WASHINGTON STATE DEPARTMENT OF TRANSPORTATION (WSDOT)

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
Per Reinhall, PhD
Professor & Chair, Mechanical Engineering
University of Washington

REVIEW OF CURRENT NOISE MITIGATION TECHNIQUES
Pile expands radially after impact

Moving bulge disturbs the water and sediment as it propagates down the pile
NO ATTENUATION - FEM

AXISYMMETRIC ACOUSTIC
FINITE ELEMENT SIMULATION
CURRENT APPROACHES

- BUBBLE CURTAIN
- COFFERDAM
- SLEEVE / BARRIER

EXPENSIVE, TIME-CONSUMING, INEFFECTIVE
BUBBLE CURTAIN

**CHALLENGES**

- Only marginally effective
- Impacted by current and placement
- Burdensome and time consuming

VIDEO COURTESY OF JOE CALLAGHAN, GEOENGEERS, INC.
INEFFECTIVE, WHY?

NOISE VIA SEDIMENT

NOISE VIA SEDIMENT

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
BUBBLE CURTAINS - FEM

NOISE ENTERS WATER FROM SEDIMENT LAYER
WHAT HAVE WE LEARNED?

CURRENT METHODS:

• Do not address noise from sediment
• Yield < 10 dB under the very best conditions
• Expensive and cumbersome

BUBBLE CURTAIN IS NOT A RELIABLE ATTENUATION METHOD
OVERVIEW OF NEW APPROACH
GOAL: LIMIT NOISE FROM SEDIMENT
SOLUTION: DOUBLE-WALL PILE
BARRIER ALONG FULL PILE LENGTH

DESIGN

- Two pipes separated by annular space and joined by special shoe
- Outer pipe serves as noise shield
- Only inner pipe is struck

FUNCTIONALITY

- Uses standard driving equipment
- Hammer energy directed to driving shoe
- Air space can be filled, post-installation, for added strength
FEM COMPARISON

**BUBBLE CURTAIN**

**DOUBLE WALL**

**WATER**

**SEDIMENT**

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
INITIAL VALIDATION

SUBSCALE TESTING ON 6” PILES

AROUND 20 DB REDUCTION OF PEAK PRESSURE

RESULTS AGREED WITH COMPUTER MODELING
FULL SCALE TEST

SPONSORS

WSDOT

PARTNERS

Port Of Tacoma
Orion Marine Group
GeoEngineers
Hart Crowser
GRL, Inc.
Citizens For A Healthy Bay
Machinists, Inc.
Marine Construction Technologies, PBC
TEST SITE

Commencement Bay
Port of Tacoma
Tacoma, Washington, USA
TEST PARAMETERS

THREE STEEL PILES

Control pile (with & without bubble curtain)

Double-wall pile

Mandrel driven double-wall pile

EXTENSIVE INSTRUMENTATION DEPLOYED

CONVENTIONAL IMPACT HAMMER USED
Thank you to Agencies and Bill Rehe of Port of Tacoma
RESULTS

AVERAGE NOISE REDUCTION*

*MEASURED FROM VERTICAL LINE ARRAY AT 8.5-9.0M

DOUBLE PILE  MANDREL PILE  BUBBLE CURTAIN

21.2  19.1  20.7  6  5.5  5

PEAK  RMS  SEL
DATA - ONE STRIKE

Control vs Double pile

Pressure (Pa)

Time (sec)

CONTROL PILE

DOUBLE WALL PILE

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
MONITORING ZONE IMPLICATIONS

CONVENTIONAL PILE WITH BUBBLE CURTAIN

DOUBLE WALL PILE

SOURCE: NMFS CALCULATOR
SUMMARY

Peak reductions > 20 dB at 10m VLA

Monitoring zones decrease dramatically

Double wall piles can be driven using conventional techniques and equipment

Full scale testing is consistent with subscale testing and computer modeling
Tim Dardis, MS
PhD Candidate, Mechanical Engineering
University of Washington

PILE DESIGN
CURRENT TECHNOLOGY

A single-walled steel pipe

TOMORROW’S TECHNOLOGY

A double-walled pile, fabricated from two concentric pipes connected at the pile toe

“THE DOUBLE PILE”
Shoe serves to join the inner and outer pipes.

Many parts of shoe are interchangeable between double and mandrel piles.

Shoe attaches to a section of pile to create “stem”.
DRIVING SHOE

DESIGN CONSIDERATIONS
Drivability, dynamic testing, pile capacity & cost

STEEL COMPONENTS
Cast, rolled, & machined

RUBBER COMPONENTS
Spring, bumpers, & seals
DESIGN VERSATILITY

ONE IDEA, THREE DESIGNS

DOUBLE PILE
FILLED DOUBLE PILE
MANDREL DOUBLE PILE
DESIGN VERSATILITY

OPEN ENDED

CLOSE ENDED

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
DESIGN VERSATILITY

STANDARD DOUBLE PILE
- Simple
- Fast installation

FILLED DOUBLE PILE
- Fast installation
- Higher strength/stiffness

MANDREL DOUBLE PILE
- Reusable inner pile
- Single wall construction

OPTIMAL CONFIGURATION DEPENDS ON PROJECT PARAMETERS
“STEM” DELIVERY

SHOE ATTACHED TO DISTAL 40’ PIPE

“STEM” DELIVERED TO CONTRACTOR

PILE LENGTH EXTENDED ON SITE

ENSURES QUALITY OF SHOE & CRITICAL CONNECTIONS
PILE SPACERS

Included in both mandrel and double pile configurations

Maintain air gap between pile walls

Essential for maneuverability
MANDREL DESIGN

MANDREL END
Reinforced toe
Serves as sealing surface

MANDREL SKIDS
Equipped with skids to ease removal & installation
ENGINEERING CONSIDERATION

DRIVABILITY

Additional testing in preparation
WEAP analysis updates in progress

CAPACITY

Typical PDA hardware is used
CAPWAP analysis updates in progress

DESIGN METHODS

Standard analysis methods apply
e.g. AASHTO, ASCE, etc.
DOUBLE PILE CONCEPT PROVEN!

One idea, multiple pile configurations

Driving shoe delivered as part of a stem

Update of design specs in progress
Bradley Morlock
Project Manager, Orion Marine Group

Jason Tarver
Project Superintendent, Orion Marine Group

HANDLING & DRIVABILITY
ORION MARINE GROUP

Leading heavy civil marine contractor

HQ in Houston, TX

Washington HQ – Port of Tacoma

1200 employees

Over 400 pieces of marine equipment

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
RECEIVING PERMANENT MATERIAL

DELIVERED BY TRUCK IN 40’ LENGTHS
CONTROL PILE FABRICATION

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
MANDREL PILE FABRICATION

HORIZONTAL SPLICING ON ROLLER BED
CRANE AND TUG

TEST CRANE:

1951 Dravo Model 60
Rebuilt 2007
Capacity: 150 Ton

TEST TUG BOAT:

1958 1,050 HP
Triple Screw
DRIVING EQUIPMENT

10 x 37 LEADS 100’
APE MODEL D46
Diesel Pile Driving Hammer
3.6 metric ton ram
Minimum Energy: 54,320 ft-lbs
Maximum energy: 107,280 ft-lbs
Speed:
  • 37-52 (blows per minute)
Weights:
  • Hammer weight: 20,000 lbs
  • Piston weight: 10,000 lbs
COMPLICATED, UNORGANIZED, TANGLED

Multiple pieces:

- Air compressor
- Manifold
- Bubbler rings
- Hoses
- Rigging

A $45,000 SET-UP
LOFTING – DOUBLE WALL PILE

ROUTINE – NO ISSUES
TEST VIDEO
APE VIBRATORY HAMMER

- Eccentric moment: 4400 in/lb
- Drive force: 202 tons
- Suspended weight: 12,760 lbs.
OVERALL IMPRESSION

“ONCE SETUP, VERY SMOOTH OPERATION”
Peter Dahl, PhD
Professor and Senior Principal Engineer
UW Applied Physics Laboratory

ACOUSTICS
Simultaneous measurements of underwater noise made at ~10 meters, ~100 meters, and ~500 meters

Control and test piles measured with same system

Key underwater sound metrics:

- PEAK pressure
- RMS pressure
- Sound exposure level (SEL)
MEASUREMENT SYSTEMS

VERTICAL LINE ARRAY (VLA)
- 9 Hydrophones
- Range: 8-9 Meters

AUTONOMOUS RECORDING HYDROPHONE #1
- Bottom Deployed
- Range: ~100 Meters

AUTONOMOUS RECORDING HYDROPHONE #2
- Boat Suspended
- Range: ~500 Meters
9 hydrophones

**Range:**
- 8 – 9 meters

**Depth:**
- Tide dependent
- 2.6 m – 8.2 m at 13:00
- 1.7 m – 7.3 m at 15:00

**Spacing:** 0.7 meters
AUTONOMOUS RECORDER #1

**DEPLOYMENT**

Depth:  
11.7 – 13.5 meters  
(depending on tide)

Range:  
~ 100 meters

HYDROPHONE:  
1.47 M ABOVE BOTTOM
AUTONOMOUS RECORDER #2

DEPLOYMENT

Depth:
10 meters

Range:
~ 500 meters

Deployed via Citizens for Healthy Bay Boat
UNDERWATER SOUND LEVEL METER (USLM)

NEW HYDROPHONE TECHNOLOGY

Deployed during Port of Tacoma Test

Offers real-time sound measurements for monitoring and compliance; easy to use and interpret

PEAK, RMS, and SEL processed in seconds

Delivers results consistent with larger and other more expensive instruments in a fraction of the time

Contact info@hydrodb.com for more information
DEPLOYMENT SUMMARY

VLA

RECORDER #1

RECORDER #2
METRIC USAGE

MARINE MAMMALS

Protective thresholds based on RMS and SEL (and its accumulation over many pile strikes called cSEL)

FISH

Protective thresholds based on cSEL, with a threshold for PEAK also used.
CONTROL PILE RESULTS

Setting 4 Control Pile Results at the VLA, 29 October

Depth (m)

dB MEASURE FOR PEAK, RMS and SEL

SEL  RMS  PEAK

160  170  180  190  200  210  220

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
DOUBLE WALL RESULTS

Setting 4 DW Test Pile Results at the VLA, 29 October

Note: Depth change from control pile to double wall pile result of tide change
DOUBLE WALL RESULTS

Note: Must compare same hydrophones, though depths may differ slightly.
DOUBLE WALL AVERAGES

AVERAGE REDUCTION AT VLA (8 – 9 m)

\( \Delta \) SEL: 17 dB
\( \Delta \) RMS: 19 dB
\( \Delta \) PEAK: 21 dB

Final Estimate via Depth Average
CONTROL PILE RESULTS

VLA
Peak: 211 dB
RMS: 198 dB
SEL: 183 dB

RECORDER #1
Peak: 186 dB
RMS: 177 dB
SEL: 164 dB

RECORDER #2
Peak: 175 dB
RMS: 165 dB
SEL: 154 dB

RECORDER #2 (~500 m)
RECORDER #1 (~100 m)
VLA (~ 8 - 9 m)
DOUBLE WALL PILE RESULTS

VLA △
Peak: 21 dB
RMS: 19 dB
SEL: 17 dB

△ = CONTROL - TEST

RECORDER #1 △
Peak: 12 dB
RMS: 14 dB
SEL: 14 dB

RECORDER #2 △
Peak: 16 dB
RMS: 19 dB
SEL: 16 dB

Δ = CONTROL - TEST

VLA (≈ 8 - 9 m)

RECORDER #1 (~100 m)

RECORDER #2 (~500 m)

BREAKTHROUGH IN MITIGATING MARINE PILE DRIVING NOISE
MANDREL PILE RESULTS

VLA $\Delta$
- Peak: 23 dB
- RMS: 21 dB
- SEL: 18 dB

$\Delta = \text{CONTROL} - \text{TEST}$

RECORER #1 $\Delta$
- Peak: 14 dB
- RMS: 16 dB
- SEL: 14 dB

RECORER #2 $\Delta$
- Peak: 17 dB
- RMS: 20 dB
- SEL: 16 dB
MORE VARIATION WITH PEAK

- Based on single time sample
- Underwater sound propagation greatly distorts a single-instant measure

LESS VARIATION WITH SEL

- Average over many time samples
- Underwater sound propagation distorts much less than average measure
SUMMARY OBSERVATIONS

Double wall piles offered superior noise attenuation vs. bubble curtain when compared to control

A higher variation observed in Peak vs. SEL and RMS attenuation

Variation is due to single-instant (Peak) vs. average measures (SEL, RMS) and influence of underwater sound propagation
Jim Laughlin
Technical Manager: Air, Acoustics, and Energy
Washington State Department of Transportation (WSDOT)

ENVIRONMENTAL IMPLICATIONS
**REQUIREMENTS**

**MEASUREMENTS**
- Peak vs. RMS vs. Cumulative SEL (cSEL)

**ADDITIONAL PERMIT PROCESS**
- Cannot exceed thresholds or ‘take’ (ESA) without permits
- Must maximize noise mitigation with available technology
- Required to monitor amount of ‘take’

**MONITOR ‘TAKE’ OF CONSTRUCTION**
- Avoid ‘take’ by shutting down
MONITORING

EXAMPLE PLAN

Monitor Zone: 201 meter

Monitoring Boats: 2

Boat Drivers: 2

Biologists: 5
- 1 lead biologist
- 2 biologists per boat
## CURRENT THRESHOLDS

<table>
<thead>
<tr>
<th></th>
<th>Injury Threshold</th>
<th>Non-Auditory Injury Threshold</th>
<th>Disturbance Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MARBLED MURRELETS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Diving Birds)</td>
<td>202 dB cSEL</td>
<td>208 dB cSEL</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>CETACEANS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(whales, porpoises)</td>
<td>180 dB RMS</td>
<td>N/A</td>
<td>160 dB RMS</td>
</tr>
<tr>
<td><strong>PINNIPEDS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(seals, sea lions)</td>
<td>190 dB RMS</td>
<td>N/A</td>
<td>160 dB RMS</td>
</tr>
<tr>
<td><strong>FISH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(≥ 2 grams)</td>
<td>187 dB cSEL</td>
<td>N/A</td>
<td>150 dB RMS</td>
</tr>
<tr>
<td><strong>FISH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(all sizes)</td>
<td>206 dB Peak</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Control w/o BC</th>
<th>Control w/BC</th>
<th>BC △</th>
<th>Double Wall</th>
<th>DW △</th>
<th>Mandrel</th>
<th>MP △</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEAK</strong></td>
<td>211 dB</td>
<td>205 dB</td>
<td>- 6 dB</td>
<td>190 dB</td>
<td>- 21 dB</td>
<td>190 dB</td>
<td>- 21 dB</td>
</tr>
<tr>
<td><strong>RMS(_{90%})</strong></td>
<td>198 dB</td>
<td>192 dB</td>
<td>- 6 dB</td>
<td>179 dB</td>
<td>- 19 dB</td>
<td>178 dB</td>
<td>- 20 dB</td>
</tr>
<tr>
<td><strong>cSEL</strong></td>
<td>198 dB</td>
<td>192 dB</td>
<td>- 6 dB</td>
<td>182 dB</td>
<td>- 16 dB</td>
<td>182 dB</td>
<td>- 16 dB</td>
</tr>
</tbody>
</table>
## RESULTS VS. THRESHOLDS

<table>
<thead>
<tr>
<th></th>
<th>DOUBLE WALL PILE</th>
<th>MANDREL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEAK</strong></td>
<td>190 dB</td>
<td>190 dB</td>
</tr>
<tr>
<td><strong>RMS&lt;sub&gt;90%&lt;/sub&gt;</strong></td>
<td>179 dB</td>
<td>178 dB</td>
</tr>
<tr>
<td><strong>CSEL</strong></td>
<td>182 dB</td>
<td>182 dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>FISH</th>
<th>CETACEAN INJURY</th>
<th>CETACEAN / PINNIPED DISTURBANCE</th>
<th>PINNIPED INJURY</th>
<th>MURRELET INJURY</th>
<th>MURRELET NON-AUDITORY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEAK</strong></td>
<td>206 dB</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>RMS&lt;sub&gt;90%&lt;/sub&gt;</strong></td>
<td>-</td>
<td>180 dB</td>
<td>160 dB</td>
<td>190 dB</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>CSEL</strong></td>
<td>187/183 dB</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>202 dB</td>
<td>208 dB</td>
</tr>
</tbody>
</table>

**RESULTS VS. THRESHOLDS**

- **Double Wall Pile**
  - **FISH**: 206 dB
  - **CETACEAN INJURY**: -
  - **CETACEAN / PINNIPED DISTURBANCE**: -
  - **PINNIPED INJURY**: -
  - **MURRELET INJURY**: -
  - **MURRELET NON-AUDITORY**: -

- **RMS<sub>90%</sub>**:
  - **FISH**: -
  - **CETACEAN INJURY**: 180 dB
  - **CETACEAN / PINNIPED DISTURBANCE**: 160 dB
  - **PINNIPED INJURY**: 190 dB
  - **MURRELET INJURY**: -
  - **MURRELET NON-AUDITORY**: -

- **CSEL**: 187/183 dB
  - **FISH**: -
  - **CETACEAN INJURY**: -
  - **CETACEAN / PINNIPED DISTURBANCE**: -
  - **PINNIPED INJURY**: -
  - **MURRELET INJURY**: 202 dB
  - **MURRELET NON-AUDITORY**: 208 dB

- **Mandrel**
  - **FISH**: 206 dB
  - **CETACEAN INJURY**: -
  - **CETACEAN / PINNIPED DISTURBANCE**: -
  - **PINNIPED INJURY**: -
  - **MURRELET INJURY**: -
  - **MURRELET NON-AUDITORY**: -

- **RMS<sub>90%</sub>**:
  - **FISH**: -
  - **CETACEAN INJURY**: 180 dB
  - **CETACEAN / PINNIPED DISTURBANCE**: 160 dB
  - **PINNIPED INJURY**: 190 dB
  - **MURRELET INJURY**: -
  - **MURRELET NON-AUDITORY**: -

- **CSEL**: 187/183 dB
  - **FISH**: -
  - **CETACEAN INJURY**: -
  - **CETACEAN / PINNIPED DISTURBANCE**: -
  - **PINNIPED INJURY**: -
  - **MURRELET INJURY**: 202 dB
  - **MURRELET NON-AUDITORY**: 208 dB
ZONE OF INJURY: FISH (CONTROL)

INJURY LEVEL:
187 dB cSEL
206 dB Peak

NO BUBBLE CURTAIN
- 206 dB Peak
  - 21 meters
- 187 dB cSEL
  - 46 meters

BUBBLE CURTAIN
- 206 dB Peak
  - 7 meters
- 187 dB cSEL
  - 18 meters

PILE
ZONE OF INJURY: FISH

INJURY LEVEL: 187 dB cSEL

- CONTROL PILE 46 meters
- DOUBLE WALL & MANDREL PILE 4 meters
- PILE
ZONE OF INJURY: PINNIPEDS

INJURY LEVEL:
190 dB RMS

CONTROL PILE
28 meters

DOUBLE WALL & MANDREL PILE
1.5 meters

PILE
ZONE OF DISTURBANCE: CETACEAN/PINNIPED

INJURY LEVEL: 160 dB RMS

CONTROL PILE 2,800 meters

DOUBLE WALL & MANDREL PILE 150 meters

PILE
ZONE OF INJURY: MARBLED MURRELETS

INJURY LEVEL:
202 dB cSEL
208 dB cSEL

- CONTROL PILE
  2 – 5 meters

- DOUBLE WALL & MANDREL PILE
  0.4 - 0.02 meters
## USLM RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Control w/o BC</th>
<th>Double Wall</th>
<th>Mandrel</th>
<th>Mandrel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEAK</strong></td>
<td>200 dB</td>
<td>173 dB</td>
<td>177 dB</td>
<td>- 23 dB</td>
</tr>
<tr>
<td><strong>RMS&lt;sub&gt;90%&lt;/sub&gt;</strong></td>
<td>187 dB</td>
<td>161 dB</td>
<td>166 dB</td>
<td>- 21 dB</td>
</tr>
<tr>
<td><strong>cSEL</strong></td>
<td>173 dB</td>
<td>151 dB</td>
<td>155 dB</td>
<td>- 18 dB</td>
</tr>
</tbody>
</table>
IMPLICATIONS

REDUCED ‘TAKE’
- Fewer environmental impacts
- Fewer animals harmed

REDUCED BIOLOGICAL MONITORING

INSTALLATION EFFICIENCIES
- No air compressors/hoses
- Eliminate vibratory driving/changing hammers?
- Consistent results

REDUCED RISK OF STOP WORK
Dave Marver
Moderator

IMPLEMENTATION
COMMERCIALIZATION

• WSDOT should be greatly commended for supporting this research
• Innovative technology is often trapped behind university walls
• Must be commercialized in order to provide maximum benefit to industry, society, and the environment
PUBLIC BENEFIT CORP, PBC

Marine Construction Technologies, PBC will commercialize double wall piles and make them widely available.

This is a new type of business entity: Mission-driven rather than profit-driven.

Dedicated to improving the efficiency of marine construction and providing environmental benefit.
Provided as stems

Shoe attached to distal 40’ pipe

“Stem” delivered to contractor

Pile length extended on site

Ensures quality of shoe & critical connections
PRACTICAL CONSIDERATIONS

• Piles may be available as early as next work window
• Pricing TBD, but cost has been a consideration from the onset
• Currently establishing supply chain
• Likely to be more expensive than typical piles, but offer superior value

SUPERIOR NOISE ATTENUATION, POTENTIAL FOR STREAMLINED PERMITTING, FASTER DRIVING, FEWER STOPPAGES
REMAINING QUESTIONS

• WSDOT will conduct another test to evaluate drivability and answer remaining structural questions
• WSDOT desires conclusive test
• Please complete surveys and participate in panel discussion to follow
• Help identify remaining issues and questions
CLOSING

There is an improved noise attenuation method consistently offering > 20 dB Peak noise reduction at 10m

Remaining structural and drivability questions will be addressed in an upcoming WSDOT test at Vashon Island

Further improvements in the technology are possible; this is only “version 1.0”

Additional information is available for download at www.marinecontech.com, where you can find a resource repository

WSDOT should be commended for their continued leadership
CONTACT INFO

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Resource Library: www.MarineConTech.com
PANEL DISCUSSION

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Tim Dardis, MS – UW, Mechanical Engineering
Peter Dahl, PhD – UW, Applied Physics Laboratory
Bradley Morlock – Orion Marine Group
Jim Laughlin - WSDOT