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Empirical estimation of peak pressure level from sound exposure level. Part II: Offshore impact pile driving noise

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Abstract: Numerical models of underwater sound propagation predict the energy of impulsive signals and its decay with range with a better accuracy than the peak pressure. A semi-empirical formula is suggested to predict the peak pressure of man-made impulsive signals based on numerical predictions of their energy. The approach discussed by Galindo-Romero, Lippert, and Gavrilov [J. Acoust. Soc. Am. **138**, in press (2015)] for airgun signals is modified to predict the peak pressure from offshore pile driving, which accounts for impact and pile parameters. It is shown that using the modified empirical formula provides more accurate predictions of the peak pressure than direct numerical simulations of the signal waveform.

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1. Introduction

The numerical prediction of the energy of impulsive signals and its decay with range can generally be achieved with sufficient accuracy in underwater acoustics, if the properties of the waveguide, such as water depth, sound speed profile and bottom parameters, are known. This is much less the case for the peak pressure, as it is much more subject to multipath interference effects and hence both spatial and temporal fluctuations of the sound channel parameters, such as the surface and bottom roughness, sound speed perturbations due to tides and internal waves, etc. Most numerical models incorporate these effects only in terms of the first-order statistics, where only the coherent component of the transmission loss is taken into consideration and consequently the mean value of sound energy can be predicted. Applying these models to predict the peak pressure through numerical simulations of the waveform often leads to an overestimation of the peak levels as scattering effects are not properly modeled.

Therefore, it is desirable to establish a relation between the peak pressure of a signal propagated in an underwater sound channel and its energy. Though this is not possible for a generalized case, it can be achieved for certain applications. In Galindo-Romero *et al.*[1,2] such a relation is established for the case of acoustic signals emitted by airguns, in the form

$$\mathrm{SPL}_{\mathrm{peak}} = A\,\mathrm{SEL} + B, \tag{1}$$

where sound pressure level $(\mathrm{SPL})_{\mathrm{peak}}$ is the peak SPL, SEL is the sound exposure level, and A and B are empirical constants, estimated from measurements.

For the case of offshore impact pile driving, several numerical models exist today to predict the radiated noise levels over long ranges, for example, see Reinhal and Dahl,[3] Zampolli *et al.*,[4] or Lippert and von Estorff.[5,6] All of these models are capable of estimating the energy characteristics of piling signals, such as the SEL, in a reasonably accurate way but suffer from the problems described above when it comes to the prediction of the peak pressure, or are only capable of estimating the energy content of the emitted signals.

Therefore, a regression formula similar to Eq. (1) is also desirable to estimate the peak pressure and its variation from the numerical prediction of the SEL, which can be obtained with satisfactory precision.

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2. Application of the regression approach to pile driving noise measurements

In this section, the applicability of the linear regression approach to the estimation of peak SPLs from offshore impact pile driving is investigated. The direct application of Eq. (1) to the case of pile driving acoustics is complicated by the variety of encountered pile dimensions and impact parameters, i.e., by the wide range of emitted acoustic signals.

The coefficients A and B of Eq. (1) are obtained on the basis of underwater sound measurements at three sites in the North Sea, i.e., the wind farms BARD Offshore I (site I), Global Tech I (site II) and Borkum Riffgrund 1 (site III). These sites represent different environmental conditions (within the North Sea) and source types, with water depths ranging from 27 to 40 m, strongly varying pile dimensions, and different foundation types, i.e., tri-piles, tripods and mono piles.

The acoustic far-field measurements for these sites were taken at ranges varying from 250 to 5000 m from the pile, and at a depth of approximately 2 m above the seafloor. In all three cases, no sound mitigation system was employed during the measurements. At site I, 65 strikes were evaluated at 7 hydrophones, leading to 455 data points, whereas at site II 145 strikes were recorded at 6 positions (870 points) and 500 strikes at 12 positions (6000 points) at site III.

For the evaluation of the peak SPL, either the zero-to-peak or the peak-to-peak variation of the sound pressure can be used. Similarly to the evaluation of airgun signals considered in Galindo-Romero *et al.*,[1] the peak-to-peak SPL will be used to obtain the regression coefficients. However, the evaluation of the used data with respect to the difference ΔL between both quantities yielded the values that are presented in Table 1, in the form of mean value μ and standard deviation σ. Because of the relatively constant offset, the derived peak-to-peak values can be conveniently transferred to the corresponding zero-to-peak values for the presented data sets.

As an example, the data points and the corresponding linear regression curves for site II are shown in Fig. 1. Similar results were obtained for the two other sites. As can be seen, the data can be approximated quite well by the applied fit, both with respect to the mean linear fit parameters A and B, and the 95% confidence bounds $B_{95\%}$. The latter parameter was obtained by keeping the slope A constant and symmetrically changing the y-intercept B to account for 95% of all data points. The actual regression coefficients for all sites can be found in Table 1.

The regression coefficient A is nearly the same for all three sites with a maximum deviation of less than 2% of its mean value. The y-intercept B exhibits a larger variation between different sites with a maximum difference of almost 5 dB, whereas its confidence bounds $B_{95\%}$ are relatively small, indicating a high temporal stability.

This last point is of special interest, as the significant wave height H_{sig}, in this particular case, was close to its maximum value of $H_{\text{sig,max}} \approx 2$ m, allowed for offshore pile driving activities (in the German North Sea). As discussed before, the peak sound pressure is sensitive to time-varying factors such as the sea surface roughness and the resulting forward scattering. The relatively small variations in the data indicate that within the existing legal boundaries for offshore pile driving, the time varying influence of the rough sea surface might be relatively small for the considered ranges of up to 5 km.

The variations in the parameter B are most likely caused by the different pile parameters and hammer setups at the three sites and the resulting difference in the emitted signal characteristic. As the aim of the regression is to get an estimation of the SPL_{peak} from the SEL, which can be predicted more precisely by existing numerical models, these relatively large offsets between different sites make the straight forward application of Eq. (1) impractical for the problem at hand, as shown subsequently.

Table 1. Linear regression coefficients and difference between peak-to-peak and zero-to-peak levels for the evaluated wind farm sites.

				ΔSPL	
Site	A	B (dB)	$B_{95\%}$ (dB)	μ	σ
I	1.40	−43.4	1.0	5.7	0.3
II	1.39	−39.4	1.5	5.3	0.5
III	1.43	−44.0	1.4	5.7	0.2

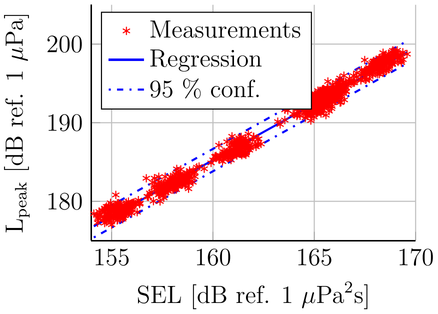

Fig. 1. (Color online) Measurement data taken at site II and according linear regression (with confidence bounds).

3. Application of the regression approach to pile driving simulation results

To illustrate the approach, a numerical model of the sound emission from offshore piling is applied to site I. The model is based on a combined finite element/wavenumber integration approach, as described in Lippert and von Estorff[5,6] and Heitmann *et al.*[7] Simplifying, an equivalent fluid half-space bottom is chosen, whose properties ($c_{p,b} = 1810\,\mathrm{m/s}$, $\rho_b = 2000\,\mathrm{kg/m^3}$, and $\alpha_{p,b} = 1.0\,\mathrm{dB}/\lambda$), are derived by averaging data from a geo-technical survey at the site with depth. The water depth is 40 m, sound speed and density are assumed to be independent of depth ($c_{p,w} = 1453\,\mathrm{m/s}$, $\rho_w = 1022\,\mathrm{kg/m^3}$), and the pile has a length of 55 m measured from the air-water interface, intruding 15 m into the bottom. Pressure time series were computed out to a range of $r_{\max} = 2\,\mathrm{km}$, with the furthest measurements being taken at 1.5 km distance.

A comparison between the simulated and measured SEL shows a maximum deviation of 1.5 dB and an average deviation of less than 1 dB, giving a reasonable basis for the derivation of the $\mathrm{SPL_{peak}}$.

In Fig. 2, the $\mathrm{SPL_{peak}}$ values derived from the numerically simulated waveform are depicted along with the values derived from the simulated SEL values in combination with the regression formula Eq. (1) and the corresponding coefficients from Table 1. In addition, the mean measurement data from this site are shown with error bars, reflecting the uncertainty in level and position, as discussed in Lippert *et al.*[8]

First of all, it has to be noted that, even though the numerically obtained SEL is in good agreement with the measurement, as mentioned above, this is clearly less the case for the $\mathrm{SPL_{peak}}$, with a maximum deviation of almost 8 dB at 1.5 km distance. The overestimation of the peak level the simulated signal waveform is most likely due to ignoring sound scattering effects in the numerical model, as discussed in Sec. 1.

The values obtained directly from the regression of site I give a good match between simulation and measurement, as this only means scaling the $\mathrm{SPL_{peak}}$ down to the SEL and vice versa. Therefore, every good estimation of the SEL will automatically yield a good estimation of the $\mathrm{SPL_{peak}}$. Also, as expected from the very similar values of A in the regression, the trends of all three $\mathrm{SPL_{peak}}$ curves derived from the SEL predictions at three different sets of the regression coefficients are very similar. The large errors in estimating the $\mathrm{SPL_{peak}}$ at site I by means of the regression coefficients obtained at the sites II and III are caused by the large offset values of B in Eq. (1).

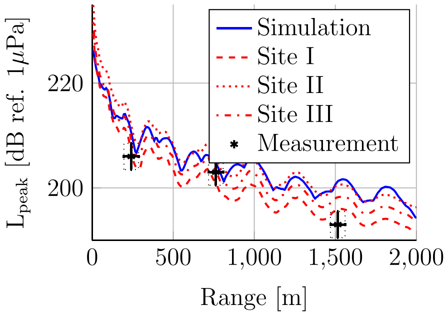

Fig. 2. (Color online) Comparison of simulated and derived $\mathrm{SPL_{peak}}$ with measurement data for site I.

In other words, for practical applications the piling noise levels have to be predicted for a newly planned site and piling conditions, while the empirical regression coefficients A and B can be available only from a different site where measurements have already been made. However, the results depicted in Fig. 2 reveal that a straightforward application of those coefficients leads to significant errors comparable to those of the direct numerical prediction, which is mainly due to the large offsets of B from site to site. Therefore, this offset is investigated in more detail in Sec. 4.

4. Extension of the regression approach for pile driving acoustics

The two terms of Eq. (1) can be given a physical significance. The first term "A SEL" determines how the peak amplitude evolves with range as the energy changes, i.e., decreases with range due to geometrical spreading and other losses, and is therefore a property of the wave guide. The second term "B" might therefore be seen as determining the initial relation between $\mathrm{SPL}_{\mathrm{peak}}$ and SEL, being a shape factor of the initial impulse, i.e., a source attribute.

In that case, the offset between the regression curves of the three sites would represent the different acoustic signals that are emitted by the piles. This in turn means that if the different initial impulse shapes, or at least some kind of shape factor, can be obtained, the results from one pile can be scaled to a different one, in other words, the offsets between the regression curves can be compensated for.

For pile driving acoustics, in the absence of mitigation systems, the $\mathrm{SPL}_{\mathrm{peak}}$ always corresponds to the impulse of the first direct shock wave front emitted by the pile in the near field, where multipath propagation effects are not dominating. This first impulse, in turn, results from the impact of the hammer mass on the pile head and the subsequent radial displacement of the pile wall traveling downward through the pile as a deformation bulge. This means that there is a direct proportionality between the force that is exerted on the pile head and the emitted acoustic signal characteristic.

As discussed by Deeks,[9] the pile-hammer interaction can be approximated by analytical models with a certain degree of accuracy. To keep the regression approach as simple as possible and to limit the number of input parameters needed for it, the most basic analytical representation is chosen. In this case, the system can be represented by a damper, for the pile, and a mass with an initial velocity, for the hammer. The only degree of freedom is the pile head motion u, to which the hammer mass is attached. In this case, the equation of motion can be written as

$$m_r\,\ddot{u} + Z_p\,\dot{u} = 0, \tag{2}$$

with m_r being the mass of the ram weight and Z_p being the pile impedance, defined as $Z_p = E_p\,A_p/c_p$, where E_p is the Young's modulus of the pile, A_p its cross-sectional area and c_p axial wave velocity in the pile which is slightly lower than the compressional wave speed in the pile material. Solving Eq. (2) for the pile head velocity, with v_0 being the initial ram mass velocity, and multiplying it by the pile impedance yields the force f_p exerted on the pile head

$$f_p = Z_p\,v_0\,e^{-(Z_p/m_r)\,t}, \tag{3}$$

to which the wall radial displacement and consequently the amplitude of the acoustic signal is proportional. The ratio in the exponential function in Eq. (3) is the inverse value of the decay time, which determines the relative sharpness of the force pulse that acts on the pile. Thereby, this ratio also governs the initial acoustic wave front emitted by the pile. To take this into account, the original regression formula 1 is extended by a third term,

Table 2. Linear regression coefficient C (in [dB ms]) and ratio Z_p/m_r for each site.

		Scaled to			
	Site	I	II	III	Z_p/m_r (ms^{-1})
Scaled from	I	0.0	0.046	0.035	365
	II	0.049	0.0	0.059	264
	III	0.034	0.057	0.0	301

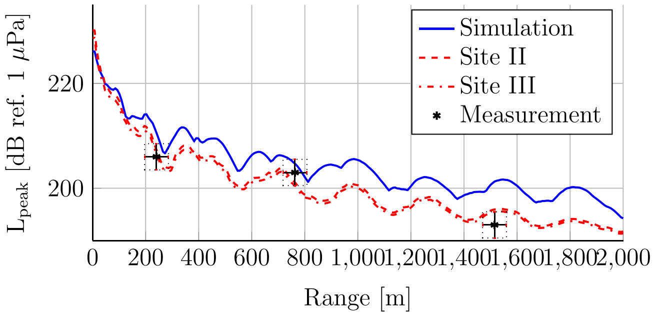

Fig. 3. (Color online) Comparison of simulated and derived SPL_{peak} (using the extended regression approach) with measurements (incl. error margins) for site I.

$$\mathrm{SPL_{peak}} = A\,\mathrm{SEL} + B + C\left(\left[\frac{Z_p}{m_r}\right]_0 - \left[\frac{Z_p}{m_r}\right]_1\right), \qquad (4)$$

where the subscript indices of the squared brackets stand for the site from which the regression coefficients A and B were derived (0) and the unknown site for which the SPL_{peak} is to be estimated (1), with the empirical factor C having the unit [dB s]. The added correction term is linear with respect to the ratio in the exponential of Eq. (3), as the SEL is a logarithmic criterion, wherefore the exponential function vanishes. The constant factor arising from the shift of the logarithmic base, i.e., from ln to $\log_{10}$, is implicitly included in C.

To estimate the factor C in Eq. (4), the measurement data from each site are scaled to the other two sites and a linear optimization scheme is applied. The obtained parameters for C are given in Table 2, along with the values of Z_p/m_r for all sites. The narrow distribution of the coefficient C indicates a good applicability of the extended approach.

5. Application of the extended regression approach

To validate the extended regression approach, Eq. (4) is applied to the numerically obtained SEL values for site I discussed in Sec. 4.

For the estimation of the SPL_{peak}, only regression coefficients from the other two sites are used. The results of the numerical simulation and the estimation based on the calculation of the SEL can be found in Fig. 3.

As can be seen, the regression-based estimation of the SPL_{peak} resembles the measurement data much closer than the prediction based on direct numerical simulation of the waveform. The decay of the peak pressure level, especially at longer ranges, is accounted for much more precisely when the regression is applied. The added term in the regression formula 4, accounting for the pile-hammer parameters at each site, leads to very consistent predictions, regardless of which of the two sites (II or III) is used to predict the SPL_{peak} at site I.

6. Conclusions and prospects

The regression approach considered in this contribution can be applied to predict peak pressure levels of pile driving noise, if the pile-hammer parameters are accounted for. By using an idealized pile geometry and the ram mass to estimate the duration of the hammer impact, results can be scaled from one piling site to another. Thereby, it is possible to obtain estimations of the SPL_{peak} even for methods which nominally only can predict the energy of signals, e.g., flux methods, and the prediction accuracy of other models can be enhanced significantly.

The prediction method was examined for different piles and foundation types in the North Sea. As a next step, the investigation of other pile driving sites and their effects on the regression coefficients is planned. With respect to the practical fact that these days most piling activities involve the use of sound mitigation measures and often vibratory drivers, the applicability of the regression approach to these cases should also be investigated.

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