Investigation of the effects of cushions and anvils on offshore pile driving noise and soil penetration

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Outlines

- Motivation
- Model 1: force and penetration
- Model 2: sound pressure
- Parameters analysis
- Conclusions
Motivation

Why this work?

\[ F_i(t) = \begin{cases} 
2\pi R F_0^i \sin \left( \frac{\pi t}{\tau_i} \right) & \text{if } 0 < t < \tau, \quad (i = 1, 2, \ldots, 21) \\
0 & \text{if } t < 0 \text{ or } t > \tau
\end{cases} \]

1. Finite differential model
2. Semi-analytical coupling model
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Model 1: force and penetration

Non-linear finite differential model

\[ D(i, t) = D(i, t - 1) + V(i, t - 1)\Delta t \]  \hspace{1cm} (1) \quad \text{Mass Displacement}

\[ C(i, t) = D(i, t) - D(i + 1, t) \]  \hspace{1cm} (2) \quad \text{Spring Compression}

\[ F(i, t) = C(i, t)K(i) \]  \hspace{1cm} (3) \quad \text{Spring force}

\[ Z(i, t) = F(i - 1, t) - F(i, t) - R(i, t) \]  \hspace{1cm} (4) \quad \text{Net force}

\[ V(i, t) = V(i, t - 1) + \frac{Z(i,t)}{M(i)} \Delta t \]  \hspace{1cm} (5) \quad \text{Velocity}
Model 1: force and penetration

Model discretization

Internal spring constant:

\[ K(i) = \frac{A_i E}{\Delta L_i} \quad (\text{Ram & Cushion & Pile}) \]

Element number:

Ram & Pile: At least 6 per \( \lambda_{f_{\text{max}}} \)  
Anvil: only 1 element

Time step:

\[ \Delta t \leq \frac{\Delta L}{\sqrt{\frac{E}{\rho}}} \]
Model 1: force and penetration

Stress-strain relation of cushion

Cushion material: wood (oak, Micarta, etc.), polymers, fibers, aluminum

\[ F = \frac{K_c}{e^2} C(t) - \left( \frac{1}{e^2} - 1 \right) K_c \overline{C(t)}_{\text{max}} \]

\[ \Rightarrow \text{temporary maximum value of } C(t) \]

Cushion force:

No tension on the cushion:

When \( C_{\text{cushion}} \leq 0 \)

\( F_{\text{cushion}} = 0 \)
Model 1: force and penetration

Penetration resistance and soil displacement

Soil quake: $Q$

Soil damping constant: $J_S$

$K_S(i) = \frac{R_u(i)}{Q}$

$R(i, t) = [D(i, t) - D_S(i, t)] K_S(i) [1 + J_S(i)V(i, t - 1)]$

$R_u(i) = (\rho_w g h_w + \rho_b g h_i) S_i \tan \phi K_0$

No tension on the pile tip:

When $D_{tip} - D_S \leq 0 \quad R_{tip} = 0$
Model 1: force and penetration

Reinhall2011 and Marshall2015 cases

Reinhall2011

\[ L_p = 32 \text{ m}, \quad R_p = 0.762 \text{ m}, \quad h_p = 0.0254 \text{ m} \]
\[ M_r = 6200 \text{ kg}, \quad V_r = 7.6 \text{ m/s} \]

Marshall2015

\[ L_r = 3.79 \text{ m}, \quad M_a = 2550 \text{ kg} \]

Cushion (oak):

\[ E_c = 3.1 \times 10^8 \text{ N/m}^2 \quad e = 0.5 \quad h_c = 30 \text{ cm} \]
Model 1: force and penetration

Impact force and penetration

Cushion (oak): \( E_c = 3.1 \times 10^8 \text{ N/m}^2 \quad e = 0.5 \)

\[ P_t = 2.1 \exp(-t/0.004) \text{ MPa} \]

\( h_c = 30 \text{ cm} \)
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Model 2: Sound pressure

Previous model

\[ p_\alpha(x, r, \theta) = -j \omega \rho_f \sum_{\alpha=0}^{1} \sum_{n=0}^{\infty} \sum_{p=0}^{\infty} D_{\alpha n p} H_n^{(2)}(k_{rp} r) \sin k_x p (x - x_{es}) \cos (n \theta + \alpha \frac{\pi}{2}) \]

Problems: Oversimplified the soil effects
Failed to model the sound propagation on the soil-water interface
Improved model

Equation of the shell:
\[
\int_{t_0}^{t_1} \sum_{i=1}^{l} (\delta T_i - \delta U_i + \delta W_i) \, dt + \int_{t_0}^{t_1} \sum_{i,i+1} \delta \Pi_{\lambda \kappa} \, dt = 0
\]

Pressure equations:
\[
\nabla^2 p_w - \frac{1}{c_w^2} \frac{\partial^2 p_w}{\partial t^2} = 0, \quad x_1 < x < x_2
\]
\[
\nabla^2 p_b - \frac{1}{c_b^2} \frac{\partial^2 p_b}{\partial t^2} = 0, \quad x_2 < x < x_3
\]

Variables separation:
\[
\tilde{p}_w = [A_1 e^{-\alpha_w(x-x_1)} + A_2 e^{\alpha_w(x-x_2)}] \cdot H_0^{(2)}(k_r r)
\]
\[
\alpha_w = \sqrt{k_r^2 - \omega^2 / c_w^2}
\]
\[
\tilde{p}_b = [A_3 e^{-\alpha_b(x-x_2)} + A_4 e^{\alpha_b(x-x_3)}] \cdot H_0^{(2)}(k_r r)
\]
\[
\alpha_b = \sqrt{k_r^2 - \omega^2 / c_b^2}
\]
Model 2: Sound pressure

Sound modes (1)

\[ \hat{p}_w = \psi_w H_0^{(2)}(k_r r) = [A_1 e^{-\alpha_w (x-x_1)} + A_2 e^{\alpha_w (x-x_2)}] \cdot H_0^{(2)}(k_r r) \]

\[ \hat{p}_b = \psi_b H_0^{(2)}(k_r r) = [A_3 e^{-\alpha_b (x-x_2)} + A_4 e^{\alpha_b (x-x_3)}] \cdot H_0^{(2)}(k_r r) \]

Boundary conditions:

\[ \hat{p}_w(x_1, r) = 0 \]

\[ \hat{p}_w(x_2, r) = \hat{p}_b(x_2, r) \]

\[ \bar{v}_w(x_2, r) = \bar{v}_b(x_2, r) \]

\[ \bar{v}_b(x_3, r) = 0 \]

\[ D A = \begin{bmatrix} 1 & e^{\alpha_w (x_1-x_2)} & 0 & 0 \\ e^{-\alpha_w (x_2-x_1)} & 1 & -1 & -e^{\alpha_b (x_2-x_3)} \\ -\rho_b \alpha_w e^{-\alpha_w (x_2-x_1)} & \rho_b \alpha_w & \alpha_b & -\alpha_b e^{\alpha_b (x_2-x_3)} \\ 0 & \rho_w & -\alpha_b e^{-\alpha_b (x_3-x_2)} & \alpha_b \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} = 0 \]

Mode normalization:

\[ \delta_{pq} = \int_{x_1}^{x_2} \frac{\psi_w^p \psi_w^q}{\rho_w} dx + \int_{x_2}^{x_3} \frac{\psi_b^p \psi_b^q}{\rho_b} dx \]
Model 2: Sound pressure

Sound modes (2)

\[ x_1 = 5.4 \text{ m}, \quad x_2 = 18 \text{ m}, \quad x_3 = 58 \text{ m} \]

\[ \rho_w = 1000 \text{ kg/m}^3, \quad c_w = 1485 \text{ m/s} \]

\[ \rho_w = 1700 \text{ kg/m}^3, \quad c_w = 1625 \text{ m/s} \]
Model 2: Sound pressure

### Sound pressure

(1) \[ j\omega \cdot \sum_{i=K-l-J+1}^{K-J} w_i(x, \omega) \ast \left[ H(x - x_i) - H(x - x_{i+1}) \right] = -\frac{1}{j\omega \rho_w} \sum_{p=1}^{\infty} D_p \psi^p_w \cdot H^{(2)}_0(k_{rp}R) \quad (x_1 \leq x < x_2) \]

(2) \[ j\omega \cdot \sum_{i=K-J+1}^{K} w_i(x, \omega) \ast \left[ H(x - x_i) - H(x - x_{i+1}) \right] = -\frac{1}{j\omega \rho_b} \sum_{p=1}^{\infty} D_p \psi^p_b \cdot H^{(2)}_0(k_{rp}R) \quad (x_2 \leq x \leq x_L) \]

Mode orthogonality: \[ \delta_{pq} = \int_{x_1}^{x_2} \frac{\psi^q_w}{\rho_w} \frac{\psi^q_w}{dx} + \int_{x_2}^{x_3} \frac{\psi^q_b}{\rho_b} \frac{\psi^q_b}{dx} \]

\[ \int_{x_1}^{x_3} [\psi^q_w \ast (1) + \psi^q_b \ast (2)] dx \implies D_q = f(a_{im}) \]

\[ \tilde{p} = \sum_{i=K-l-J+1}^{K} \sum_{m=1}^{M} a_{im} \sum_{p=1}^{\infty} \{P_{imp}(x, r) \}
\]

\[ P_{imp}(x, r) = \omega^2 \psi_p(x) \cdot \frac{H^{(2)}_0(k_{rp}r)}{H^{(2)}_0(k_{rp}R)} \int_{x_i}^{x_{i+1}} T_m(x - x_i) \psi_p dx \]

\[ \psi_p(x) = \begin{cases} \psi_{wp}(x) & (x_1 < x < x_2) \\ \psi_{bp}(x) & (x_2 < x < x_3) \end{cases} \]

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**Fourier TR**

Frequency domain \( \leftrightarrow \) Time domain
Model 2: Sound pressure

Comparison to measured data

Without cushion or anvil:

\[ M_r = 6200 \, \text{kg}, \quad V_r = 7.6 \, \text{m/s} \]
\[ x_1 = 5.4 \, \text{m}, \quad x_2 = 18 \, \text{m}, \quad x_3 = 62 \, \text{m} \]

Hydrophones from pile:

\[ r = 12 \, \text{m} \]

Measure data (Reinhall2013)

Computation results

SPL\(_{\text{peak}} \) errors

2.0 dB
2.3 dB
2.3 dB
2.0 dB
1.6 dB
1.3 dB
2.4 dB
2.3 dB
Model 2: Sound pressure

Bottom truncation

Pressure at water-soil interface

Arriving time difference:

$$\Delta t = \frac{\sqrt{2(x_3 - x_2)^2 + r^2} - r}{c_b}$$
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Parameter analysis

Influence of the cushion and the anvil

Position:
\[ r = 12 \, m \]
\[ d = 8.4 \, m \]
Parameter analysis

SPL_{peak} & penetration

SPL_{peak} = 20 \log_{10} \left( \frac{\max[abs(p)]}{p_0} \right) \quad p_0 = 1 \, \mu Pa

Position: \quad r = 12 \, m \quad d = 8.4 \, m
Parameter analysis

SEL VS Penetration

\[
\text{SEL} = 10 \log_{10}\left( \frac{1}{t_0} \int_{t_1}^{t_2} \frac{p^2}{p_0^2} \, dt \right) \quad p_0 = 1 \mu Pa \quad t_0 = 1 \text{ s}
\]

\[
\text{Position: } \quad r = 12 m \quad d = 8.4 m
\]

Reference case: Without cushion or anvil

![Graph showing SEL decrement for unit penetration vs. cushion stiffness]
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Conclusions

- A finite difference model and a semi-anatical vibro-acoustic coupling model are established and combined to investigate the influence of cushions and anvils on the pile driving noise.

- Overlook of the rebounds and re-impacts between the ram, anvil and pile could lead to incorrect prediction of the pile driving noise, especially when steel-on-steel impacts occur between the anvil and the pile.

- Cushions with proper stiffness can reduce the peak pressure of underwater noise remarkably by weakening high-frequency component of impact force.

- The increase of the cushion restitution coefficient results in a lower peak sound pressure but a larger soil penetration.

- The increase of the anvil mass doesn’t change the peak pressure significantly but does reduces the soil penetration.

- Within a certain range of cushion stiffness, using a softer cushion can reduce the SEL per unit penetration depth notably.
Thanks for attention

Any problem?