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Analytical model for the effect of a nonlinear piledriver cushion on underwater sound pressure waveforms radiated from off-shore piledriving

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ABSTRACT

Piledriving involves a ram striking an anvil, below which is a cushion, helmet, and pile. For a steel pile, the cushion is usually an assembly of Micarta and aluminium layers. Following impact, the waveform of the cushion strain and hence the stress on the pile head are derived by solving the nonlinear equations of cushion motion using the Runga-Kutta method, based on two reported compressive stress-strain curves (CSSC) for Micarta: one for an annular cushion and the other for a solid disc. The vibration of the immersed pile and sound radiated into the water are modelled theoretically. The model is applied to an acoustic measurement described in the literature, and the initial positive and negative peaks of the predicted pressure waveforms are compared with data measured at nine depths. When the cushion is neglected, the errors over the nine depths are -1 to 5 dB for the positive peaks and -1 to 9 dB for the negative peaks. For the annular cushion those errors are -7 to -5 dB for the positive peaks and -5 to -1 dB for the negative peaks. The corresponding errors for the solid cushion are only -2 to 0 dB and -1 to 3 dB.

1 INTRODUCTION

In a piledriver, a ram strikes an anvil, below which is a cushion, helmet, and pile. A cushion is included to prevent damage to the other components. For an offshore pile, the vibration of the immersed portion causes intense sound waves to radiate into the water.

The scenario to be addressed here is the measurement of underwater sound radiated from a DELMAG D62 piledriver operated in Puget Sound (near Seattle) during 2009. The acoustic data have been presented by both Reinhall & Dahl (2011) and Dahl & Reinhall (2013), the former of which assumed that no cushion was used. Fortunately, neither their phase-array PE-based propagation modelling (2011), nor their beam forming analysis (2013), depended on, or related to, the presence of a cushion. Subsequently, I presented an analytical model for the underwater sound radiated from a pile driven by a cushion-less piledriver (Hall, 2015). That paper compared the model with the Puget Sound data, with mixed results. Recently, it has been acknowledged that using a cushion accords with the protocol of the organisation that commissioned the piledriving, and information on the cushion installed in the piledriver during the 2009 operation has become available. The purpose of the present paper is to amend the 2015 version of my model to take account of the cushion.

2 VIBRATION OF CUSHION AND PILE HEAD

The cushion consisted of five layers of Micarta alternating with five Aluminium plates. Micarta is a composite material made from synthetic resin reinforced with layers of paper, fibreglass and/or cloth. The thickness of each Micarta layer and aluminium plate have been estimated at around 25.4 mm and 3.2 mm respectively. The total cushion thickness is thus estimated at 143 mm.

To incorporate the effect of a cushion it is necessary to have a model of the relation between its stress and strain. Measurements of stress and strain for Micarta-like materials have been reported for a solid cylinder (Fishbein, 1939) and an annular disc (Hirsch et al, 1966; Lowery et al, 1967). For a given strain, the annulus stresses are at least 10 times smaller than those of the (solid) cylinder. Lowery presented curves for both the first loading and unloading phases, of which the latter indicated that when the stress returns to zero there is a residual strain (compression) of around half the maximum strain. The Lowery curves thus exhibit significant hysteresis. Fishbein's curve for the unloading phase showed a smaller residual strain. The solid cylinder is thus stiffer than the annulus. This is to be expected since, under compression, the hole in the annulus can shrink and thus allow the thickness to decrease to a greater degree.

Because the stress-strain curves are nonlinear, the (coupled) equations of motion for the cushion upper surface (the anvil) and lower surface (the helmet) are also nonlinear. The waveform of the cushion strain has been obtained by solving these two coupled non-linear equations using the Runga-Kutta method (Korn & Korn, 1968). The common axial velocity of the helmet and pile head was determined from the cushion strain.

3 ACOUSTIC RESULTS

The initial positive and negative peaks of the predicted pressure waveforms are compared with data measured at 12-m horizontal range and nine receiver depths from 5.5 to 11.1 m. The measured negative peak pressures range between -90 and -35 kPa, and the positive peaks range between 46 and 91 kPa.

3.1 Cushion neglected

When the cushion is neglected, the model peak pressures are significantly higher than the data at the shallow receivers but approach them when the receiver depth exceeds 8 or 9 m. The mean and standard deviation of the decibel errors (over the nine depths) are 2 ± 3 dB for the positive peaks and 4 ± 5 dB for the negative peaks. Between 1 kHz and 2 kHz, the model spectra for the shallow hydrophones remain somewhat flat until they decrease rapidly near the pile's natural ring frequency near 2 kHz (Hall 2015). This flatness is attributed to radiated pressure being proportional to acceleration (rather than displacement) of the vibrating pile.

3.2 Cushion included

When the CSSC for the annular cushion is used, the model peak pressures are significantly less than the data in all cases except for the negative peaks at receiver depths near 6 m. The errors are -6 ± 1 dB for the positive peaks and -3 ± 2 dB for the negative peaks. When the CSSC for the solid cylinder is employed the positive peaks agree well with the data at receiver depths up to 8 m but become somewhat less as the depth increases further. The negative peaks are somewhat higher (in magnitude) than the data at the shallow depths, but the agreement becomes good as depth exceeds 8 m. The errors over the nine depths are only -1 ± 1 dB (positive peaks) and $+1 \pm 2$ dB (negative peaks). Between 1 kHz and 2 kHz, the model spectra for the shallow hydrophones are less than the no-cushion levels; the differences decrease from 10 - 15 dB at the shallow hydrophones to 5 – 10 dB at the deep hydrophones.

4 CONCLUSIONS

If the cushion is neglected, the disparity between model and measurement is generally between -1 dB and +9 dB. If the annular-cushion CSSC is used, the disparities are generally between -7 dB and -1 dB. If the solid-cylinder CSSC is used, the disparity generally varies between -2 dB and +3 dB. It is reasonable to conclude that the original pile driver was fitted with solid, rather than annular, cushions.

The empirical spectrum in Reinhall & Dahl (2011), an average over the nine hydrophones, reduces by 10 dB as frequency increases from 1 to 2 kHz. It has been shown that this 10-dB reduction can be attributed to the presence of a cushion.

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