum are almost equal. Thus, $L_{peak\text{-}to\text{-}peak} = L_{peak} + 6$ dB is an adequate approximation for converting peak levels to peak-to-peak levels and vice versa. In the example in Figure 2.1, the difference between them is 5.8 dB.*

## M-weighting

Broadband single-number $L_{eq}$ or SEL values do not account for the frequency-specific hearing capability of the species in question. Hence Southall et al. (2007) have introduced a frequency weighting function. This M-weighting moderately attenuates high and low frequency components of the signal, similar to the A- and C-weighting curves implemented in common sound level meters. The letter M stands for marine mammals.

There are different M weighting curves; the two relevant ones for the North Sea and the Baltic Sea are shown in Figure 2.2. For pile driving noise, sound levels weighted with the $M_{HF\ cetaceans}$ curve are typically 5 to 7 dB lower than unweighted levels. $M_{pinnipeds}$ weighted levels fall in between unweighted and $M_{HF\ cetaceans}$ levels.

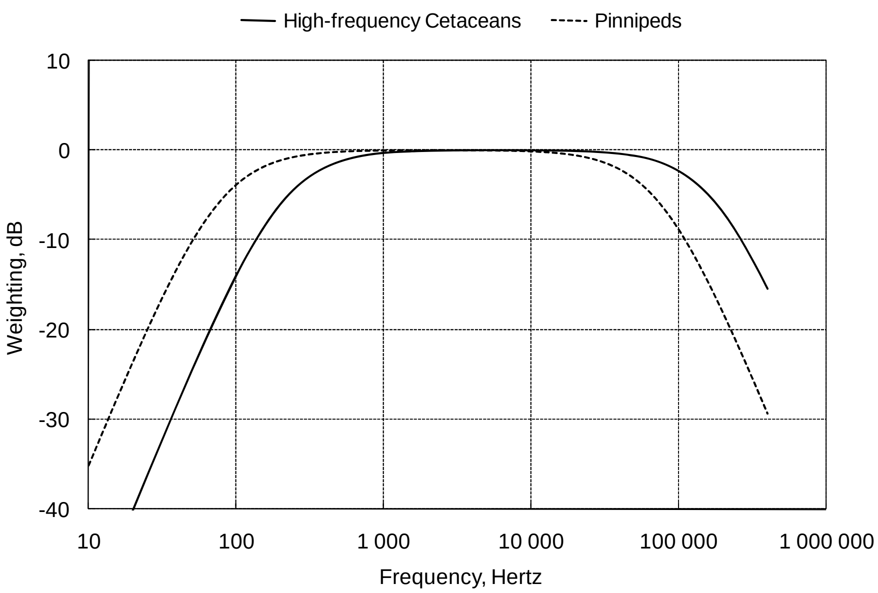


*Fig. 2.2. M-weighting curves for "high frequency" cetaceans, e.g. harbour porpoises, and for pinnipeds (after Southall et al. 2007)*

## 2.2 Sound propagation effects

Sound propagation in the sea is affected by the water depth; below a certain frequency, no sound propagation is possible. This limiting frequency $f_0$ is also a function of the speed of sound c in the sediment (Urick 1983 p. 175):

$$f_0 = \frac{c_{water}}{4\,h}\sqrt{\frac{1}{1-\left(c_{water}-c_{sediment}\right)^2}} \tag{2.6}$$

In this formula, h is the water depth. The speed of sound in the sediment is slightly larger than in water, where it is approximately 1500 m/s. With $c_{sediment}$ = 1600 m/s and 3 m depth, for example, $f_0$ is about 350 Hz.

At this frequency, significant parts of pile driving sound energy would be cut off, see for example the spectrum in Figure 4.4. Pile driving noise from Horns Rev II travelling across the Rev (Figure 2.3) is thus subject to a stronger attenuation than sound propagating in northern and western directions.

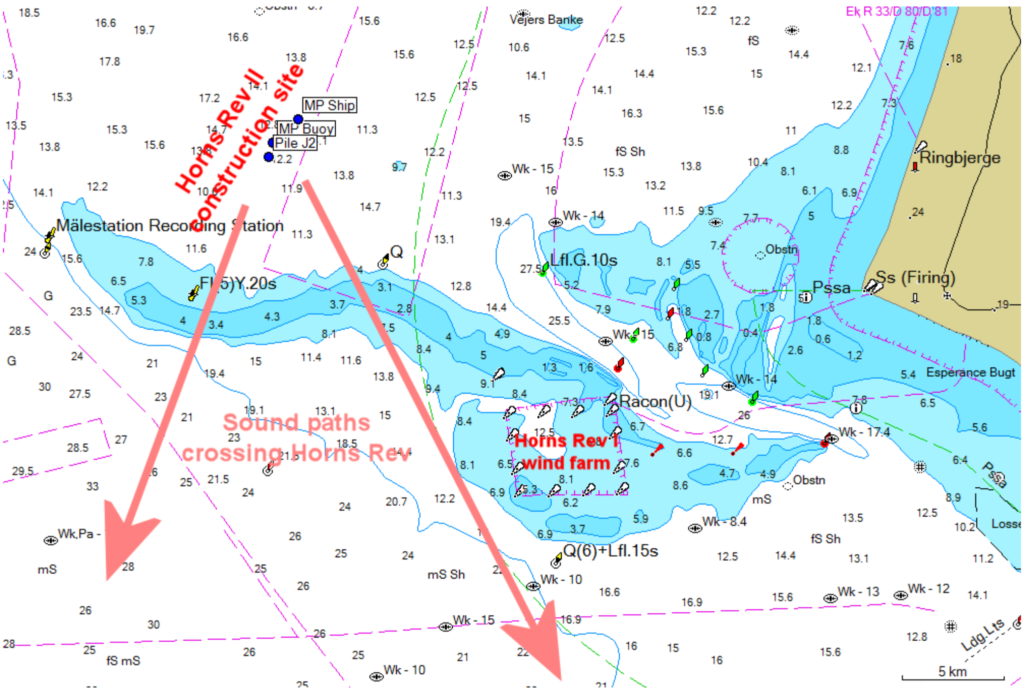


*Fig. 2.3. Construction noise emanating from Horns Rev II and travelling across Horns Rev is subject to larger transmission loss than in other directions*

Table 2.1 lists the approximate level reduction that can be expected if the pile driver noise travels across a shallow water path. The computation is based on a speed of sound in the sediment of 1600 m/s to 1700 m/s and a spectrum in Figure 4.4. Example: If the pile driving noise was 155 dB SEL at 10 km distance in "deep" water (10 m depth or more), a level of 145 – 150 dB can be estimated at the same distance, but in a direction with a 3 m shallow zone in between construction site and receiver.

| Water depth in shallow zone | Broadband level reduction of pile driver sound passing a shallow zone, compared to sound travelling in "deep" water only |
|---|---|
| 2 m | 8 – 13 dB |
| 3 m | 5 – 10 dB |
| 4 m | 3 – 8 dB |
| 5 m | 1 – 6 dB |

*Table. 4.2. Approximate effect of shallow water paths on pile driving noise*

# 3. Measurement procedure

The measurements were done on 07 September 2008 during installation of pile #71, or J2. There were two measurement points: An autonomous recording buoy was deployed at about 700 m distance from the pile, while manual recordings were made aboard M/V Tine Bødker at 2300 m, see Figure 3.1 and Table 3.1. The buoy is shown in Figure 3.2. Equipment is listed in Table 3.2.

At both positions, time signals were recorded. These data were evaluated later with MATLAB programs. Spectral analyses are based on Fast Fourier Transform (FFT) of signal intervals with a duration of at least 5 seconds and containing at least 8 pile driving strikes. In addition, a HP 35760A spectrum analyzer was used for verification and for calibration purposes.

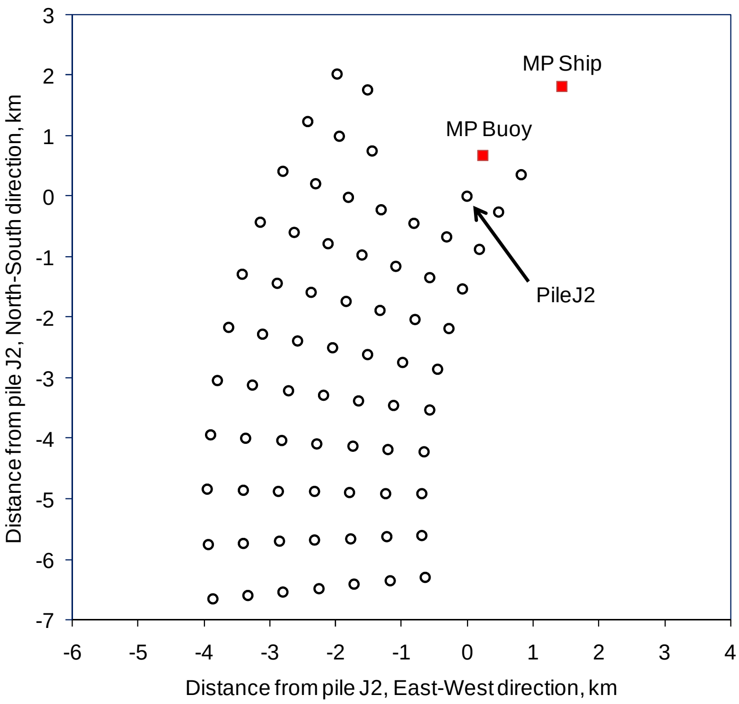


*Fig. 3.1. Underwater sound during the installation of pile J2 was measured at two positions: MP Ship at 2300 m distance and MP Buoy at 720 m distance from the pile*

| Measurement position | MP Ship | MP Buoy |
|---|---|---|
| Geographical position<br>(Pile J2: 55°36.978'n 07°36.507'e) | 55°37.959'n 07°37.888'e | 55°37.342'n 07°36.735'e |
| Distance from pile J2 | 2300 m | 720 m |
| Water depth | 11 - 13 m | 10 – 12 m |
| Hydrophone depth | 7 – 8 m | 1.5 m above sea bottom |
| Recording bandwidth | 20 kHz | 40 kHz |

*Table 3.1. Details for the two measurement positions*

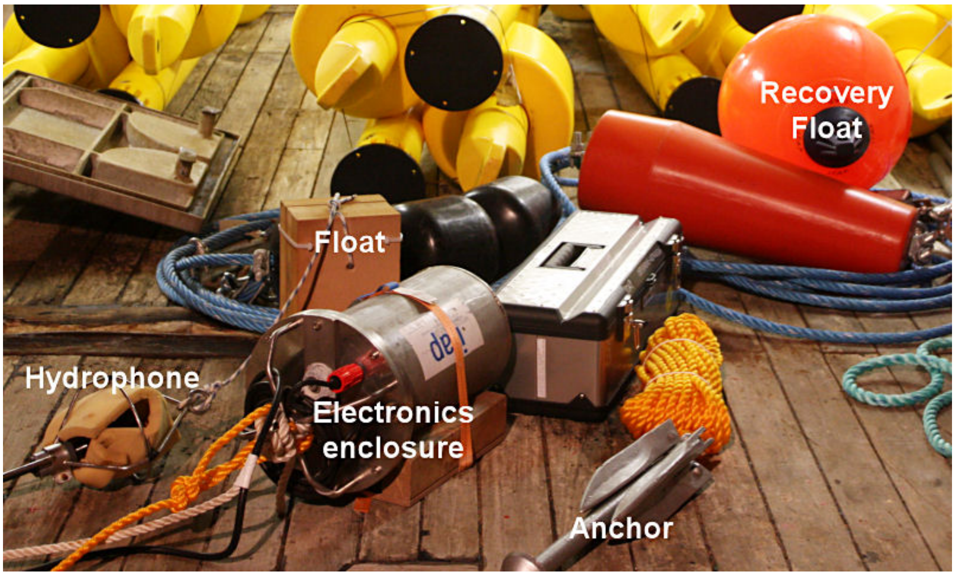


*Fig. 3.2. Sound measurement buoy aboard M/V Tine Bødker, shortly before deployment (the hydrophone is still wrapped in protective foam)*

| Device | Manufacturer |
|---|---|
| Hydrophone 8105 (ship) | Brüel & Kjær |
| Charge amplifier 2635 (ship) | Brüel & Kjær |
| Recorder HD-P2 (ship) | Tascam |
| Hydrophone ITC-1001 (buoy) | International Transducer Corp. |
| Recorder PMD 670 (buoy) | Marantz |
| Calibration source 1 $V_{rms}$ and 100 $pC_{rms}$ | itap |
| Pressure chamber for hydrophone calibration | itap |
| Microphone 4189 (in calibration chamber) | Brüel & Kjær |
| Dynamic Signal Analyzer HP35670a | Hewlett-Packard |

*Table 3.2. Equipment used for the measurements*

# 4. Results

## 4.1 General

The pile driving process was relatively short; according to the pile driver record file, only 449 blows were necessary to reach the final penetration of 21 m. The time from the first to the last blow was about half an hour.

The peak levels in Figure 4.1 reflect the working process. After a number of single and short groups of blows around 04:55, most blows were between 05:05 and 05:15, followed by a pause and a final block of 22 blows at 05:24. The peak level reached 195 dB at 720 m distance from the pile and 180 dB at 2300 m.

The highest blow energy of approx. 850 kJ was applied around 05:12. The time function of a blow recorded at this time is shown in Figure 4.2. Here, SEL values of 176 dB at 720 m and 164 dB at 2300 m distance were observed (Figure 4.3).

The spectra in Figure 4.4 exhibit the typical pattern of underwater pile driving noise, which is a maximum between 75 Hz and a 500 Hz, a soft decay of 6 – 12 dB/octave to higher frequencies and a slope of 18 dB/octave or steeper towards low frequencies.

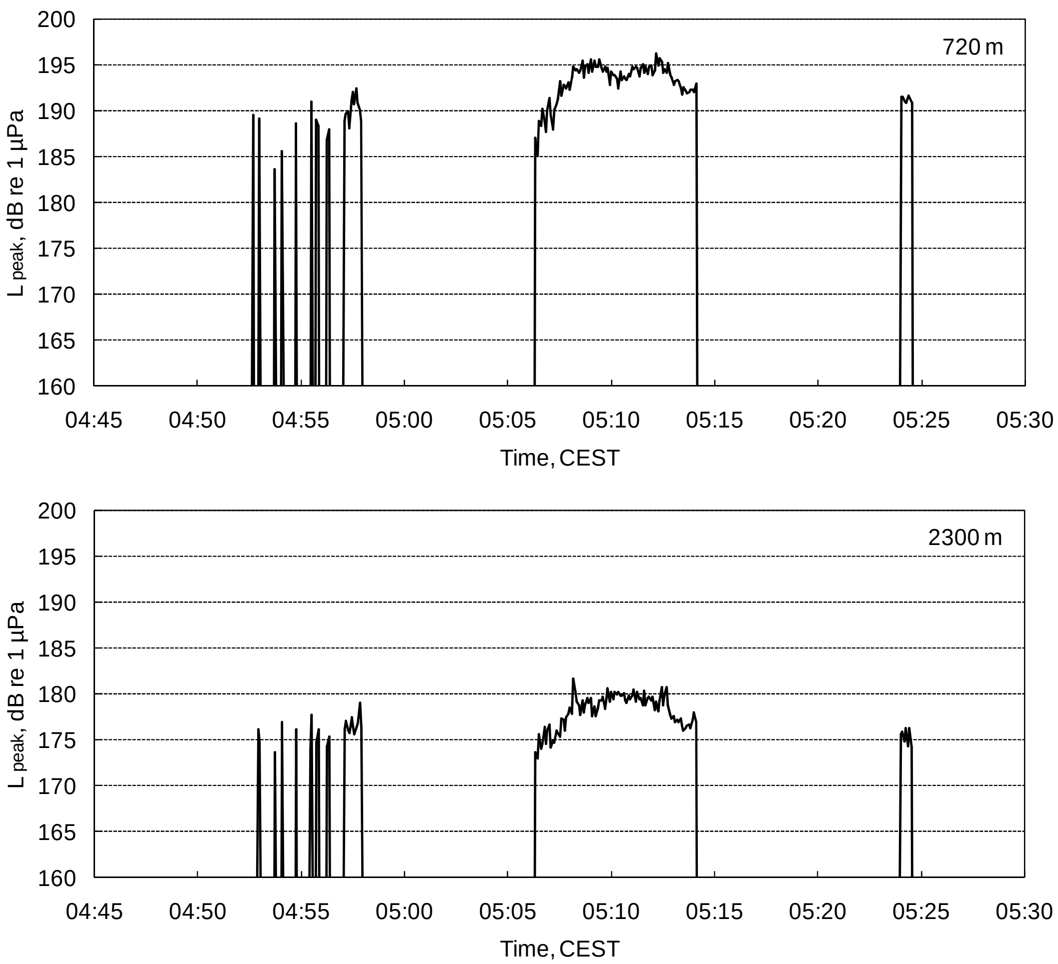


*Fig. 4.1. Peak levels measured at 720 m distance (upper curve) and 2300 m in the course of the whole pile driving process. Time resolution of this analysis is 5 s.*

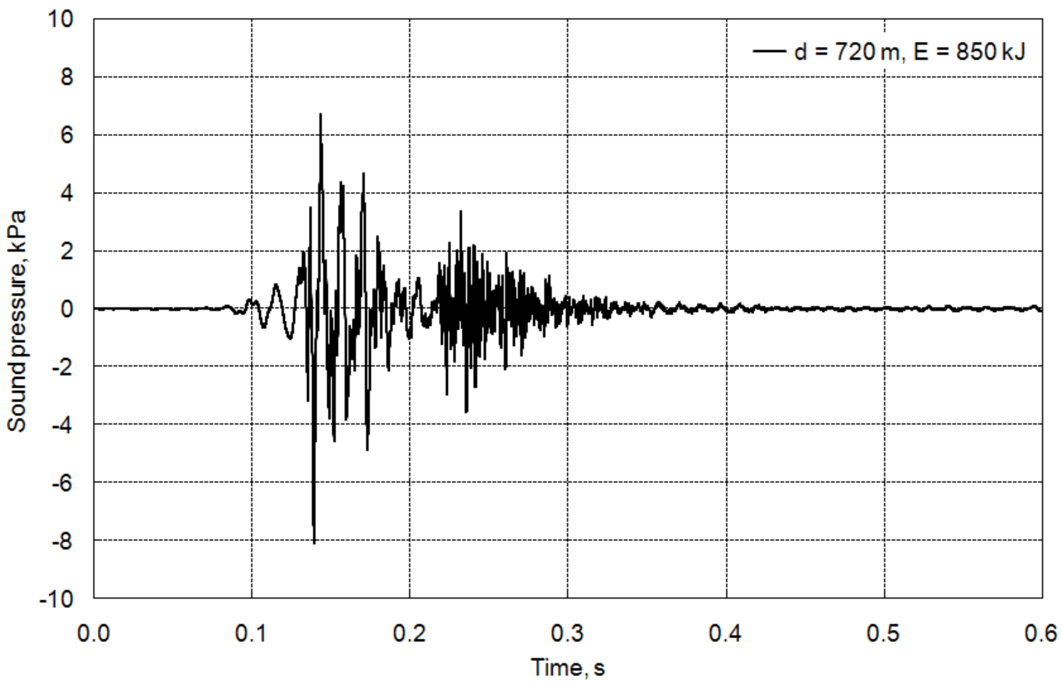


*Fig. 4.2. Typical time signal of a pile driving strike, recorded at 05:12 CEST*

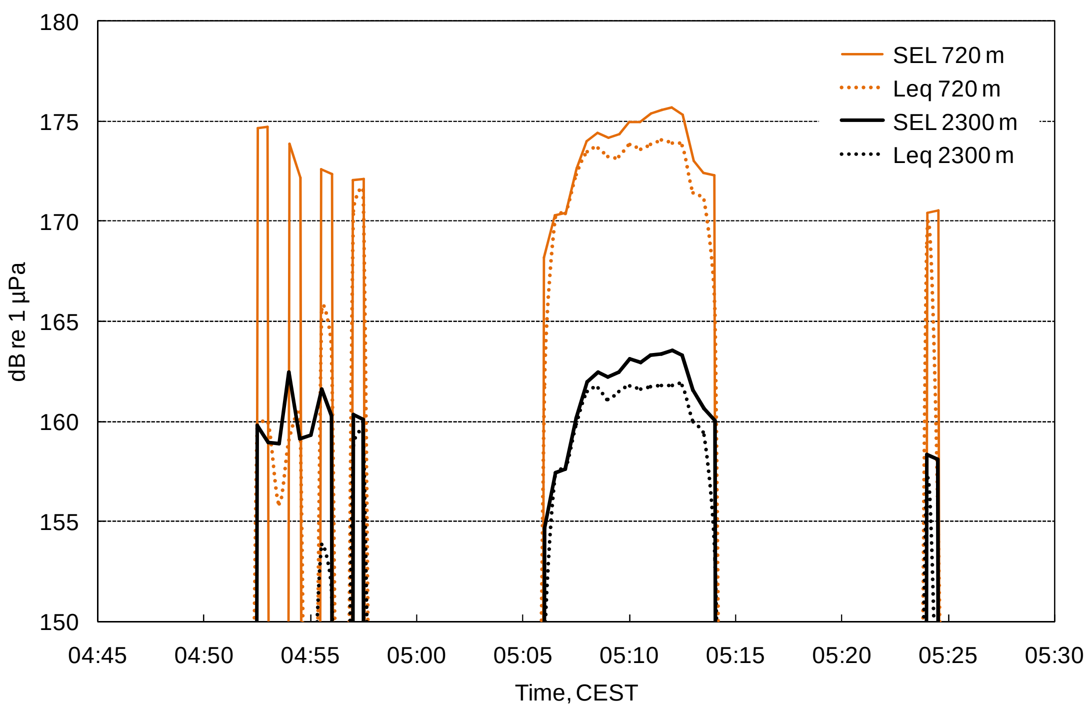


*Fig. 4.3. Broadband single-strike SEl and $L_{eq}$ (30 s averages). At the beginning of the work around 04:55, the difference between SEL and $L_{eq}$ was relatively large because of only few irregular strikes within the averaging intervals (see equation 2.5). Later, the blow rate increased to 40/min to 60/min; hence the difference between SEL and $L_{eq}$ reduced to less than 2 dB.*

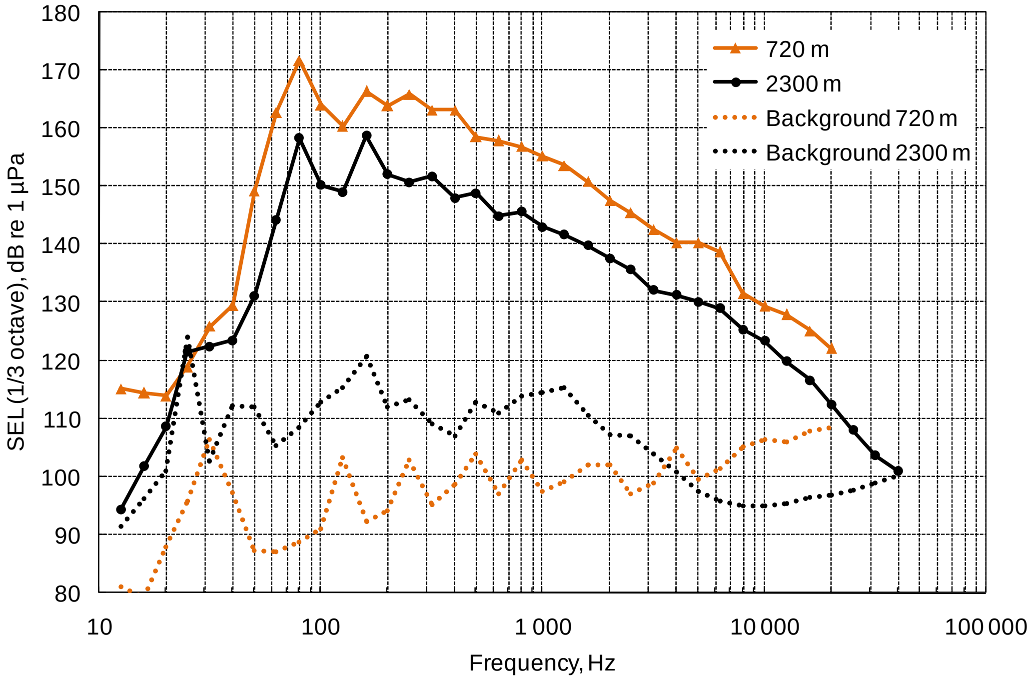


*Fig. 4.4. SEL spectra (average of 24 strikes with 850 kJ). Background level at 2300 m is higher due to the measurement vessel's self noise.*

Broadband levels measured at 720 m and 2300 m differ by about 12 dB. This suggests a level decrease of 24 $\log(R_2/R_1)$ dB for an increase of distance from $R_1$ to $R_2$. Typical values measured in the North Sea are 15...17 $\log(R_2/R_1)$. The reason for this higher-than-average decrease is unknown.

## 4.2 Cumulative M-weighted level

Figure 4.5 shows the cumulative, M-weighted SELs according to Southall et al. (2007) and as described in chapter 2 of this report. The $M_{hf\ cetaceans}$ weighting curve was used, which is valid for e.g. harbour porpoises. At the end of the pile driving process, the M-weighted $SEL_{cum}$ reached 194 dB at 720 m distance and 182 dB at 2300 m distance.

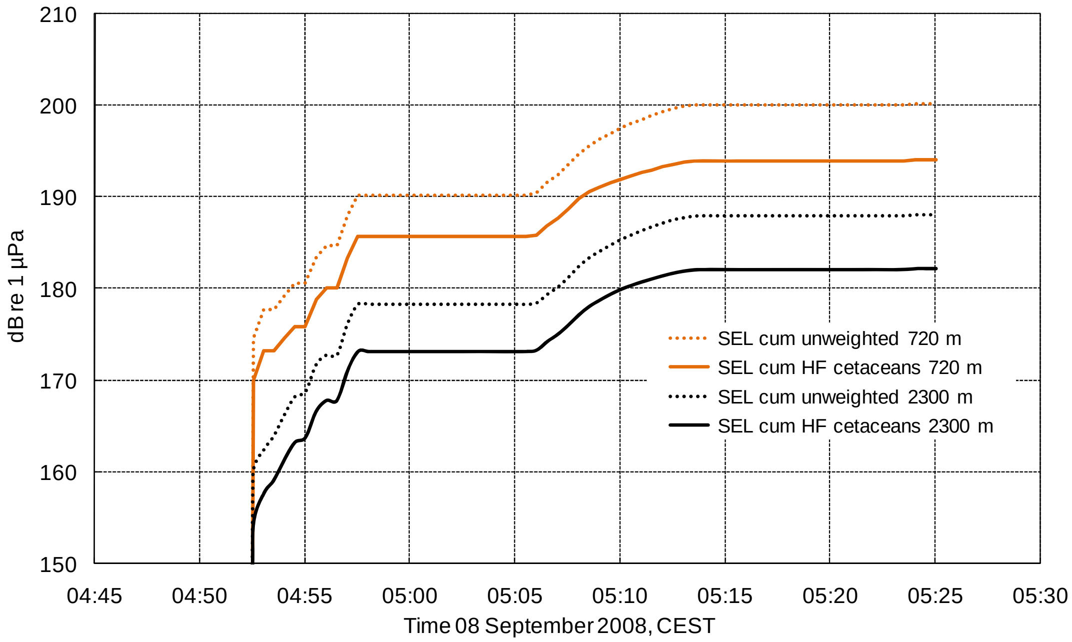


*Fig. 4.5. M-weighted and unweighted cumulative SELs for both measurement distances*

## 4.3 Sound level versus blow energy

The sound level increases with blow energy. From the pile driver log file, a number of recording periods with different blow energies were selected (Table 4.1). Broadband SELs for these periods in Figure 4.6 suggest a level increase of 7…9 $\log(E_2/E_1)$ dB, if the blow energy is raised from $E_1$ to $E_2$. This is lower than the value of 12 $\log(E_2/E_1)$ found by Schultz-von Glahn et al. (2006), however with a different type of pile driver (free fall hammer). Note: If the radiated sound energy was exactly proportional to the applied blow energy, the level increase would be 10 $\log(E_2/E_1)$ dB.

The increase of sound level with blow energy is frequency-dependent and varies from the above-mentioned 7…9 $\log(E_2/E_1)$ in the frequency range of maximum sound radiation, to about 15 $\log(E_2/E_1)$ at 10 kHz, see Figure 4.7.

| Blow energy, kJ | 90 | 130 | 330 | 390 | 500 | 850 |
|---|---|---|---|---|---|---|
| Number of blows averaged | 8 | 22 | 16 | 26 | 16 | 24 |
| Recording time, CEST | 05:06:24 | 05:07:05 | 05:24:00 | 05:13:30 | 05:08:30 | 05:12:15 |

*Table 4.1. Recording periods selected to examine the effect of pile driving energy on sound level*

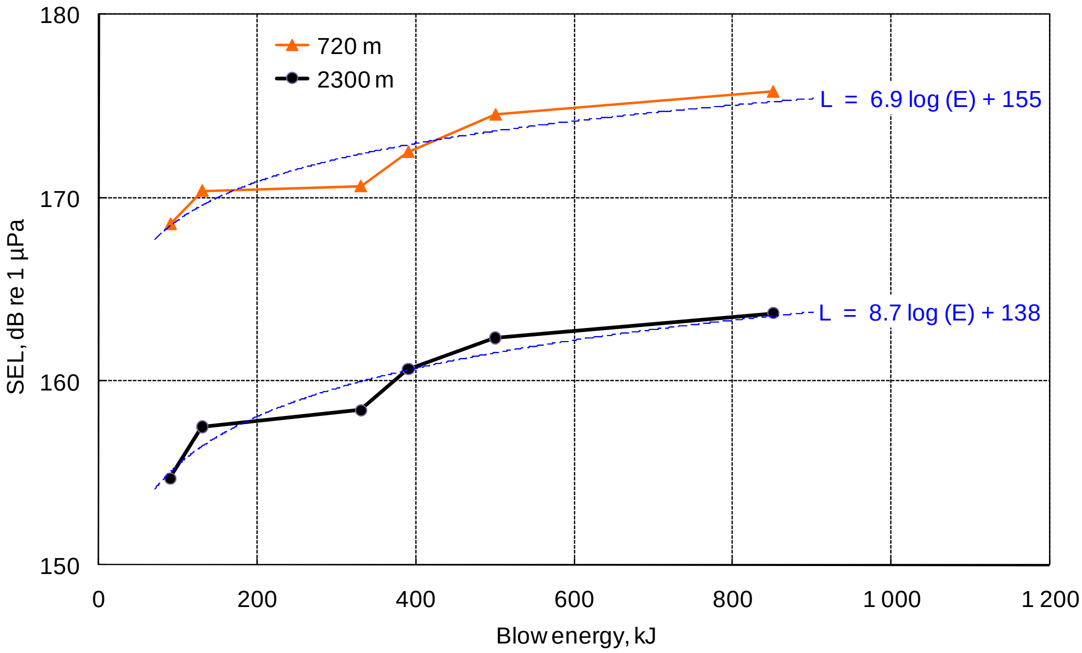


*Fig. 4.6. Sound level versus blow energy*

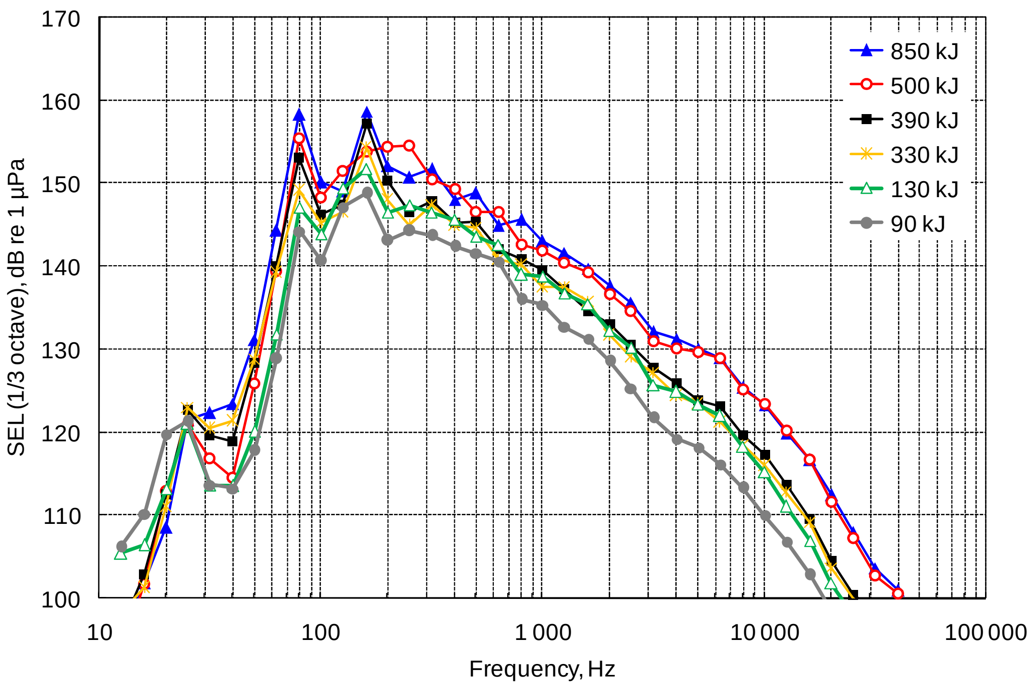


*Fig. 4.7. Spectral representation of sound level versus blow energy*

## 4.4 Comparison to other offshore pile driving operations

Figure 4.8 shows peak levels and SELs measured at pile driving works in the North Sea and the Baltic Sea; data sources are listed in Table 4.2. The pile diameter reflects pile driving energy as an implicit parameter. For better comparability, all levels are normalised to 750 m distance by adding 15 log($D_{meas}$/750 m) to the measured values. The levels observed at Horns Rev II are well within the level range measured in comparable situations elsewhere.

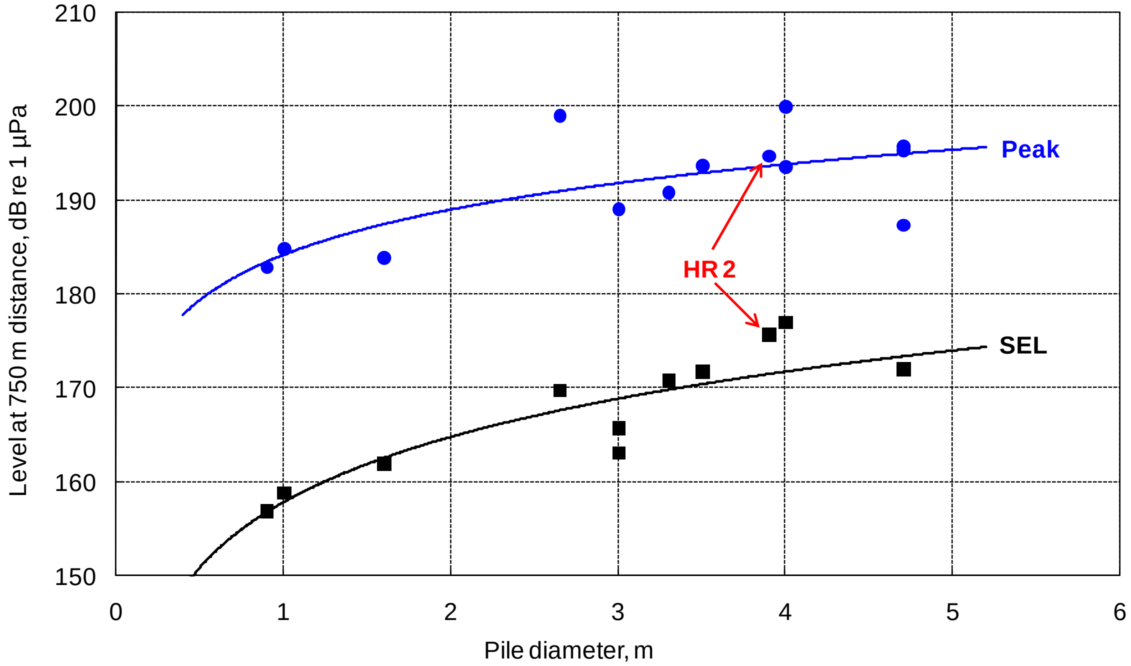


*Fig. 4.8. Maximum SEL and peak level at Horns Rev II, compared to pile driving noise measured elsewhere*

| | Pile diameter, m | Water depth, m | Measurement distance D, m | Measured peak level, dB re 1 µPa | Measured SEL, dB re 1 µPa | SEL normalised to 750 m, dB re 1 µPa | Peak level normalized to 750 m, dB re 1 µPa | References | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| Port construction, 2005 | 0.9 | 11 | 340 | 188 | 162 | 183 | 157 | 1 | |
| Port construction, 2005 | 1 | 11 | 340 | 190 | 164 | 185 | 159 | 2 | |
| FINO 1, 2003 | 1.6 | 30 | 400 | 188 | 166 | 184 | 162 | 3 | |
| Alpha Ventus, 2008 | 2.7 | 28 | 1100 | 197 | 167 | 199 | 170 | 3 | |
| Utgrunden, 2000 | 3 | 10 | 720 | n/a | 166 | n/a | 166 | 5 | |
| SKY 2000, 2002 | 3 | 21 | 260 | 196 | 170 | 189 | 163 | 4 | |
| FINO 2, 2006 | 3.3 | 24 | 530 | 190 | 170 | 189 | 169 | 1 | |
| Amrumbank West, 2005 | 3.5 | 23 | 850 | 196 | 174 | 191 | 171 | 1 | |
| Horns Rev II, 2008 | 3.9 | 12 | 720 | 195 | 176 | 195 | 176 | | |
| North Hoyle, 2003 | 4 | 9 (7-11) | 955 | 192 | n/a | 194 | n/a | 6 | a |
| Q7, 2007 | 4 | 20 | 750 | 200 | 177 | 200 | 177 | 7 | |
| Barrow, 2005 | 4.7 | 17 (15-20) | 500 | 198 | n/a | 195 | n/a | 8 | a |
| FINO 3, 2008 | 4.7 | 23 | 900 | 195 | 171 | 196 | 172 | 2 | b |

References: 1) ISD/DEWI/ITAP 2007, 2) ITAP, unpublished, 3) Betke & Matuschek 2008, 4) CRI/DEWI/ITAP 2004, 5)°McKenzie Maxon 2000, 6) Nedwell et al. 2003, 7) De Jong & Ainslie 2008, 8) Parvin et al. 2006a

Remarks: a) Peak level converted from published peak-to-peak value by subtracting von 6 dB; b) Measured levels increased by 10 log(80% / 20%) ≈ 6 dB to compensate for reduced blow energy during measurement

*Table 4.2. Details for the data plotted in Figure 4.8*

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# 6. Appendix:

**Pile driver log file for pile #71, supplied by IHC Hydrohammer**

Note: Times listed in the file are approx. 1 minute fast with respect to standard time.

I H C H y d r o h a m m e r

| | | | |
|---|---|---|---|
| Filenaam | : horns2.A36 | Datum(jj/mm/dd) | : 08/09/07 |
| Rapportnr. | : 35 | Paalnr. | : 71 |
| Project | : HornsRev2 | Lokatie | : HornsRev2 |
| Aannemer | : ABJV | Klant | : DONG |
| Paal lengte(m) | : 29,80/40,80 | materiaal | : steel |
| profiel | : pipe40/80mm | afmetingen(mm) | : 3900 mm |
| Type hamer | : S-1200 | Type paalmuts | : sleeve |
| Type aggregaat | : 2 x P-1600 | Mutsvulling | : steel |

| Penetratie (m) | Kalender (sl/afst) | Totaal slagen (-) | Slagenergie (kJ) | Slagen/min (-) | Totale energie (kJ) |
|---|---|---|---|---|---|
| Start | | (04:48:53) | | | |
| Stop | | (04:48:57) | | | |
| | | 00000 | 0000.0 | 000 | 0000000 |
| 002.25 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| Start | | (04:49:31) | | | |
| Stop | | (04:49:34) | | | |
| | | 00000 | 0000.0 | 000 | 0000000 |
| 002.50 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| 002.75 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| 003.00 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| 003.25 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| Start | | (04:51:23) | | | |
| Stop | | (04:51:27) | | | |
| | | 00000 | 0000.0 | 000 | 0000000 |
| Start | | (04:51:42) | | | |
| Stop | | (04:51:47) | | | |
| | | 00000 | 0000.0 | 000 | 0000000 |
| 003.50 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| Start | | (04:52:32) | | | |
| 003.75 | 000 | 00000 | 0000.0 | 000 | 0000000 |
| Stop | | (04:52:36) | | | |
| | | 00000 | 0000.0 | 000 | 0000000 |
| Start | | (04:52:51) | | | |
| 004.00 | 001 | 00001 | 0000.0 | 000 | 0000000 |
| Stop | | (04:52:57) | | | |
| | | 00001 | 0000.0 | 000 | 0000000 |
| Start | | (04:53:30) | | | |
| Stop | | (04:53:36) | | | |
| | | 00003 | 0080.0 | 053 | 0000160 |
| Start | | (04:54:12) | | | |
| 004.25 | 002 | 00003 | 0080.0 | 053 | 0000160 |
| 004.50 | 003 | 00006 | 0086.0 | 054 | 0000418 |
| Stop | | (04:54:20) | | | |
| | | 00006 | 0000.0 | 054 | 0000418 |
| Start | | (04:54:31) | | | |
| 004.75 | 001 | 00007 | 0055.0 | 054 | 0000473 |
| Stop | | (04:54:38) | | | |
| | | 00009 | 0105.5 | 052 | 0000684 |
| Start | | (04:55:01) | | | |
| 005.00 | 004 | 00011 | 0091.2 | 048 | 0000838 |
| Stop | | (04:55:10) | | | |
| | | 00013 | 0104.5 | 057 | 0001047 |
| Start | | (04:55:51) | | | |
| 005.25 | 003 | 00014 | 0088.7 | 057 | 0001104 |
| 005.50 | 003 | 00017 | 0105.7 | 055 | 0001421 |
| 005.75 | 004 | 00021 | 0117.5 | 055 | 0001891 |
| 006.00 | 004 | 00025 | 0107.8 | 057 | 0002322 |
| 006.25 | 005 | 00030 | 0081.6 | 064 | 0002730 |
| 006.50 | 004 | 00034 | 0112.0 | 057 | 0003178 |
| 006.75 | 003 | 00037 | 0088.3 | 058 | 0003443 |
| 007.00 | 004 | 00041 | 0107.8 | 055 | 0003874 |
| 007.25 | 004 | 00045 | 0123.0 | 053 | 0004366 |
| 007.50 | 004 | 00049 | 0109.5 | 058 | 0004804 |
| 007.75 | 006 | 00055 | 0111.3 | 058 | 0005472 |
| Stop | | (04:56:45) | | | |
| | | 00060 | 0105.6 | 058 | 0006000 |
| Start | | (05:05:07) | | | |
| 008.00 | 008 | 00063 | 0089.5 | 080 | 0006188 |
| 008.25 | 012 | 00075 | 0105.6 | 064 | 0007455 |
| 008.50 | 011 | 00086 | 0117.5 | 058 | 0008748 |
| 008.75 | 012 | 00098 | 0127.7 | 060 | 0010280 |
| 009.00 | 009 | 00107 | 0132.7 | 070 | 0011474 |
| 009.25 | 012 | 00119 | 0126.8 | 061 | 0012995 |

| | | | | | |
|---|---|---|---|---|---|
| 009.50 | 012 | 00131 | 0182.3 | 057 | 0015183 |
| 009.75 | 009 | 00140 | 0232.8 | 054 | 0017278 |
| 010.00 | 008 | 00148 | 0299.6 | 057 | 0019675 |
| 010.25 | 010 | 00158 | 0328.0 | 057 | 0022955 |
| 010.50 | 008 | 00166 | 0403.4 | 055 | 0026182 |
| 010.75 | 009 | 00175 | 0508.7 | 051 | 0030760 |
| 011.00 | 008 | 00183 | 0494.1 | 052 | 0034713 |
| 011.25 | 005 | 00188 | 0503.4 | 052 | 0037230 |
| 011.50 | 007 | 00195 | 0506.6 | 052 | 0040776 |
| 011.75 | 004 | 00199 | 0566.5 | 048 | 0043042 |
| 012.00 | 005 | 00204 | 0574.6 | 048 | 0045915 |
| 012.25 | 005 | 00209 | 0582.8 | 048 | 0048829 |
| 012.50 | 005 | 00214 | 0594.4 | 048 | 0051801 |
| 012.75 | 007 | 00221 | 0586.9 | 048 | 0055909 |
| 013.00 | 007 | 00228 | 0609.4 | 048 | 0060175 |
| 013.25 | 006 | 00234 | 0632.3 | 047 | 0063969 |
| 013.50 | 007 | 00241 | 0612.1 | 048 | 0068254 |
| 013.75 | 008 | 00249 | 0700.0 | 046 | 0073854 |
| 014.00 | 005 | 00254 | 0776.6 | 048 | 0077737 |
| 014.25 | 006 | 00260 | 0768.7 | 045 | 0082349 |
| 014.50 | 005 | 00265 | 0774.0 | 045 | 0086219 |
| 014.75 | 006 | 00271 | 0800.7 | 042 | 0091023 |
| 015.00 | 007 | 00278 | 0811.6 | 042 | 0096704 |
| 015.25 | 007 | 00285 | 0797.4 | 043 | 0102286 |
| 015.50 | 006 | 00291 | 0793.8 | 043 | 0107049 |
| 015.75 | 006 | 00297 | 0799.3 | 043 | 0111845 |
| 016.00 | 006 | 00303 | 0799.2 | 043 | 0116640 |
| 016.25 | 006 | 00309 | 0801.8 | 042 | 0121451 |
| 016.50 | 006 | 00315 | 0855.8 | 040 | 0126586 |
| 016.75 | 007 | 00322 | 0850.6 | 040 | 0132540 |
| 017.00 | 006 | 00328 | 0847.8 | 040 | 0137627 |
| 017.25 | 006 | 00334 | 0854.3 | 040 | 0142753 |
| 017.50 | 007 | 00341 | 0855.9 | 040 | 0148744 |
| 017.75 | 007 | 00348 | 0839.0 | 041 | 0154617 |
| 018.00 | 006 | 00354 | 0833.8 | 041 | 0159620 |
| 018.25 | 011 | 00365 | 0836.6 | 041 | 0168823 |
| 018.50 | 009 | 00374 | 0779.4 | 042 | 0175838 |
| 018.75 | 009 | 00383 | 0581.4 | 042 | 0181071 |
| 019.00 | 012 | 00395 | 0461.2 | 042 | 0186605 |
| 019.25 | 016 | 00411 | 0387.2 | 043 | 0192801 |
| 019.50 | 014 | 00425 | 0386.9 | 042 | 0198217 |
| Stop | | (05:12:56) | | | |
| | | 00428 | 0390.7 | 042 | 0199389 |
| Start | | (05:22:46) | | | |
| 019.75 | 022 | 00447 | 0334.7 | 044 | 0205581 |
| Stop | | (05:23:19) | | | |
| | | 00449 | 0319.0 | 044 | 0206219 |

Samenvatting : horns2.A36

Werkelijke penetratie : 021.05

Totaal slagen : 449
Totale energie : 206219
Totale tijd (h:m) : 00:35:29
Netto tijd (h:m) : 00:10:11

**IHC Hydrohammer**

| | | | | |
|---|---|---|---|---|
| **Filenaam** | | : horns2.A36 | **Datum(jj/mm/dd)** | : 08/09/07 |
| **Rapportnr.** | | : 35 | **Paalnr.** | : 71 |
| **Project** | | : HornsRev2 | **Lokatie** | : HornsRev2 |
| **Aannemer** | | : ABJV | **Klant** | : DONG |
| **Paal** | lengte(m) | : 29,80/40,80 | **materiaal** | : steel |
| | profiel | : pipe40/80mm | **afmetingen(mm)** | : 3900 mm |
| **Type hamer** | | : S-1200 | **Type paalmuts** | : sleeve |
| **Type aggregaat** | | : 2 x P-1600 | **Mutsvulling** | : steel |

| **Penetratie** (m) | **Kalender** (sl/afst) | **Totaal slagen** (-) | **Slagenergie** (kJ) | **Slagen/min** (-) | **Totale energie** (kJ) | **Totale energie/ Penetratie** (kJ) |
|---|---|---|---|---|---|---|
| Start | | (04:48:53) | | | | |
| Stop | | (04:48:57) | | | | |
| 2.25 | | | | | | |
| Start | | (04:49:31) | | | | |
| Stop | | (04:49:34) | | | | |
| 2.50 | | | | | | |
| 2.75 | | | | | | |
| 3.00 | | | | | | |
| 3.25 | | | | | | |
| Start | | (04:51:23) | | | | |
| Stop | | (04:51:27) | | | | |
| Start | | (04:51:42) | | | | |
| Stop | | (04:51:47) | | | | |
| 3.50 | | | | | | |
| Start | | (04:52:32) | | | | |
| 3.75 | | | | | | |
| Stop | | (04:52:36) | | | | |
| Start | | (04:52:51) | | | | |
| 4.00 | 1 | 1 | | | | |
| Stop | | (04:52:57) | | | | |
| | | 1 | | | | |
| Start | | (04:53:30) | | | | |
| Stop | | (04:53:36) | | | | |
| | | 3 | 80 | 53 | 160 | |
| Start | | (04:54:12) | | | | |
| 4.25 | 2 | 3 | 80 | 53 | 160 | 160 |
| 4.50 | 3 | 6 | 86 | 54 | 418 | 258 |
| Stop | | (04:54:20) | | | | |
| | | 6 | | 54 | 418 | |
| Start | | (04:54:31) | | | | |
| 4.75 | 1 | 7 | 55 | 54 | 473 | 55 |
| Stop | | (04:54:38) | | | | |
| | | 9 | 106 | 52 | 684 | |
| Start | | (04:55:01) | | | | |
| 5.00 | 4 | 11 | 91 | 48 | 838 | 365 |
| Stop | | (04:55:10) | | | | |
| | | 13 | 105 | 57 | 1047 | |

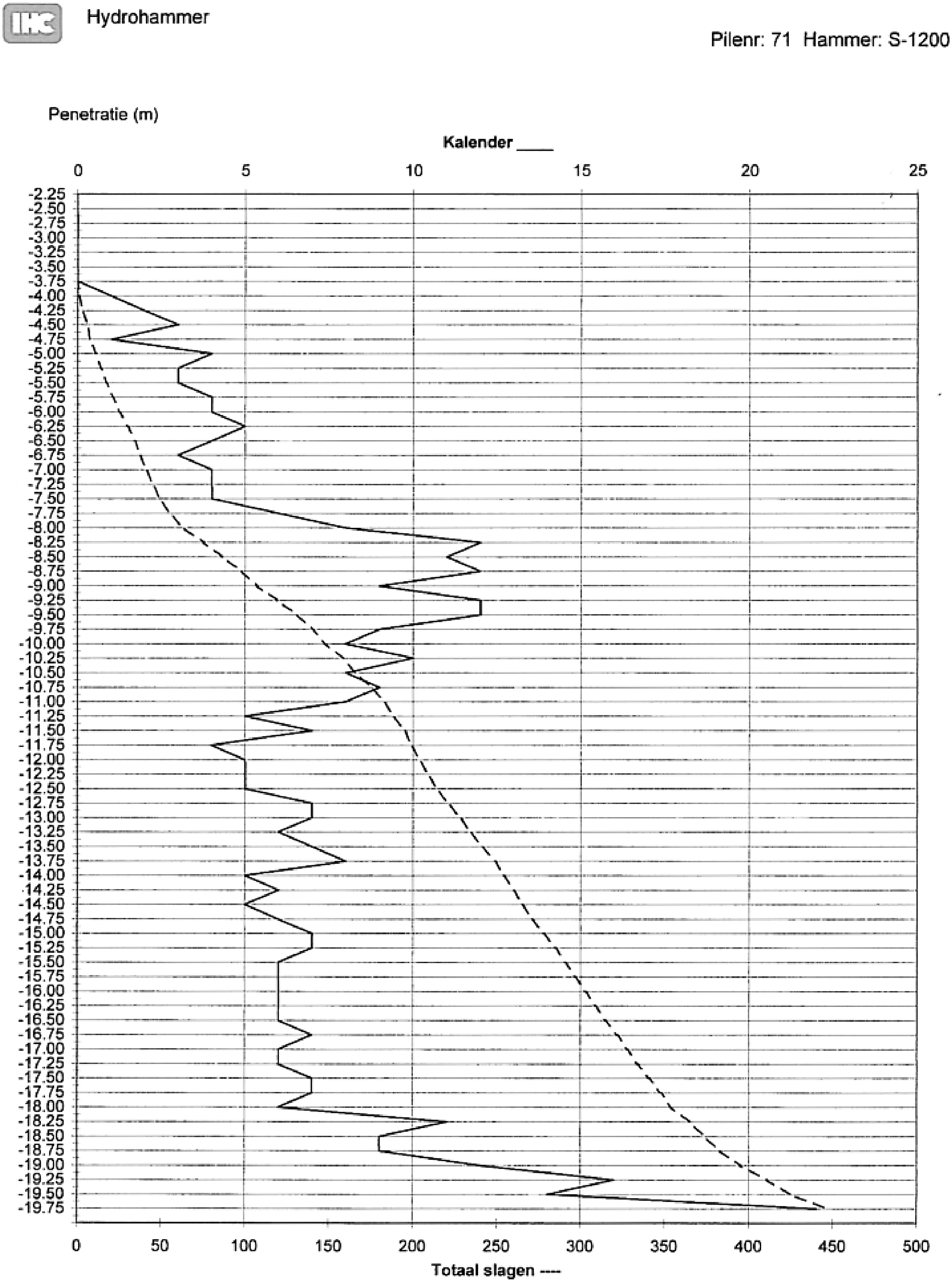
| Penetratie (m) | Kalender (sl/afst) | Totaal slagen (-) | Slagenergie (kJ) | Slagen/min (-) | Totale energie (kJ) | Totale energie/ Penetratie (kJ) |
|---|---|---|---|---|---|---|
| Start | | (04:55:51) | | | | |
| 5.25 | 3 | 14 | 89 | 57 | 1104 | 266 |
| 5.50 | 3 | 17 | 106 | 55 | 1421 | 317 |
| 5.75 | 4 | 21 | 118 | 55 | 1891 | 470 |
| 6.00 | 4 | 25 | 108 | 57 | 2322 | 431 |
| 6.25 | 5 | 30 | 82 | 64 | 2730 | 408 |
| 6.50 | 4 | 34 | 112 | 57 | 3178 | 448 |
| 6.75 | 3 | 37 | 88 | 58 | 3443 | 265 |
| 7.00 | 4 | 41 | 108 | 55 | 3874 | 431 |
| 7.25 | 4 | 45 | 123 | 53 | 4366 | 492 |
| 7.50 | 4 | 49 | 110 | 58 | 4804 | 438 |
| 7.75 | 6 | 55 | 111 | 58 | 5472 | 668 |
| Stop | | (04:56:45) | | | | |
| | | 60 | 106 | 58 | 6000 | |
| Start | | (05:05:07) | | | | |
| 8.00 | 8 | 63 | 90 | 80 | 6188 | 716 |
| 8.25 | 12 | 75 | 106 | 64 | 7455 | 1267 |
| 8.50 | 11 | 86 | 118 | 58 | 8748 | 1293 |
| 8.75 | 12 | 98 | 128 | 60 | 10280 | 1532 |
| 9.00 | 9 | 107 | 133 | 70 | 11474 | 1194 |
| 9.25 | 12 | 119 | 127 | 61 | 12995 | 1522 |
| 9.50 | 12 | 131 | 182 | 57 | 15183 | 2188 |
| 9.75 | 9 | 140 | 233 | 54 | 17278 | 2095 |
| 10.00 | 8 | 148 | 300 | 57 | 19675 | 2397 |
| 10.25 | 10 | 158 | 328 | 57 | 22955 | 3280 |
| 10.50 | 8 | 166 | 403 | 55 | 26182 | 3227 |
| 10.75 | 9 | 175 | 509 | 51 | 30760 | 4578 |
| 11.00 | 8 | 183 | 494 | 52 | 34713 | 3953 |
| 11.25 | 5 | 188 | 503 | 52 | 37230 | 2517 |
| 11.50 | 7 | 195 | 507 | 52 | 40776 | 3546 |
| 11.75 | 4 | 199 | 567 | 48 | 43042 | 2266 |
| 12.00 | 5 | 204 | 575 | 48 | 45915 | 2873 |
| 12.25 | 5 | 209 | 583 | 48 | 48829 | 2914 |
| 12.50 | 5 | 214 | 594 | 48 | 51801 | 2972 |
| 12.75 | 7 | 221 | 587 | 48 | 55909 | 4108 |
| 13.00 | 7 | 228 | 609 | 48 | 60175 | 4266 |
| 13.25 | 6 | 234 | 632 | 47 | 63969 | 3794 |
| 13.50 | 7 | 241 | 612 | 48 | 68254 | 4285 |
| 13.75 | 8 | 249 | 700 | 46 | 73854 | 5600 |
| 14.00 | 5 | 254 | 777 | 48 | 77737 | 3883 |
| 14.25 | 6 | 260 | 769 | 45 | 82349 | 4612 |
| 14.50 | 5 | 265 | 774 | 45 | 86219 | 3870 |
| 14.75 | 6 | 271 | 801 | 42 | 91023 | 4804 |
| 15.00 | 7 | 278 | 812 | 42 | 96704 | 5681 |
| 15.25 | 7 | 285 | 797 | 43 | 102286 | 5582 |
| 15.50 | 6 | 291 | 794 | 43 | 107049 | 4763 |
| 15.75 | 6 | 297 | 799 | 43 | 111845 | 4796 |
| 16.00 | 6 | 303 | 799 | 43 | 116640 | 4795 |
| 16.25 | 6 | 309 | 802 | 42 | 121451 | 4811 |
| 16.50 | 6 | 315 | 856 | 40 | 126586 | 5135 |
| 16.75 | 7 | 322 | 851 | 40 | 132540 | 5954 |
| 17.00 | 6 | 328 | 848 | 40 | 137627 | 5087 |
| 17.25 | 6 | 334 | 854 | 40 | 142753 | 5126 |
| 17.50 | 7 | 341 | 856 | 40 | 148744 | 5991 |
| 17.75 | 7 | 348 | 839 | 41 | 154617 | 5873 |
| 18.00 | 6 | 354 | 834 | 41 | 159620 | 5003 |
| 18.25 | 11 | 365 | 837 | 41 | 168823 | 9203 |

| Penetratie (m) | Kalender (sl/afst) | Totaal slagen (-) | Slagenergie (kJ) | Slagen/min (-) | Totale energie (kJ) | Totale energie/ Penetratie (kJ) |
|---|---|---|---|---|---|---|
| 18.50 | 9 | 374 | 779 | 42 | 175838 | 7015 |
| 18.75 | 9 | 383 | 581 | 42 | 181071 | 5233 |
| 19.00 | 12 | 395 | 461 | 42 | 186605 | 5534 |
| 19.25 | 16 | 411 | 387 | 43 | 192801 | 6195 |
| 19.50 | 14 | 425 | 387 | 42 | 198217 | 5417 |
| Stop | | (05:12:56) | | | | |
| | | 428 | 391 | 42 | 199389 | |
| Start | | (05:22:46) | | | | |
| 19.75 | 22 | 447 | 335 | 44 | 205581 | 7363 |
| Stop | | (05:23:19) | | | | |
| | | 449 | 319 | 44 | 206219 | |

Samenvatting : horns2.A36

Werkelijke penetratie : 021.05

Totaal slagen : 449
Totale energie : 206219
Totale tijd (h:m) : 00:35:29
Netto tijd (h:m) : 00:10:11


Hydrohammer
Pilenr: 71 Hammer: S-1200
Penetratie (m)
Kalender ____
0
5
10
15
20
25
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
-9.25
-9.50
-9.75
-10.00
-10.25
-10.50
-10.75
-11.00
-11.25
-11.50
-11.75
-12.00
-12.25
-12.50
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-16.00
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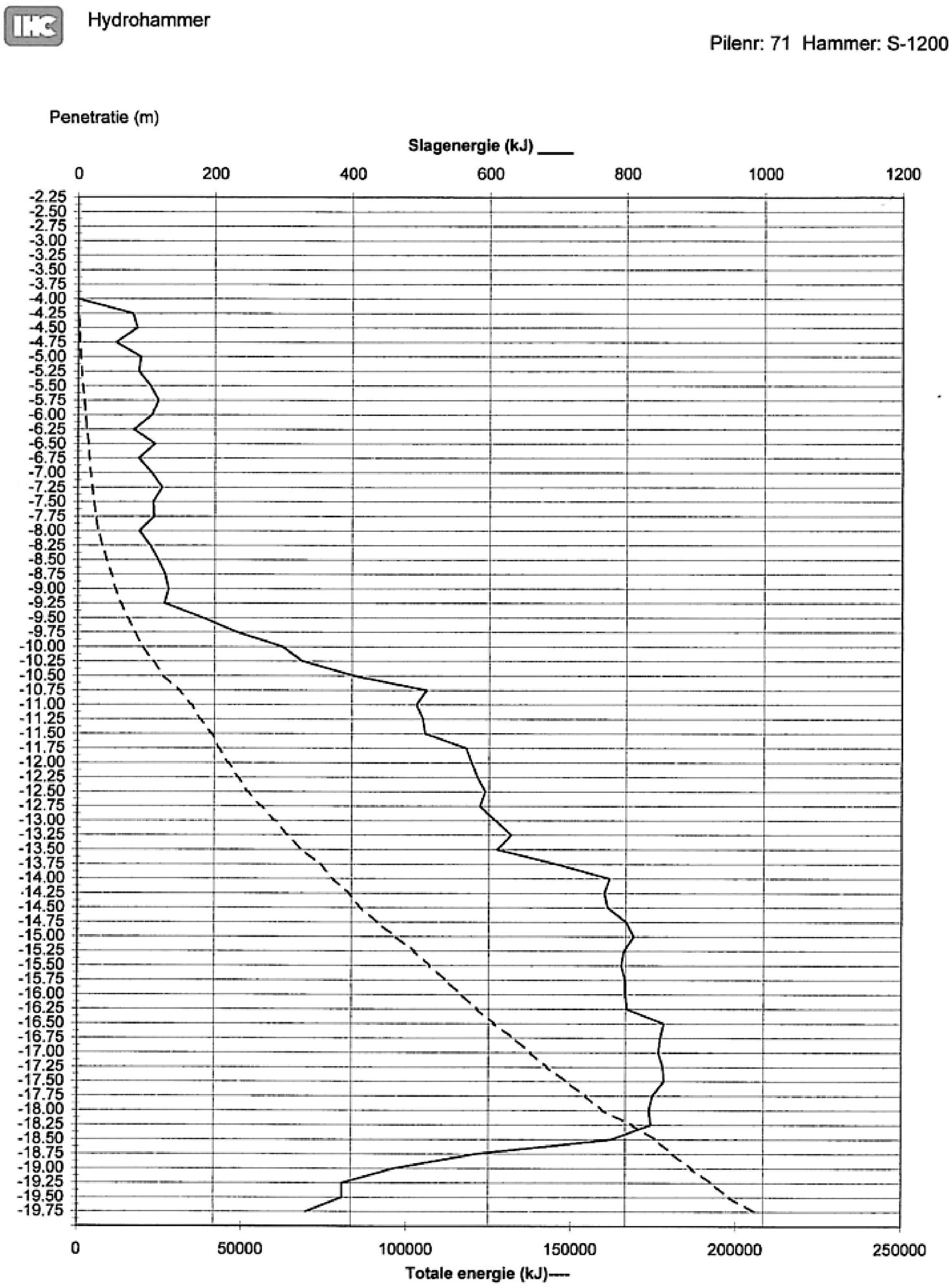
-16.50
-16.75
-17.00
-17.25
-17.50
-17.75
-18.00
-18.25
-18.50
-18.75
-19.00
-19.25
-19.50
-19.75
0
50
100
150
200
250
300
350
400
450
500
Totaal slagen ----


Hydrohammer
Pilenr: 71 Hammer: S-1200
Penetratie (m)
Slagenergie (kJ) ____
0
200
400
600
800
1000
1200
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
-4.50
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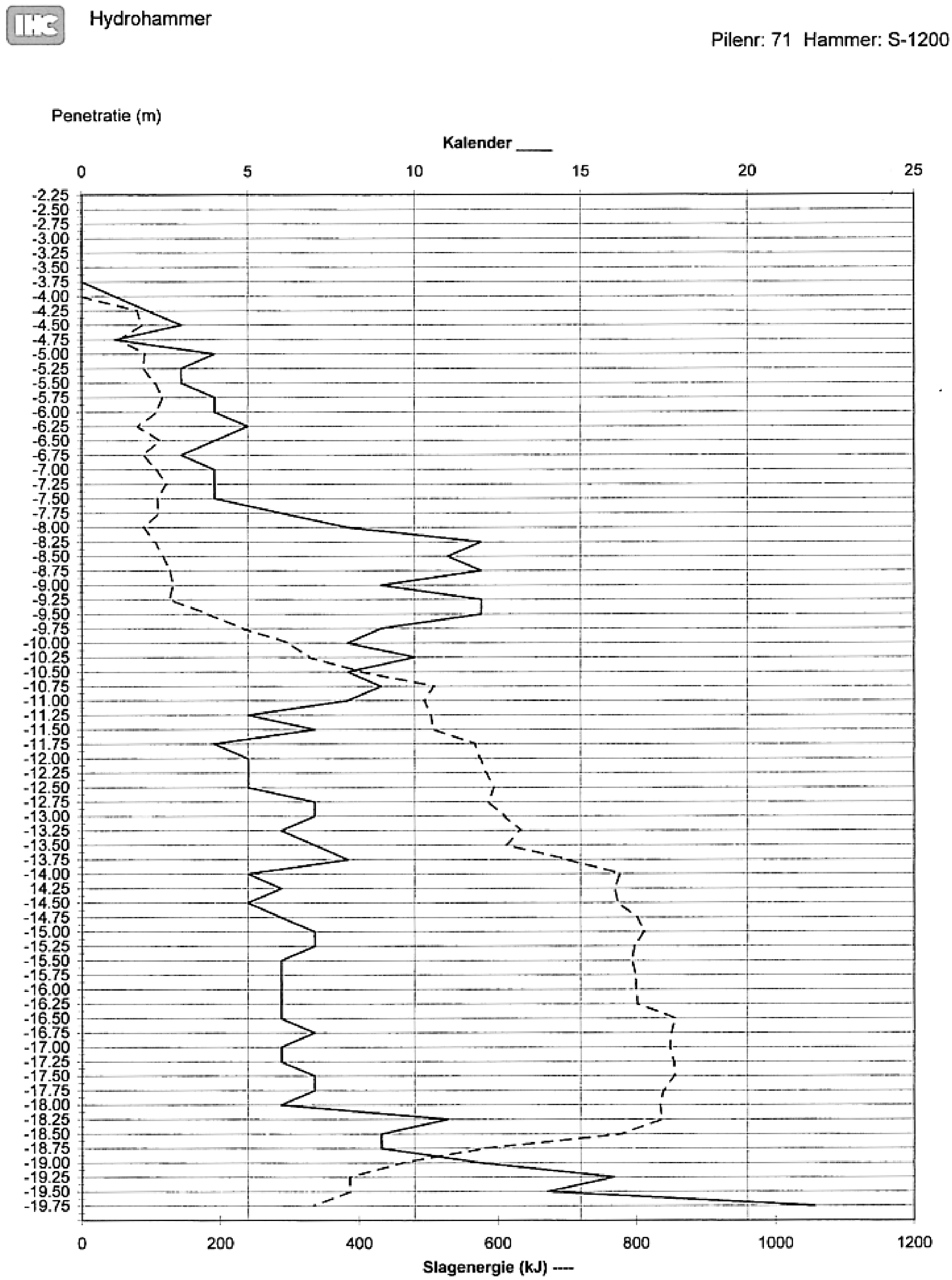
200000
250000
Totale energie (kJ)----


IHC
Hydrohammer
Pilenr: 71 Hammer: S-1200
Penetratie (m)
Kalender ____
0
5
10
15
20
25
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
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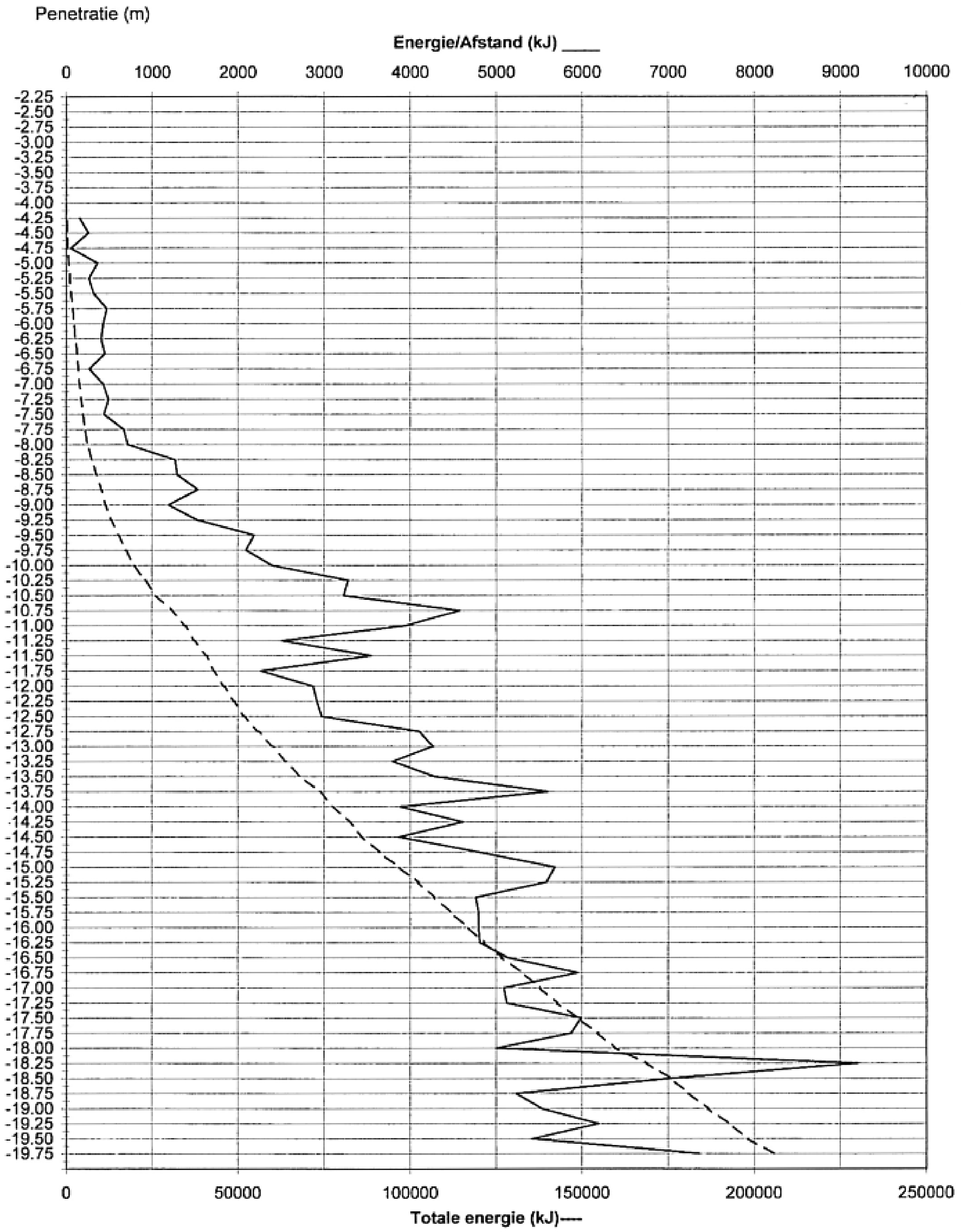
-18.50
-18.75
-19.00
-19.25
-19.50
-19.75
0
200
400
600
800
1000
1200
Slagenergie (kJ) ----

Hydrohammer

Pilenr: 71 Hammer: S-1200



Gefilterd bestand

| | | | | | |
|---|---|---|---|---|---|
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| -2.50 | 0 | 0 | 0 | 0 | 0 |
| -2.75 | 0 | 0 | 0 | 0 | 0 |
| -3.00 | 0 | 0 | 0 | 0 | 0 |
| -3.25 | 0 | 0 | 0 | 0 | 0 |
| -3.50 | 0 | 0 | 0 | 0 | 0 |
| -3.75 | 0 | 0 | 0 | 0 | 0 |
| -4.00 | 1 | 1 | 0 | 0 | 0 |
| -4.25 | 2 | 3 | 80 | 53 | 160 |
| -4.50 | 3 | 6 | 86 | 54 | 418 |
| -4.75 | 1 | 7 | 55 | 54 | 473 |
| -5.00 | 4 | 11 | 91 | 48 | 838 |
| -5.25 | 3 | 14 | 89 | 57 | 1104 |
| -5.50 | 3 | 17 | 106 | 55 | 1421 |
| -5.75 | 4 | 21 | 118 | 55 | 1891 |
| -6.00 | 4 | 25 | 108 | 57 | 2322 |
| -6.25 | 5 | 30 | 82 | 64 | 2730 |
| -6.50 | 4 | 34 | 112 | 57 | 3178 |
| -6.75 | 3 | 37 | 88 | 58 | 3443 |
| -7.00 | 4 | 41 | 108 | 55 | 3874 |
| -7.25 | 4 | 45 | 123 | 53 | 4366 |
| -7.50 | 4 | 49 | 110 | 58 | 4804 |
| -7.75 | 6 | 55 | 111 | 58 | 5472 |
| -8.00 | 8 | 63 | 90 | 80 | 6188 |
| -8.25 | 12 | 75 | 106 | 64 | 7455 |
| -8.50 | 11 | 86 | 118 | 58 | 8748 |
| -8.75 | 12 | 98 | 128 | 60 | 10280 |
| -9.00 | 9 | 107 | 133 | 70 | 11474 |
| -9.25 | 12 | 119 | 127 | 61 | 12995 |
| -9.50 | 12 | 131 | 182 | 57 | 15183 |
| -9.75 | 9 | 140 | 233 | 54 | 17278 |
| -10.00 | 8 | 148 | 300 | 57 | 19675 |
| -10.25 | 10 | 158 | 328 | 57 | 22955 |
| -10.50 | 8 | 166 | 403 | 55 | 26182 |
| -10.75 | 9 | 175 | 509 | 51 | 30760 |
| -11.00 | 8 | 183 | 494 | 52 | 34713 |
| -11.25 | 5 | 188 | 503 | 52 | 37230 |
| -11.50 | 7 | 195 | 507 | 52 | 40776 |
| -11.75 | 4 | 199 | 567 | 48 | 43042 |
| -12.00 | 5 | 204 | 575 | 48 | 45915 |
| -12.25 | 5 | 209 | 583 | 48 | 48829 |
| -12.50 | 5 | 214 | 594 | 48 | 51801 |
| -12.75 | 7 | 221 | 587 | 48 | 55909 |
| -13.00 | 7 | 228 | 609 | 48 | 60175 |
| -13.25 | 6 | 234 | 632 | 47 | 63969 |
| -13.50 | 7 | 241 | 612 | 48 | 68254 |
| -13.75 | 8 | 249 | 700 | 46 | 73854 |
| -14.00 | 5 | 254 | 777 | 48 | 77737 |
| -14.25 | 6 | 260 | 769 | 45 | 82349 |
| -14.50 | 5 | 265 | 774 | 45 | 86219 |
| -14.75 | 6 | 271 | 801 | 42 | 91023 |
| -15.00 | 7 | 278 | 812 | 42 | 96704 |
| -15.25 | 7 | 285 | 797 | 43 | 102286 |
| -15.50 | 6 | 291 | 794 | 43 | 107049 |
| -15.75 | 6 | 297 | 799 | 43 | 111845 |
| -16.00 | 6 | 303 | 799 | 43 | 116640 |

Gefilterd bestand

| | | | | | |
|---|---|---|---|---|---|
| -16.25 | 6 | 309 | 802 | 42 | 121451 |
| -16.50 | 6 | 315 | 856 | 40 | 126586 |
| -16.75 | 7 | 322 | 851 | 40 | 132540 |
| -17.00 | 6 | 328 | 848 | 40 | 137627 |
| -17.25 | 6 | 334 | 854 | 40 | 142753 |
| -17.50 | 7 | 341 | 856 | 40 | 148744 |
| -17.75 | 7 | 348 | 839 | 41 | 154617 |
| -18.00 | 6 | 354 | 834 | 41 | 159620 |
| -18.25 | 11 | 365 | 837 | 41 | 168823 |
| -18.50 | 9 | 374 | 779 | 42 | 175838 |
| -18.75 | 9 | 383 | 581 | 42 | 181071 |
| -19.00 | 12 | 395 | 461 | 42 | 186605 |
| -19.25 | 16 | 411 | 387 | 43 | 192801 |
| -19.50 | 14 | 425 | 387 | 42 | 198217 |
| -19.75 | 22 | 447 | 335 | 44 | 205581 |

Gefilterd bestand

| | | |
|---|---|---|
| | | 0 |
| | | 0 |
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| | | 0 |
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| | | 0 |
| 160 | 160 | 160 |
| 258 | 258 | 418 |
| 55 | 55 | 473 |
| 365 | 365 | 838 |
| 266 | 266 | 1104 |
| 317 | 317 | 1421 |
| 470 | 470 | 1891 |
| 431 | 431 | 2322 |
| 408 | 408 | 2730 |
| 448 | 448 | 3178 |
| 265 | 265 | 3443 |
| 431 | 431 | 3874 |
| 492 | 492 | 4366 |
| 438 | 438 | 4804 |
| 668 | 668 | 5472 |
| 716 | 716 | 6188 |
| 1267 | 1267 | 7455 |
| 1293 | 1293 | 8748 |
| 1532 | 1532 | 10280 |
| 1194 | 1194 | 11474 |
| 1522 | 1522 | 12995 |
| 2188 | 2188 | 15183 |
| 2095 | 2095 | 17278 |
| 2397 | 2397 | 19675 |
| 3280 | 3280 | 22955 |
| 3227 | 3227 | 26182 |
| 4578 | 4578 | 30760 |
| 3953 | 3953 | 34713 |
| 2517 | 2517 | 37230 |
| 3546 | 3546 | 40776 |
| 2266 | 2266 | 43042 |
| 2873 | 2873 | 45915 |
| 2914 | 2914 | 48829 |
| 2972 | 2972 | 51801 |
| 4108 | 4108 | 55909 |
| 4266 | 4266 | 60175 |
| 3794 | 3794 | 63969 |
| 4285 | 4285 | 68254 |
| 5600 | 5600 | 73854 |
| 3883 | 3883 | 77737 |
| 4612 | 4612 | 82349 |
| 3870 | 3870 | 86219 |
| 4804 | 4804 | 91023 |
| 5681 | 5681 | 96704 |
| 5582 | 5582 | 102286 |
| 4763 | 4763 | 107049 |
| 4796 | 4796 | 111845 |
| 4795 | 4795 | 116640 |

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|---|---|---|
| 4811 | 4811 | 121451 |
| 5135 | 5135 | 126586 |
| 5954 | 5954 | 132540 |
| 5087 | 5087 | 137627 |
| 5126 | 5126 | 142753 |
| 5991 | 5991 | 148744 |
| 5873 | 5873 | 154617 |
| 5003 | 5003 | 159620 |
| 9203 | 9203 | 168823 |
| 7015 | 7015 | 175838 |
| 5233 | 5233 | 181071 |
| 5534 | 5534 | 186605 |
| 6195 | 6195 | 192801 |
| 5417 | 5417 | 198217 |
| 7363 | 7363 | 205581 |