Plan for Pile-Driving Research

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Plan for Pile-driving Research

Thomas J. Carlson
Susan L. Sargeant
Gary E. Johnson

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16. ABSTRACT This document presents a plan pile driving research based on the issues and needs of the WSDOT and resource agencies and on discussions that took place during an April 2004 pile driving workshop that was sponsored by WSDOT and coordinated by Battelle. The work plan is designed to meet WSDOT/WSF needs for pile driving research and to further understanding of pile driving impacts to aquatic animals in the Puget Sound.		
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BACKGROUND

The Washington State Department of Transportation (WSDOT) currently supports a comprehensive research strategy to determine whether ferry terminals affect migrating juvenile salmon and other fish species, and if so, what design features can be incorporated into future Washington State Ferries (WSF) terminal improvements and expansions to minimize and mitigate these potential impacts. One growing concern centers on the driving of pilings. WSDOT drives a large number of temporary and permanent piles each year to develop and maintain transportation infrastructure. During driving of steel piling, significant levels of sound are generated both in the air and underwater. Underwater sounds may have adverse effects on salmonids, other fish species, marine mammals, and diving sea birds. The sound generated underwater has been shown to cause physical injury to fish under conditions and by mechanisms yet to be fully understood. Besides this potential for injury, other mechanisms for potential disruption of fish include alteration of foraging behavior or migratory patterns, and masking ambient noises or habituating fish to pile-driving sounds, thereby decreasing their ability to detect predators (Feist et al., 1992, Carlson et al., 2001). Both the above-water and underwater sounds may affect marine diving bird species by altering their normal behavior patterns and potentially causing physical injury. In response to this threat to aquatic animals, the resource agencies responsible for managing and protecting aquatic resources have set interim criteria that WSDOT must consider when undertaking their normal work. WSDOT is collaborating with other parties with similar concerns and with the environmental resource agencies to conduct research to clarify the mechanisms of injury and the means of mitigation.

Regulatory Agency Concerns

Endangered Species Act (ESA) issues drive regulatory agency (e.g., NOAA Fisheries and U.S. Fish and Wildlife) concerns about impacts of pile driving. Eight species of salmonids are known to use nearshore habitats in Puget Sound. A number of populations in the region are currently listed as "threatened" under the ESA, including chinook salmon (*Oncorhynchus tshawytscha*) within the Puget Sound Evolutionary Significant Unit (ESU) summer-run chum salmon (*O. keta*) within the Hood Canal, and bull trout (*Salvelinus confluentus*) within the Coastal-Puget Sound Distinct Population Segment (DPS). Coho salmon (*O. kisutch*) (within the Puget Sound/Strait of Georgia ESU) is a candidate species for listing. Most juvenile salmon enter estuaries and nearshore marine habitats between early March and late June, feeding and rearing in the protective cover of shallow, productive habitats for extended periods. The juvenile outmigration period is considered particularly critical to juvenile chum and chinook salmon, which spend more time in estuarine and nearshore habitats and may enter marine waters at only 30- to 80-mm length. The marbled murrelet (*Brachyrampus marmoratus*) is a marine diving bird listed as "endangered" under the ESA that may also be affected by pile-driving activities. Both adults and juveniles can be affected.

In addition to ESA-listed species, other fish species have federal Fish Management Plans that provide recommendations for protection of their essential fish habitat. These species include rockfish, flatfish, and salmonids, as well as prey items for salmonids, such as anchovies, sardines, herring, smelt, and surfperches. At the state level, Washington Department of Fish and Wildlife resource managers are tasked with preventing the loss or injury to all fish and shellfish, and protection of the habitat that supports fish and shellfish populations.

Pile-driving Impact Studies

Few studies have specifically addressed impacts to salmonids because of pile-driving activities, but some information is known. For example, recent research has defined the hearing ability in salmon and analyzed avoidance responses in some species under both laboratory and field conditions (Carlson 1998; Ploskey et al., 2000; Carlson et al. 2001; Popper et al. 1998). Salmonid hearing is most sensitive below 150 Hz and maintains maximum sensitivity through the infrasound region. Carlson et al. (2001) indicates that most of the energy in pile-driving hammer-impact impulses is contained at frequencies around 200 Hz and higher, above the region of maximum hearing response by salmonids. Effective stimuli that have produced an avoidance response in salmonids existed only in the near-field, and generally between 5 Hz and 30 Hz for sources able to generate particle acceleration greater than 0.01 ms^{-2} (Carlson et al. 2001). Avoidance responses that resulted in fish actively swimming away from the source generally required several seconds of exposure (Carlson et al. 2001). Studies also indicated that exposed fish habituated with continued exposure, but recovered from habituation after short periods of no exposure. The conclusions reached regarding potential impacts to salmonids from pile driving in Carlson et al. (2001) were that the range that the stimulus (water-particle motion) is above threshold levels is small, on the order of several meters. Also, the need for several seconds of continuous exposure to provoke a sustained avoidance response makes it unlikely that most impulsive sources (e.g., pile driving) will elicit an avoidance response likely to impede migratory behavior.

However, other studies indicate that pile driving does affect the distribution and general behavior of fish schools near pile-driving activity. Feist et al. (1992) found that pile-driving noise within the range of salmonid hearing could be expected to be heard by the fish within a 600-m radius of the activity. However, the report did not provide an indication of distance from the source within which salmonids react negatively.

Documented cases of fish mortality linked to pile driving in California and Washington were of nonsalmonid species (Holstege 2002; FHWA and ADOT&PF 2003). In these cases, autopsied fish had ruptured swim bladders. What is not known is whether there is potential for such injuries or other forms of hearing damage in salmonids because of pile-driving activity. Vulnerability to injury from sound varies with the physiology and anatomy of different fish species, and salmonids may be at a lesser or greater risk than the species that were found dead.

To our knowledge, no research has been conducted on the effects of pile-driving impacts to diving birds. Studies by Yelverton et al. (1973, 1981) found that birds exposed to underwater blasts sustained injuries to gas/air-filled organs and eardrums at some impulse levels. In all, however, little information is available to allow transportation and regulatory agencies to accurately predict impact levels that will occur during a pile-driving project. Appropriate methods for avoiding or reducing the impacts are also unclear.

Perspectives

From the regulatory agency perspective, because of the paucity of data on pile-driving impacts, the current practice should be to err on the side of caution when permitting pile-driving projects, including restriction of in-water work based on time of year. Current regulations restrict all pile-driving activities between March 15 and June 14. In addition, regulatory agencies often require that protective measures (e.g., behavioral and/or sound barriers, such as bubble curtains) be used during pile-driving activity. From the WSDOT perspective, the loss of in-water work time and the requirement to use behavioral barriers under some circumstances has resulted in increased project costs and delays while the benefit to protected species is unknown. A general consensus is the acknowledgement that more data are needed to be able to balance the costs of losing work opportunities and ferry service with the loss of fish and birds. To address these mutual concerns, WSDOT sponsored a pile-driving workshop that provided a forum for discussion on prioritizing pile-driving research.

PILE-DRIVING WORKSHOP

On April 29, 2004, WSDOT sponsored a Pile-driving Workshop at the University of Washington Center for Urban Horticulture in Seattle. One goal of the workshop was to have the attendees agree upon the direction for upcoming pile-driving research so that specific issues could be resolved that would provide a net benefit to all parties. The WSF incorporates technical information of this type in making decisions on designs for terminal improvements and modifications, and in negotiating projects, permit conditions, and mitigation requirements necessary to project construction and the maintenance of uninterrupted ferry service. This research also directly responds to regulatory agency concerns relevant to a wide variety of WSDOT shoreline modification projects.

The workshop was coordinated by Battelle and was attended by representatives from WSDOT, WSF, the Federal Highway Administration, the Port of Tacoma, state and federal resource agency representatives (i.e., Washington State Department of Fish and Wildlife, U.S. Fish and Wildlife, and NOAA Fisheries), and experts in the field of pile driving, sound propagation, and animal hearing. Prior to the meeting, Battelle staff had prepared a draft outline that listed a variety of potential pile-driving research objectives, descriptions of possible approaches that could be pursued, and a brief summary of the type of deliverable that could be expected at the conclusion of each stage of research. These research objectives were presented during the workshop. The workshop agenda, list of attendees, draft outline, and other materials presented at the workshop can be found in Appendices A through K.

WSDOT representatives opened the workshop meeting by presenting the following problem statement (Figure 1), research goals (Figure 2), and workshop goals (Figure 3).

PROBLEM STATEMENT

Impact driving of large steel piles generates underwater sound that may have adverse effects on salmonids, other fish species, marine mammals and diving sea birds. While fish kills have been documented at several pile driving sites at ferry terminals in Washington State, bridge construction sites in California and at the Port of Vancouver, British Columbia very little information is available to allow transportation and regulatory agencies to accurately predict impact levels that will occur during a pile driving project. It is also unclear what the appropriate methods are to avoid or reduce the impacts. Since there is a lack of scientifically valid information, regulatory agencies must rely on conservative interpretations of the available data, which may not directly correlate to the impacts caused by pile driving, to protect species under their jurisdiction. This conservative approach has resulted in increased project costs and delays, while the benefit to protected species is unknown. There is a real need to obtain scientifically valid information on the effects of pile driving on salmonids, and other species of interest.

Figure 1. Problem Statement presented by WSDOT at the Pile-driving Workshop, April 29, 2004.

RESEARCH GOALS

Currently our Research Goals are focused on the impacts of pile driving in and adjacent to marine waters on salmon and physoclistous species. We recognize that impacts to diving birds and impacts to fish in freshwater are also areas that have major informational gaps. Goals include:

- Identify the characteristics of sound impacts that WSDOT projects, which occur in or adjacent to marine waters, have or potentially have on salmonids and other species of interest.
- Identify the necessary conditions for barotrauma of salmonids and physoclistous species (e.g. hammer energy, substrate, duration of exposure, etc.).
- Investigate the effect of pile driving sound on the inner ear of salmonids or physoclistous species (hearing and vestibular senses).
- Identify methods that will eliminate or significantly reduce the level and or characteristic of sound propagated away from piles.
- Determine the bioeffect radius for selected species of pile driving as a function of pile driving and biological variables.
- Investigate the behavioral response of salmonids and physoclistous species to mitigated and unmitigated pile driving

Figure 2. Research Goals presented by WSDOT at the Pile-driving Workshop, April 29, 2004.

WORKSHOP GOALS

1. Evaluate the Research Strawman Outline.
2. Review the research program objectives for completeness.
3. Determine the type of information each approach will provide and evaluate the utility of the information to address the problem as described in the Problem Statement.
4. Estimate the time for completion (e.g., field seasons) and relative cost for selected approaches.
5. Assess the experimental risks (e.g., probability of successfully providing desired information within estimated time for completion and relative costs) of selected approaches.
6. Prioritize the order in which the research objectives should be investigated.
7. Identify the "best" approaches for each objective in their order of priority (Research objectives 1-5).

Figure 3. Research Goals presented by WSDOT at the Pile-driving Workshop, April 29, 2004.

Following these opening statements, WSDOT, WSF, and the regulatory agencies outlined issues and needs regarding pile driving (Figure 4 and Figure 5).

WSDOT / WSF: Issues and Needs

- Need to build or replace docks and pilings, bridges, and temporary work trestles
- Need cost-effective, efficient ways to install new pilings
- Need to balance cost-effective and biologically effective means to install piles
- Need timely Agency input so as not to impact the primary construction windows with late or last-minute decisions
- Would like to reduce the complexity of consultations with the Agencies

Figure 4. WSDOT and WSF: Issues and needs regarding pile-driving research.

Regulatory Agencies: Issues and Needs

- Proper protection of fish life (organisms and habitat)
- No net loss (of fish, habitat function or habitat area)
- Consistent and appropriate mitigation measures for pile driving activities
- Minimize risk to fish based on best available data – decrease risk and uncertainty
- Err on the side of caution
- Protect Essential Fish Habitat (EFH)
- Protect Endangered Species Act (ESA) species, including fish and birds (i.e., the marbled murrelet that dives under water to feed on forage fish species, some of which have documented mortalities associated with pile-driving activity.
- Do not "Harm or Harass"
- What characteristics of pile driving sounds are most important?
- What are the thresholds for physical and behavioral disruption?
- Are there cumulative impacts? If so, what are they?
- What are the most useful characteristics that are:
  - Easily measurable
  - Protect species of concern
- How effective are mitigation measures?
  - Are they sufficient for a "no effect" determination?
  - If not, how much is "take" reduced by having the mitigation measure in place?
  - Are they sufficient to protect fish life?
- To raise current thresholds, data must be scientifically sound and presentable (and understood) in a court of law

Figure 5. Regulatory agencies' (Washington Department of Fish and Wildlife, NOAA Fisheries, and U.S. Fish and Wildlife) issues and needs regarding pile-driving research.

Experts then summarized what is currently known about sound propagation through air and water during pile-driving events and how the sounds may affect fish and diving birds. Following these presentations, an outline for a comprehensive pile-driving research program with five proposed research objectives was presented by Battelle. The five research objectives were as follows:

1. Characterize the unmitigated sound (field) generated by pile driving at WSDOT/WSF projects.
2. Investigate the necessary conditions for barotraumas (immediate and delayed mortality) of salmonids and one selected physoclistous species.
3. Investigate effects of pile-driving sound on the inner ear of fish (hearing and vestibular senses).
4. Investigate the design of mitigation measures (primarily bubble curtains) to eliminate or significantly reduce the levels and characteristics of sound propagated away from a pile being driven.
5. Investigate the behavioral response of salmonids and one selected physoclistous species to mitigated and unmitigated pile-driving sounds.

To reach a consensus on the prioritization of research objectives, discussions of each research objective focused on workshop goals (Figure 3) and prioritization criteria (Figure 6). During the workshop, WSDOT indicated that Criteria D, the 1-year time frame, was not an absolute requirement, but that a short-term project (less than 3 years) with useful results was preferred. At the conclusion of the workshop, no single research objective was singled out as the highest priority for future research, although emphasis was placed on the importance of developing a model of the acoustic fields generated by pile-driving activity at WSDOT projects in Puget Sound.

Prioritization Criteria

Extent to which the research objective meets:

A. The research goals
B. WSDOT/WSF needs
C. Resource Agency needs
D. A one-year time frame for useful results
E. Technical risk requirements
F. Cost constraints
G. The need to be at the fulcrum of pile-driving research
H. A compatibility but not redundancy, with other ongoing work

Figure 6. Prioritization criteria used at the Pile-driving Workshop to try to rank the research objectives from highest to lowest priority.

In the month following the workshop, Battelle developed the following work plan for pile-driving research based on the issues and needs of the WSDOT/WSF and the attending resource agencies and on the discussions that took place during the workshop. The work plan is designed to meet WSDOT/WSF needs for pile-driving research and to further understanding of pile-driving impacts to aquatic animals in the Puget Sound.

PLAN FOR PILE-DRIVING RESEARCH

The reasonably well documented injuries to aquatic animals from exposure to sound fall into two categories: barotrauma and hearing trauma. A third category of impact to aquatic animals, behavioral modification, remains much less well-documented. Mitigation for pile driving is focused on the mechanisms of sound production and modification of the sound field produced.

Of primary interest are the characteristics of underwater sound generated by impact steel pile driving that cause injury to aquatic animals. Exception from mitigation has been given to steel piles driven using vibratory hammers and to wood and concrete piles driven by either impact or vibratory hammers. Although it is clear from observations made to-date that impact pile driving of wooden piles can result in underwater sound that exceeds the criteria set by the environmental resource agencies, exception is given to these piles and the impact method of driving, because other characteristics of the produced sound, primarily rise time, appear to not result in impacts to exposed fish. Impact driving of steel pile is the central focus of both regulation and research.

Based on the results of the pile-driving workshop, a number of research priorities need to be addressed by WSDOT and its collaborators. Each research objective is important, and it is recommended they be addressed using a modular approach, as time and funding allow. **Individually, the modules will result in the development of tools that aid in the prediction of impacts to aquatic animals, knowledge about the biological effects of pile-driving sounds, and designs that mitigate the impacts of pile driving on aquatic animals. Together they will allow the development of science-based criteria and guidelines for pile driving (Figure 7).** Five proposed research modules include the following:

- Module 1. Modeling of the relationship between pile and substrate characteristics, the hammers and techniques used to drive steel pile, and the time and frequency domain characteristics of produced impulsive underwater sound fields for mitigated and unmitigated pile-driving operations.
- Module 2. Clarification of the time and frequency domain characteristics of impulsive sound causing barotrauma to fish.
- Module 3. Determination of the impulsive-sound exposure causing degradation in the hearing and vestibular senses of fish.
- Module 4. Assessment of the effects of behavioral response of fish to impact pile-driving sound.

Module 5. Investigation of the means to mitigate impulsive underwater sound generated by pile driving.

The integration of all the work plan elements with opportunities for collecting field data during planned and ongoing projects will require coordination between all the collaborating agencies and institutions. Additionally, a reassessment of existing information should be conducted, particularly of existing data on impulsive underwater sound generated by explosions, to aid in development of criteria for barotrauma to fish and diving birds from pile-driving impulsive-sound exposure.

A description of the activities that would be conducted to implement each module is presented in the following section. During the workshop, Module 1 (acoustic field modeling) was given highest priority by WSDOT managers and other workshop attendees, met the research objective criteria, and will likely be addressed first. The remaining modules are presented in the order shown in Figure 7.

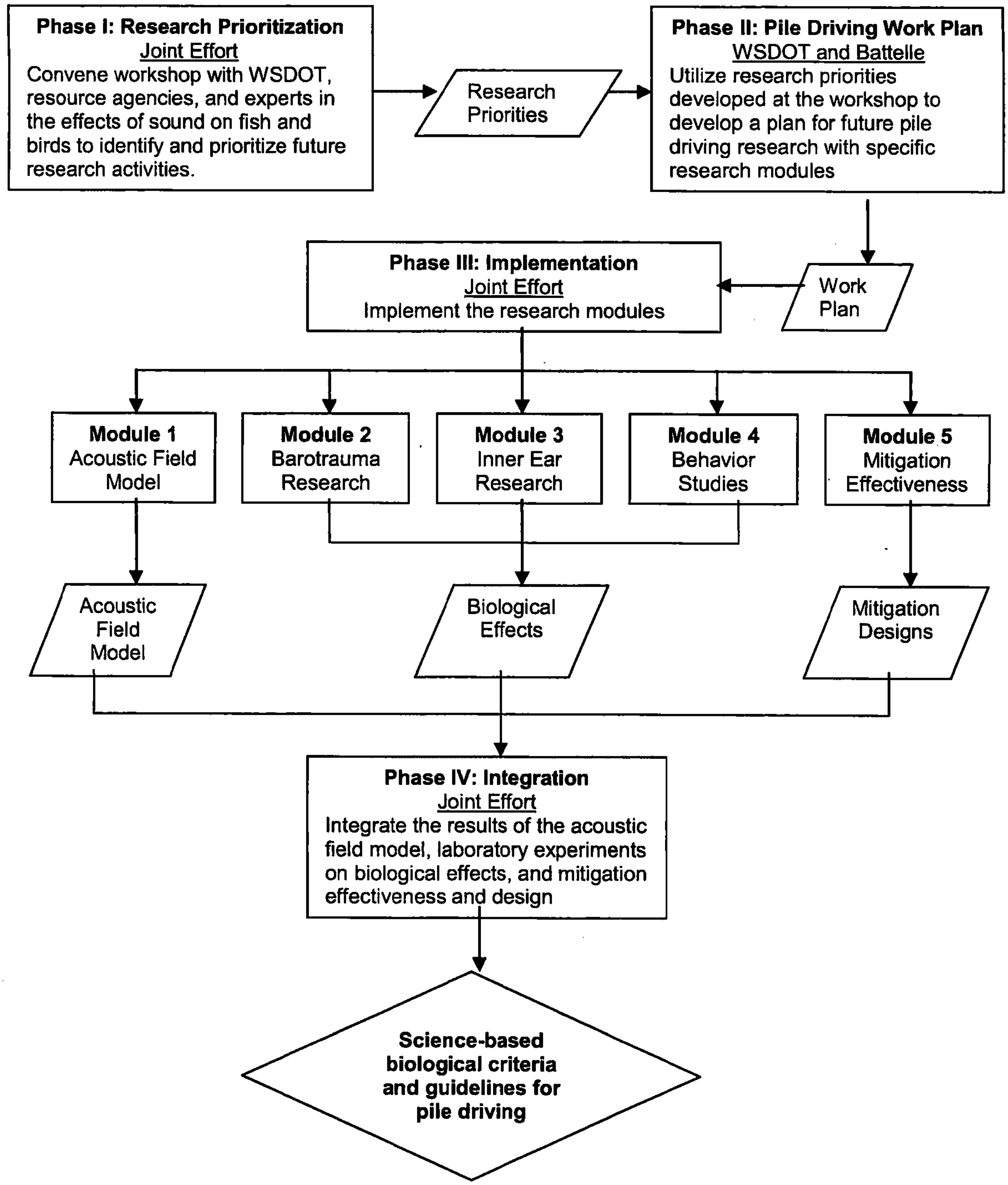

Figure 7. Organization of research phases in joint studies on pile-driving impacts on aquatic animals in Puget Sound.

MODULE 1: Modeling the Acoustic Field Generated by Pile Driving at WSDOT Projects in or near Marine Environments

Currently, assessment of the acoustic fields generated by impact driving of steel piles is based on point measurements of acoustic field characteristics. Such measurements have limited utility in understanding the three-dimensional characteristics of a sound field. Because it would be prohibitively expensive to measure a sound field at enough points to adequately describe the field, estimation of sound-field characteristics is best accomplished using mathematical models. Fortunately, this goal can be accomplished in a reasonable time at reasonable cost with current computers and codes. The ultimate utility in a sound field model would be to predict the sound field likely to be generated by pile-driving activity in a specified location and to be able to plan mitigation to accomplish environmental protection measures when needed. Mitigation measures to reduce biological impacts of pile driving could include application of bubble screens or other measures that would either reduce or change the character of sound produced or features of the propagating sound field.

Critical assumptions for the following work plan are as follows:

1. Sufficient data of adequate quality to specify boundary conditions and to provide calibration and validation data sets for acoustic field models for both mitigated and nonmitigated pile driving of steel pile over the range of application are available or will become available in the course of planned acoustic field monitoring and dynamic pile-driving monitoring. The acquisition of calibration and validation data is not identified as a task within the work plan, although calibration and validation protocols would be a necessary element of any modeling effort.
2. Elements of the work plan schedule are dependent upon the schedule for availability of boundary condition data and model calibration and validation data sets.
3. Peer review by qualified independent experts during model construction, calibration, and validation is a critical element of model development and is included in the work plan. In science, external peer review is standard practice, especially for complex tasks that will be used as an element in high-value decision-making.
4. Model development will be expedited by utilizing an existing model rather than writing a new model. Commercial model codes and open source codes will be reviewed for their applicability to the problem. If a commercial code is selected, it will require purchase of software licenses.
5. Model development will initially focus on a case study of a representative site for which necessary data sets (see assumption 1 above) are available. Site selection will be made by WSDOT based on the availability of data sets and other information, such as bathymetry and bottom composition. Battelle will assist with site selection at WSDOT request.

6. The initial model will be intended for use by modeling experts. Only after model utility is evaluated and documented will effort go into developing a user interface and other elements necessary to make it available to other users.

The main tasks for the work plan are as follows:

1. Select the members of a peer review team
2. Review current applicable acoustic models and select the model to be used
3. Define and acquire model boundary condition calibration and validation data sets for the selected case study site
4. Apply the model to the case study site using calibration data sets and perform independent verification of model performance using validation data sets
5. Apply the model to a second study site if necessary boundary condition and validation data sets are available
6. Perform peer review of the model and document the conclusions of the review.
7. Develop and review model user interface and output display module specifications with a committee representative of the intended nonexpert user group
8. Integrate model components and document for use by nonexperts, as necessary. A trial use of the model will also be conducted with this nonexpert user group, with revisions made to the model after the trial
9. Deliver model and documentation.

The following are descriptions of the work to be accomplished under each Task and Subtask.

Task 1 – Perform peer review of the model

Subtask 2.1 – Select peer review team members
A peer-review team, expert in the physics and modeling of acoustic fields generated by water-loaded structures, will be recruited. The membership of the panel will include a well-known physical acoustician, such as Dr. P. Marston from Washington State University, an expert acoustic modeler, such as Dr. V. Sparrow from Pennsylvania State University, and a senior mechanical engineer expert in pile-driving mechanics.

Subtask 1.1 – Perform model reviews
The panel will be paid to periodically review the work of the model development team. Reviews will be conducted at critical junctures, such as model selection, model validation, and definition of the range of use of the developed model. Reviews will be managed by the project principal investigator in consultation with the WSDOT research manager and will be independent of the acoustic model development team. All review comments and decisions will be provided in a

memo, letter, or document to the WSDOT research manager for distribution within WSDOT.

Task 2 – Select acoustic model

Subtask 2.1 – Identify applicable models

A list of applicable models will be selected for evaluation. The list will be developed in consultation with other acoustic modeling experts to ensure that as many applicable models as possible are identified for consideration. Identification of applicable models will be aided by using a list of evaluation criteria developed for model identification and evaluation. The peer-review panel will review the evaluation criteria for completeness.

Subtask 2.2 – Select model to be used

Models identified in Subtask 2.1 will be evaluated using the evaluation criteria identified previously. The selected model will be procured. All review comments and decisions will be provided in a memo, letter, or document to the WSDOT research manager for distribution within WSDOT.

Task 3 – Acquire model data sets

Subtask 3.1 – Receive data sets for model calibration and validation

(Note: The time of receipt of calibration and validation data sets depends upon the schedule for their acquisition by WSDOT.)
Calibration and validation data sets will be handed over to Battelle by WSDOT on a schedule to be determined. The formats for the data sets and metadata will be discussed with WSDOT at project initiation.

Subtask 3.2 – Process acquired data sets and assemble in a database

Acquired data sets will be assembled into a database and otherwise processed into a form ready for utilization for model calibration and validation. Upon completion of this task, a memorandum to files will be written documenting the disposition of the received data. This memo will be provided to WSDOT for appropriate distribution.

Task 4 – Simulate the acoustic field for the primary case study site and conditions

Subtask 4.1 – Develop the computational mesh and other elements of the model basic structure

The basic framework of the model will require preparation of the computational mesh that discretizes the physical environment within which simulation will take place. The mesh will include the pile and the environment within which pile driving is occurring. The mesh for this application may be more complicated than similar types of simulation because of the dynamic nature of the application. As a pile is driven in a marine environment, it is wetted and its embedded length changes due to changes in water elevation and increased penetration of the pile into the substrate. The force applied to the pile also changes as necessary to accommodate changes in resistance as the pile is driven.

Subtask 4.2 – Calibrate the model for the primary case study
Calibration is the task of fitting the model to the application and typically involves a range of tasks, from parameter estimation through changes or additions to computer code, to better simulate the basic physics of the pile-driving activity. Calibration is typically one of the most demanding phases of model development. The model will be calibrated using a data set acquired specifically for this purpose.

Subtask 4.3 – Validate the model for the primary case study
Validation involves comparing model predictions with observations that are independent of those used to calibrate the model. Validation of a model requires model predictions to be within error bounds set to define acceptable model performance. The model will be validated and its performance assessed using a data set that is independent from the calibration data. Statistical measures of model performance, such as mean absolute error, root mean square error, and bias, will be used.

Task 5 – Challenge model with blind test

Subtask 5.1 – Acquire basic parameters for blind test
Basic parameters, such as the bathymetry, tidal cycles, pile type, pile location, hammer type, and hammer operations, will be required to adjust the acoustic field model to a new site. This process will be helpful in identifying what portions of the model must be changed and to begin to assess how such changes might be made possible by novice users.

Subtask 5.2 – Simulate acoustic field generated by pile driving
The calibrated and validated acoustic field model will be run and the acoustic field generated by simulated pile driving. The performance of the model will be assessed by comparing model predictions with measurements previously acquired for the blind test site.

Task 6 – Perform peer review of the model

Subtask 6.1 – Perform a peer review of the model
The peer-review team will have been involved in periodic review of the model as it has evolved, so this review will conclude the work of the review team. In this review, the team will assess the overall performance of the model and document their findings in a memorandum to project files. Findings will be provided in a memo, letter, or other document to the WSDOT research manager for distribution within WSDOT.

Task 7 – Develop model user interface and output display module

Subtask 7.1 – Convene a sample of representative uses, demonstrate the model, and identify key features of a user interface and output display capability

WSDOT staff have already provided some input on the model, mostly addressing user operation options and display needs. This meeting will consolidate and finalize these requests and reconcile them against available budget and cost. The goal of this subtask is a specification for a user interface that will permit a novice user to apply the model and to display the model output. The deliverable for this task will be a memorandum to project files documenting the user interface specifications necessary to the model to allow for use by novice users.

Subtask 7.2 – Create user interface

User interface creation will require programming to prompt the user for needed input, offer a selection of representative values for parameters, and many other features. The typical development path for this type of work is to develop a prototype and test repeatedly until novice users can navigate the user interface and run the model. More difficult is guarding against novice users running the model in modes or with parameters that produce output that is incorrect, but not obviously erroneous.

Task 8 – Integrate the model components and document

Subtask 8.1 – Integrate model

The model may conclude in a number of forms. The most likely is a number of separate programs that each perform a particular function. For example, one program may aid the user in selection of program parameters, another may aid in modification to the computational mesh for specific applications, another would simulate the acoustic field, whereas others would perform statistical calculations and permit printing and display. A number of options for model integration are possible. One that has worked well for this type of model and user group is to integrate on a server and provide web access for model use. This option may be necessary if the computing requirements for the model are high and simulations must be performed as an activity separate from the final regulatory decision.

Subtask 8.2 – Document model

Final model documentation will focus on the user interface and aids for application of the model. The deliverable for this task will be a model user manual.

Task 9 – Deliver model

Subtask 9.1 – Conduct seminar and training session for model use

Potential users will have to be trained in the use of the acoustic field model. Although it is expected that WSDOT research managers will keep abreast of model development and others may be aware of the model and its capability, they will need to be informed about the basis of the model and its range of application, and have the opportunity to learn how to use it in an environment in which expert users are available to assist. The deliverable for this task will be a 1-day training session consisting of one or more presentations on the model function and training in model use for typical WSDOT pile-driving applications.

MODULE 2: Work plan to determine the necessary conditions for barotrauma to fish

Barotrauma is caused by rapid changes in the size of air cavities and bubbles in the bodies of fish. Air is compressible, therefore, changes in pressure cause changes in the volume of the air bladder or bubble containing the air. Changes in the volume of a fish's swimbladder or in bubbles contained in blood or tissue can cause a variety of injuries, which, depending on their location and severity, may cause death. The consequences of pressure cycling of air-filled organs and bubbles depend upon many biological and physical factors. One factor of importance is the rate of change in pressure at the leading edge of the pulse. The more rapidly the pressure changes and the higher the maximum pressure in the pulse, the greater the risk of injury. There has not been a systematic investigation of the features of an underwater pressure pulse from pile driving that are necessary to cause barotrauma in fish.

The research goal of this work plan is to describe the temporal and frequency characteristics of underwater sound signals generated by pile driving that cause barotrauma in fish.

Critical assumptions for the barotrauma work plan are as follows:

1. Sufficient information to clarify criteria for the onset of barotrauma to fish can be obtained from laboratory studies of a selected salmonid species and one physoclistous species of marine fish.
2. Fish size (age) within species may be an important factor in risk of barotrauma from exposure to underwater sound.
3. Field studies will be limited to validation of laboratory test results.

The main tasks for the work plan are as follows:

1. Review methods and mechanisms for simulating pile-driving pressure sound signals under laboratory conditions
2. Construct exposure apparatus
3. Develop techniques for detecting sublethal barotrauma injury to fish
4. Perform sound exposure experiments
5. Analyze sound exposure data
6. Prepare draft and final reports.

Task Descriptions

In the following section, the main tasks necessary to accomplish the work-plan objectives are broken into subtasks and described in more detail.

Task 1 – Review methods and mechanisms for simulating pile-driving pressure sound signals under laboratory conditions

Subtask 1.1 – Conduct analysis of existing pile-driving-sound data sets to define one or more signals to use in laboratory tests

WSDOT, California Department of Transportation (Caltrans), and others have monitored pile-driving activities and have observed underwater sound signatures for both mitigated and unmitigated pile driving. Observations have also been made of biological impacts. These data would be analyzed to identify the characteristics of pile-driving underwater sound signals known to be dangerous to fish and to ensure that the sound signals used in laboratory experiments were representative of pile-driving-sound signals of interest. A memorandum to files would be written to document the results of the selection of sound signals for live fish testing.

Subtask 1.2 – Review the performance of devices, such as piston-driven hyperbaric chambers and other apparatuses, to assess their ability to generate the desired exposure sound signals

A variety of devices have been used to generate sound signals under laboratory conditions. Piston-driven hyperbaric chambers, such as those used by Battelle for various fish pressure cycling experiments, are appealing because they permit test fish to be held under static-pressure conditions similar to those they would experience in nature, and to be exposed to sound signals equivalent to those generated by pile driving. However, other methods may also be available with features preferable to those of the hyperbaric chambers. A memorandum to files would be written documenting the review of sound-exposure devices and the device selected for use.

Task 2 – Construct and verify the performance of the sound-signal exposure apparatus

Subtask 2.1 – Construct the sound-exposure test apparatus

Special materials and tools will be required to construct a test apparatus to work safely at higher pressure. The test apparatus will most likely be computer controlled so that all aspects of its function and condition can be continuously monitored and so that the subsections of the apparatus needed to simulate the pressure time histories of pile driving can be controlled well enough to accurately and reliably simulate pile-driving sound signals.

Subtask 2.2 – Verify the performance of the test apparatus

Verification of the performance of the test apparatus will require both biological testing as well as sound pressure field testing. Because it will be necessary to hold test fish for long enough periods of time for pressure and other acclimation, the test apparatus must allow flow through of water while retaining pressure. This feature is common in state of the art hyperbaric test chambers. However, it will be necessary to test the apparatus under simulated test conditions using live fish.

Verification of the pressure in the test chamber will be accomplished using one or more pressure transducer permanently mounted in the chamber. Cross correlation analysis will be used to evaluate how well the desired sound signal was generated in the test chamber. Special emphasis will be place on signal features such as rise time and peak amplitude.

Task 3 – Develop techniques for detecting sublethal barotrauma injury to fish and evaluating its significance

Biological effects of barotrauma leading to immediate death are readily detected. However, it is possible that significant numbers of fish may suffer significant barotrauma injury, which, although not resulting in immediate death, results in reduced fitness, which may lead to mortality in the near future.

Subtask 3.1 – Non intrusive detection of barotrauma
Sublethal methods, such as high-intensity light or ultrasound, will be evaluated as means to detect internal injury to fish organs.

Subtask 3.2 – Intrusive detection of barotrauma
Various surgical means have been used to investigate internal barotrauma injury; however, the surgical processes necessary often result in reduced ability to detect many types of injury. Procedures and protocol development will be required to optimize the use of intrusive means to detect barotrauma injury.

Subtask 3.3 – Evaluation of the significance of sublethal barotrauma injury
The risk of various types of barotrauma injury to fish survival will be difficult to assess. Methods may be needed to assess the risk of sublethal barotrauma injury, such as delayed mortality or predator challenges.

Task 4 – Perform sound-exposure experiments

Subtask 4.1 – Finalize the experimental design for sound-exposure experiments
It is expected that the experimental design will have features of a toxicity study in which the stimulus is sound rather than some chemical quantity. Under this assumption, the experimental design would consist of a sequence of sound exposures in which the sound stimulus is designed to vary in rise time (frequency content), peak amplitude, duration, and other key features in a systematic way.

Subtask 4.2 – Acquire test fish
It will be necessary to identify surrogate species that can be easily acquired and are more amenable to holding and handling or to capture samples of fish of interest and hold them until they are used in experiments.

Subtask 4.3 – Execute experimental design
Execution of the experimental design will consist of conducting a sequence of sound-exposure tests in a systematic fashion until all experimental treatments have been satisfactorily completed.

Task 5 – Analyze sound-exposure data

Subtask 5.1 – Apply analysis model
Analysis of experimental data will be dictated by the experimental design. It is likely the purpose of the analysis will be to identify the characteristics of pile-driving sound that create an unacceptable risk to injury to fish species of interest. Definition of "unacceptable risk" will need to be addressed when the experimental design of the study is being developed.

Task 6 – Prepare draft and final reports

Subtask 6.1 – Prepare review draft report
Following completion of data analysis, a review draft report will be prepared. This report will be submitted for internal Battelle review and WSDOT review. The length of the review period will adhere to contract specifications.

Subtask 6.2 – Prepare final report
After receipt of all review comments, any data analysis or other work required to address the comments will be conducted and the results integrated into the draft report to produce the final project report.

<u>MODULE 3</u>: Work plan for the effects of pile-driving sound on the inner ear of fish

The inner ear of fish is essential to their survival. In addition to hearing, the inner ear is also a fish's vestibular organ. The inner ear of fish can be damaged by exposure to prolonged sound at lower levels and also by shorter-term exposure at higher levels. Damage to the inner ear is typically very difficult to detect except under laboratory conditions, the exceptions being loss of equilibrium or escape-response malfunction, which can be observed under field conditions.

Experts in fish hearing suggested during the WSDOT pile-driving workshop that sound exposure causing a permanent hearing-threshold shift would be the best candidates for determination of the "dose" of sound causing significant inner-ear damage, the assumption being that permanent loss of inner-ear function is a significant detriment to the vitality of otherwise healthy fish.

The research goal of this work plan is to determine the "dose" of sound required to cause a permanent hearing-threshold shift in salmonids and one candidate physoclistous species.

A critical assumption of this research is that findings can be extrapolated to the population of fish of concern exposed to underwater sound caused by pile driving.

The main tasks of the work plan are as follows:

1. Review methods and mechanisms for simulating pile-driving-pressure sound signals under laboratory conditions.
2. Construct exposure and evaluation apparatus.
3. Establish criteria for determination of permanent threshold shifts in test fish.
4. Design hearing-threshold-shift experiments.
5. Perform sound-exposure experiments.
6. Analyze sound-exposure data.
7. Prepare draft and final reports.

Task Descriptions

In the following section, the main tasks necessary to accomplish the work-plan objectives are broken into subtasks and described in more detail.

Task 1 – Review methods and mechanisms for simulating pile-driving-pressure sound signals under laboratory conditions (Note: this task is common to all laboratory-based work plans)

Subtask 1.1 – Conduct analysis of existing pile-driving-sound data sets to define one or more signals to use in laboratory tests

WSDOT, Caltrans, and others have monitored pile-driving activities and have observed underwater-sound signatures for both mitigated and unmitigated pile driving. No observations have been made of hearing or vestibular-sense impacts in any pile-driving monitoring or research to date. The primary objective of this task is to define the characteristics of underwater-sound signals to be used for treatments in research of hearing and vestibular impacts on fish exposed to pile-driving sound. A memorandum to files would be written to document the sound signals selected for research and the criteria used for their selection.

Subtask 1.2 – Review the performance of devices such as piston-driven hyperbaric chambers and other devices to assess their ability to generate the desired exposure sound signals

A variety of devices have been used to generate sound signals under laboratory conditions. Piston-driven hyperbaric chambers, such as those used by Battelle for various fish-pressure cycling experiments, are appealing because they permit test fish to be held under static-pressure conditions similar to those they would experience in nature and exposed to sound signals equivalent to those generated by pile driving. However, other methods may also be available with features preferable to those of the hyperbaric chambers. A memorandum to files would be written documenting the review of sound-exposure devices and of the device selected for use.

Task 2: Construct sound-exposure and hearing-evaluation apparatus

Subtask 2.1 – Construct sound-exposure apparatus

The finding from Task 2 will determine the test-apparatus features and approach best suited to work-plan objectives. The time and cost for construction will be a function of apparatus features. If modification of existing equipment is determined to be the best approach, it is possible that costs and time requirements will be lower than if new apparatus are required.

Subtask 2.2 – Construct hearing-evaluation apparatus

Apparatus to evaluate hearing-threshold shift in fish require anechoic, sound-proofed enclosures and instruments to present low-level sound signals to fish and to measure the activity of neural fibers responding to sound stimuli. Although surgery is not required for the process, holding fish for long periods of time in a confined space is a requirement. It is not clear at this time whether all species and age groups of fish of potential interest can tolerate the level of handling required.

Task 3: Establish criteria for permanent threshold shift in fish

Subtask 3.1 – Conduct pilot studies using test species and ages of fish to define criteria for permanent threshold shift

Fish can regenerate hair cells; therefore, "permanent" may not have the same meaning for fish as it does for humans who cannot regenerate hair cells damaged by exposure to high intensity sound. In addition, the ability to regenerate hair cells may differ between species and age groups within species. The definition of "permanent" for fish will have to be defined in this task. It is likely to be a period of threshold shift of sufficient magnitude to impact the vitality of a fish (which also requires definition). Pilot studies, range finding in nature using positive controls, will be conducted to validate experimental procedures for sound exposure and evaluation of hearing-threshold-shift determination. Test fish will need to be held for longer periods of time to evaluate the "permanence" of "permanent" hearing-threshold shifts. Setting thresholds for what constitutes "significant" hearing-threshold shift will need to be determined by consultation with fish managers following review of pilot-study findings. Memoranda to files will be written to document task findings.

Task 4: Design hearing-threshold shift experiments

Subtask 4.1 – Determine experimental design

Experimental design issues that must be clarified prior to conduct of experiments are the species and age groups of fish to be tested, the treatments (sound-exposure doses) to be evaluated, the measurement metrics to be used for evaluation of threshold shift, and statistical procedures for determination of significance of observed effects, which will determine required sample sizes.

Task 5: Perform sound exposure experiments

Subtask 5.1 – Obtain and hold test fish
Sufficient numbers of live test fish to satisfy sample size requirements need to be collected and held prior to experimental use and, for this type of study, held for a period of time after exposure and initial evaluation. The availability of test fish of the species and size (age) of interest may be severely restricted to particular times and locations. Although salmonids of appropriate species and size can most likely be acquired from hatcheries, other species of potential interest will probably need to be acquired from the field, unless surrogate species more easily obtained and handled can be identified.

Subtask 5.2 – Evaluate initial hearing thresholds
Prior to sound exposure (treatment), the hearing threshold of a sample of fish from the population of interest would be determined. This task would involve taking a sample of individual fish and determining their "normal" hearing threshold at a number of frequencies across their hearing range. A population-level approach is assumed, because it may not be possible to repeatedly handle individual test fish without significant levels of mortality.

Subtask 5.3 – Determine hearing-threshold shift
Depending upon the response to handling of test fish used in Subtask 6.3, the same fish or a sample of new fish will be used for this subtask. Samples of fish will be exposed to treatments and evaluated for hearing-threshold shifts. The number of treatments and number of fish per treatment would be those determined during experimental design.

Subtask 5.4 – Determine "permanence" of observed threshold shifts
Following a holding period determined during experimental design, a sample of fish exposed to sound (this may or may not be the same fish used in Subtask 6.4, depending upon the response of test fish to handling) would be evaluated for hearing-threshold shift.

Task 6: Analyze sound-exposure experiment data

Subtask 6.1 – Perform statistical analyses to determine threshold values of sound exposure leading to permanent hearing-threshold shifts
Statistical analysis of acquired data would proceed according to the analysis model identified during experimental design. Rejection of a hypothesis that hearing-threshold shifts occurred would imply the level of sound (amplitude, duration, and other factors) was not sufficient to cause a "permanent" threshold shift. Acceptance of the hypothesis that hearing-threshold shifts meeting population-level statistical criteria for permanence occurred would indicate the level of sound was sufficient to cause "permanent" threshold shifts.

Task 7: Prepare draft and final reports

Subtask 7.1 – Prepare draft report
Following completion of data analysis, a draft report will be prepared. This report will be submitted for internal Battelle review and WSDOT review. The length of the review period will adhere to contract specifications.

Subtask 7.2 – Prepare final report
After receipt of all review comments, any data analysis or other work required to address the comments will be conducted and the results of this work integrated into the draft report to produce the final project report.

MODULE 4: Work plan to investigate the behavioral response of fish to pile-driving sounds

Fish-management agencies have established criteria for pile driving that consider the behavioral response of fish to pile-driving sounds. To-date, very little research has been done to assess the behavioral response of fish to pile-driving sounds. Information is available in the literature for the response of rock fish and cod to impulsive sounds generated by seismic survey arrays. However, no analysis has been conducted to compare seismic impulsive sounds with those generated by pile driving. A single study is available for a single period of very limited observation of the response of juvenile salmonids to pile-driving sound. Although laboratory and field cage studies can be conducted to observe fish responses, such as startle, when exposed to pile-driving sounds, it is considerably more difficult to determine whether any observed behavioral responses reduce the fitness of the exposed fish to increased risks of one form or another. Because of these complexities, this work plan will focus on laboratory and field studies using caged or otherwise constrained fish in which response to specific sound treatments can be observed. It is assumed that other studies for barotrauma and inner-ear impacts would provide data about physical injury resulting from pile-driving-sound exposure.

The main tasks of the work plan are as follows:

1. Complete experimental designs for laboratory and field studies
2. Construct sound-exposure apparatus for laboratory and field studies
3. Conduct behavioral-response experiments
4. Analyze data
5. Prepare reports.

Task Descriptions

Task 1 – Prepare experimental designs for laboratory and field studies

Behavioral studies are complicated for a variety of reasons. For example, although an animal may be aware of a stimulus (presence of sound), it may not be motivated to respond, or the response may be startle or some other unconditioned response that is almost instantaneous but of short duration with no other effect, such as longer-range movement. Even if a marked behavior is observed, the behavior may not have a negative impact on the animal. This work plan will focus on behavioral responses that can be observed in fish that are caged or otherwise constrained in an environment where they are more easily observed. Future work might consider evaluation of the larger-scale behavior of fish that are not constrained.

Subtask 1.1 – Prepare experimental designs for laboratory studies
It is assumed that the sound-exposure devices used for other modules would also be partially or wholly usable for this module as well. Laboratory experiments would focus on the response of smaller samples of fish of interest contained in an environment where there response could be evaluated using tools, such as high speed video. Pilot studies may be necessary to obtain data for sample-size estimation for designs that test hypotheses rather than being purely observational.

Subtask 1.2 – Prepare experimental designs for field-cage studies
Experimental designs for field-cage studies should probably be delayed until laboratory studies are completed. Observational technique development and experience with the sound stimulus in the laboratory will most likely contribute to decisions, such as locations of cages, to obtain stimuli with characteristics of interest. Cage studies have been conducted by others to observe the behavioral response of fish to stimuli, such as seismic survey sounds, so there is precedence for this method of behavior assessment.

Task 2 – Construct sound-exposure apparatus for laboratory and field studies

Various instruments and devices will be needed to create sounds of interest in a laboratory setting and to observe constrained fish in both laboratory and field settings. It is assumed that the methods used to create pile-driving sounds with the correct acoustic characteristics under laboratory conditions that might be built for other research modules would also work for behavioral assessment. Methods for construction and deployment of cages to hold test fish under field conditions are well known.

Subtask 2.1 – Construct sound-exposure apparatus for laboratory studies
Development of sound-exposure apparatus that can create sound with the characteristics of pile-driving sounds in an environment also conducive for holding test fish under laboratory conditions is a challenge. However, there is precedence for construction of laboratory-scale apparatus that permit the rapid change in

pressure within a chamber. We assume that modification of existing instruments of this type will provide the needed experimental environment.

Subtask 2.2 – Construct sound-exposure apparatus for field studies
Methods that have proved effective for similar studies will be used. In general, the necessary cages are inexpensive to build and deploy, and the observations tools are readily available off-the-shelf at reasonable costs. Sound exposure stimuli will be provided by pile-driving activities. The main constraint for this type of field work is coordination with ongoing construction activities and the availability of fish species and sizes of interest when construction work is being conducted.

Task 3 – Conduct laboratory and field behavioral experiments

It is assumed that field behavioral experiments would follow laboratory experiments. It is probable that this progression of studies will permit more effective and productive use of opportunities to observe the behavior of test fish exposed to actual pile-driving sounds under field conditions.

Subtask 3.1 – Conduct laboratory experiments
The number of treatments, sample size, and other elements of experimental design would control the schedule and cost for laboratory experiments. For example, the "dose" for a treatment may be the mean duration for driving a specific type of pile. At a duration of 15 minutes to complete driving a single pile, the total number of hammer impacts would be 900 at a rate of 1 hammer impact per second. If the response of test fish to all 900 impacts were processed, there would be 900 sequences of video from one or more cameras that would have to be processed.

Subtask 3.2 – Conduct field experiments
Field experiments would likely be higher in cost; therefore, a limited number of individual experiments with a clearly defined focus would be best. It would probably be most efficient to use the field studies as validation trials for extrapolation of laboratory results to the population of interest. In this case, field trials would be limited to a smaller number of conditions (treatments) selected from among the large number of treatments tested in the laboratory.

Task 4 – Analyze data

Unprocessed experimental data would consist of stimulus records and observations of test-fish response for both laboratory and field experiments. Video and other records of fish-behavioral response would be processed, and fish responses graded and placed into categories. Comparisons of category scores would be used to statistically test the significance of response patterns between species, ages, and other categories for the various sound-exposure treatments.

Task 5 - Prepare draft and final reports

Subtask 5.1 – Prepare draft report
Following completion of data analysis, a draft report will be prepared that will be submitted for internal Battelle review and WSDOT review. The length of the review period will adhere to contract specifications.

Subtask 5.2 – Prepare final report
After receipt of all review comments, any data analysis or other work required to address the comments will be conducted and the results of this work integrated into the draft report to produce the final project report.

<u>MODULE 5:</u> Work plan to evaluate the effectiveness of mitigation measures

Because underwater sound generated by driving of steel piles exceeds criteria set by fish-management agencies, studies have been conducted to evaluate a variety of methods, such as bubble curtains, to reduce the peak amplitude of sound radiated away from the pile. Previous research and operational experience has indicated that sound signal characteristics in addition to peak amplitudes, such as rise time, also affect the risk to fish of injury from a particular sound impulse. The objective of this work plan is to investigate means to reduce the characteristics of sound created during driving of steel pile as well as the sound radiated away from the pile. For example, less forceful impacts or "shaped" impacts, possibly with the addition of cushions on the top of the pile, might significantly reduce peak amplitudes and the rate of change in pressure at the leading edged of the impact pulse. Likewise, careful design and use of bubble curtains might result in additional reductions in peak amplitudes and filtering of higher frequencies, further modifying impact signal characteristics believed to increase the risk of injury to fish.

A critical assumption of this work plan is that most of the research could be conducted during scheduled pile-driving activities.

The main tasks of the work plan are as follows:

1. Conduct a tradeoff analysis
2. Test the most promising mitigation measures during routine construction activities
3. Analyze acquired data
4. Prepare draft and final reports.

Task Descriptions

Task 1 – Conduct a tradeoff analysis to identify mitigation methods with higher effectiveness and lower costs

Subtask 1.1 – Identify criteria for tradeoff analysis

WSDOT construction managers will be interviewed to identify factors for construction activities that must be considered in a tradeoff analysis. In addition, reports of previous pile-driving-sound mitigation research, the physics and practical conduct of pile driving, and the literature for the effects of bubbles on propagating sound would also be reviewed to identify additional factors affecting sound mitigation that should be considered in any tradeoff analysis.

Subtask 1.2 – Conduct tradeoff analyses to identify highest priority mitigation measures

A primary challenge with mitigation of pile-driving sound is not lack of measures that are effective in reducing sound radiated away from a pile, but identification of methods that can achieve desired results at lower costs. A tradeoff analysis must consider such factors as reductions in hammer energy that might lower the level of sound generated during pile driving but at a cost of greatly increased time to drive a pile. On the other hand, mitigation measures, such as placing a larger diameter pipe around a pile and evacuating water from the interior, might be very effective in reducing peak pressures but at an unacceptable increase in construction costs. The results of this subtask, including a listing of mitigation measures in order of their priority, would be summarized in a memorandum to project files.

Subtask 1.3 – Summarize tradeoff analyses in the form of a sequence of experiments to be systematically conducted as elements of ongoing pile-driving construction work

In this subtask, the prioritized listing of mitigation alternatives would be assembled into a sequence of experiments with defined endpoints. The document summarizing this activity would become the experimental plan for the work plan.

Task 2 - Test the most promising mitigation measures during routine construction activities

Subtask 2.1 – Identify construction projects in which mitigation alternatives could be tested

A plan to systematically work through acquisition of data for the various mitigation measures identified in the tradeoff analysis would be prepared. The plan would identify the construction projects in which conditions would be best to acquire data for specific mitigation measures.

Subtask 2.2 – Conduct mitigation alternative field studies

Field studies would consist of testing one or more mitigation alternatives during driving of one or more piles during the otherwise-normal course of construction activities. Many of the potential mitigation measures would likely require the use of specialized equipment that would have to be constructed or otherwise obtained, as well as mobilized and demobilized at the construction site. It is also likely that specialized measurement techniques would be required to obtain some of the data required for analysis of some alternatives.

Task 3 - Analyze acquired data.

Subtask 3.1 – Computation of performance measures
A number of performance measures would be computed from acquired data. Examples of measures likely include the modal response of the pile to impacts of energy with various hammers and cap treatments, radiated sound-field measures for unmitigated pile impacts, and sound-field measures for sound-field mitigation.

Subtask 3.2 – Cost-benefit analyses.
Benefits assessment of mitigation measures would be in the context of reduction in sound impact characteristics known to pose a risk of injury to fish. An approach that would permit grading of benefits would be developed. The cost component of the analysis would assess the economic impact of mitigation measures using as a baseline expected construction costs without mitigation measures.

Task 4 - Prepare draft and final reports

Subtask 4.1 – Prepare draft report
Following completion of data analysis, a draft report will be prepared that will be submitted for internal Battelle review and WSDOT review. The length of the review period will adhere to contract specifications.

Subtask 4.2 – Prepare final report
After receipt of all review comments, any data analysis or other work required to address the comments will be conducted and the results of this work integrated into the draft report to produce the final project report.

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APPENDICES A-K

The following appendices are materials from the Pile-driving Workshop sponsored by the Washington State Department of Transportation and held on April 29, 2004, at the University of Washington Center for Urban Horticulture in Seattle. The workshop was coordinated and facilitated by staff from the Battelle Memorial Institute, at offices located in Sequim, Washington, and Portland, Oregon.

Appendices A through D are materials developed prior to or during the workshop.

Appendix A is the workshop agenda.
Appendix B is a list of individuals that attended the workshop.
Appendix C presents the draft outline of potential pile-driving research objectives that was discussed at the workshop.
Appendix D provides background information on Puget Sound and species of concern.

Appendices E through K are copies of PowerPoint presentations that were given during the workshop.

Appendix E contains introductory material presented by WSDOT on the pile-driving problem statement, research goals, and workshop goals.
Appendix F presents the WSF point of view on future programs, projects, and schedules.
Appendix G presents an overview of Hydraulic Project Approvals by WDFW.
Appendix H presents USFWS & NOAA Fisheries concerns regarding protected resources.
Appendix I presents NOAA Fisheries statutory responsibilities.
Appendix J presents an introduction to the mechanics of pile driving.
Appendix K presents potential mitigation measures.

Some material presented at the workshop was not made available for inclusion in this document. However, an overview of fish hearing, similar to what was presented by Dr. Arthur Popper during the workshop, may be found by accessing the website for the aquatic bioacoustics laboratory (ABL) at the University of Maryland.
http://www.life.umd.edu/biology/popperlab/background/index.htm

Additional information presented by Dr. Mardi Hastings and Dr. Arthur Popper can be found at the following URL:
http://www.cartage.org.lb/en/themes/Sciences/Physics/Acoustics/SoundEffects/IntenseSounds/IntenseSounds.htm

Please note that copyright rules apply to the presentation materials in this document.

APPENDIX A: Workshop Agenda

AGENDA – PILE-DRIVING WORKSHOP
29 April 2004
Center for Urban Horticulture, University of Washington, Seattle

9:00 Introduction

9:00 Welcome, Purpose of the Workshop, Context within WSDOT Research Strategy – Marion Carey, WSDOT

[Problem Statement, Research Goals, Workshop Goals]

9:15 Workshop Format and Schedule – Gary Johnson, Battelle

9:20 Issues and Needs

9:20 WSDOT Pile-driving Issues and Information Needs – Russ East and Joel Colby, WSF; and Marion Carey

9:40 Resource Agency Views and Policies Regarding Pile Driving -- John Stadler, NOAA Fisheries; Jennifer Quan, USFWS; Randy Carman, WDFW

10:00 Discussion and Synopsis of Issues and Needs – Gary Johnson

[Focused List of Priority Issues and Needs]

10:15 Break

10:30 Strawman Research Program, Part 1: Baseline of Past Research and Current Knowledge

10:30 Physics of Pile Driving – Bert Miner, Robert Miner Dynamic Testing, Inc.

10:45 Biological Impacts of Pile Driving – Mardi Hastings,

11:00 Mitigation Approaches and Results – Tom Carlson, Battelle

11:15 Synthesis of Baseline Information – Gary Johnson

[Conceptual model relating pile driving/biological effects/mitigation measures]

11:20 Strawman Research Program, Part 2: Summary of Proposed Objectives and Tasks

11:20 Overview of Proposed Research Objectives – Tom Carlson

11:35 Panelist Insight into the Research Objectives and Tasks

[List of research objectives and tasks, annotated with panelist comments]

12:10 Working Lunch (provided)

12:30 Foundation to Prioritize the Objectives and Tasks

12:30 Prioritization Criteria – Gary Johnson

[List of criteria that will be used to prioritize the research objectives]

12:40 Detailed Discussion of the Research Objectives and Tasks – Tom Carlson and Panelists

2:00 Open Question/Answer Session – All

2:30 Break

2:45 Prioritization

[Draft matrix: Research objectives and tasks scored using the prioritization criteria. Sum totals provided for each research objective]

2:45 Detailed Discussion of the Prioritization of the Research Objectives and Tasks – Gary Johnson

[Revised matrix with prioritized research objectives]

3:15 Implementation

3:15 Recommended Approach to Implement the Prioritized Research– Tom Carlson

[Recommended implementation steps]

3:45 Wrap-Up

3:45 Summarize Accomplishments – Gary Johnson and Tom Carlson

3:50 Describe Next Steps for WSDOT/WSF -- Marion Carey and Joel Colby

4:00 Adjourn

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APPENDIX B: Workshop Attendees

Attendees
Pile Driving Workshop, April 29, 2004

Name	Representing	E-Mail
Anderson, Jim	University of Washington	jim@cbr.washington.edu
Brooks, Rhonda	Washington State Department of Transportation	brookrh@wsdot.wa.gov
Carey, Marion	Washington State Department of Transportation	careym@wsdot.wa.gov
Carlson, Tom	Battelle	thomas.carlson@pnl.gov
Carman, Randy	Washington Department of Fish and Wildlife	carnarec@dfw.wa.gov
Colby, Joel	Washington State Ferries	colby@wsdot.wa.gov
Dooling, Robert	University of Maryland	dooling@psyc.umd.edu
East, Russ	Washington State Ferries	eastrus@wsdot.wa.gov
Fordjour, Kojo	Washington State Ferries	fordjok@wsdot.wa.gov
Gray, Mary	US DOT, Federal Highway Administration	mary.gray@whwa.dot.gov
Hastings, Mardi	Self	hastings.6@osu.edu
Johnson, Gary	Battelle	gary.johnson@pnl.gov
Laughlin, Jim D	Washington State Department of Transportation	laughlj@wsdot.wa.gov
McKenzie, Tracey	Anchor Environmental/WSF*	tmckenzie@anchorenv.com
Miner, Bert	Robert Miner Dynamic Testing, Inc.	rminer@tscnet.com
Missildine, Brian	US Fish and Wildlife Service	brian.missildine@fws.gov
O'Haleck, Shandra	NOAA Fisheries, National Marine Fisheries Service	shandra.o'haleck@noaa.gov
Popper, Arthur	University of Maryland	apopper@umd.edu
Quan, Jennifer	US Fish and Wildlife Service	jennifer_quan@fws.gov
Sargeant, Sue	Battelle	sue.sargeant@pnl.gov
Shaw, Michael	Port of Tacoma	mshaw@portoftacoma.com
Stadler, John	NOAA Fisheries, National Marine Fisheries Service	john.stadler@noaa.gov
Steinmetz, Michelle	Washington State Department of Transportation	steinmi@wsdot.wa.gov
Thom, Ron	Battelle	ron.thom@pnl.gov
Thurston, Randi	Washington Department of Fish and Wildlife	thursrlt@dfw.wa.gov
Visconty, Sasha	Anchor Environmental	svisconty@anchorenv.com
Wagner, Paul	Washington State Department of Transportation	wagnerp@wsdot.wa.gov
Waters, Mia	Washington State Department of Transportation	watersy@wsdot.wa.gov
Widener, Ross	Widener & Associates	rwidener@prodigy.net
Woodruff, Dana	Battelle	dana.woodruff@pnl.gov

APPENDIX C: Draft Outline

Prepared by
Battelle

Pile-driving research Program Strawman Outline

TJC-4/5/04

Includes reviewer comments

1. **Establish baseline**
   a. **Stimulus (answer question: How much is known about sound generated by pile driving?)**
      i. **Catalog of sound measurements**
         1. **Time and frequency domain characteristics**
         2. **Correlation with factors such as pile, hammer, wetted length, substrate, etc.**
         3. **Sound propagation models in use.**

   b. **Mitigation (answer question: What sound mitigation devices have been tested and what is their effectiveness?)**
      i. **Designs of mitigation devices.**
      ii. **Measures of sound mitigation effectiveness.**
         1. **Alteration in time and frequency domain characteristics of propagated sound.**
         2. **Minimum depth mitigation required.**

   c. **Biological impacts of pile driving (answer question: What are the observed and suspected lethal and sublethal effects on fish of pile driving?)**
      i. **Barotrauma**
      ii. **Inner Ear (hearing and vestibular function)**
      iii. **Behavior**

   d. **Construction permit requirements (answer question: What actions are required of WSDOT by NOAA, USFWS and WDFW to obtain permits for pile driving?)**
      i. **Monitoring and reporting.**
      ii. **Sound level thresholds.**
      iii. **Conditions or special provisions.**

2. **Proposed critical path for research program**
   a. **Goals:**
      i. **Identify the characteristics of sound generated by pile driving (of representative WSDOT projects) that present a health risk to fish (selected species).**

ii. **Identify methods (sound field mitigation, use of different lower energy hammer types, ??) to reduce health risks to fish caused by pile driving.**

iii. **"BioEffect" radius for pile driving as a function of pile driving and biological variables.**

b. **Research objective 1: Characterize the unmitigated sound (field) generated by pile driving at WSDOT projects.**

   i. **Approach: Obtain representative sound field measurements for WSDOT pile-driving projects**

      1. **Time and frequency domain characteristics of sound pulses as a function of pile-driving variables obtained from standardized sound measurement obtained during WSDOT pile-driving activities.**

   ii. **Approach: Investigate the utility of numerical modeling to extend limited field measurements to a broader range of potential pile-driving situations.**

   iii. **Approach: Investigate the use of "hearing threshold" filters (similar to dB A filter for assessment of the effect of sound on humans) as a means of assessing the sound field perceived by specific species of fish.**

   iv. **Deliverable: Research report describing results of analysis of sound field measurements obtained at WSDOT pile-driving projects. Report to include results of investigation into numerical modeling of sound fields generated by pile driving. Report to address issue of pressure signals to be used in laboratory tests of barotrauma.**

c. **Research objective 2: Investigate the necessary conditions for barotrauma (immediate and delayed mortality) of salmonids and one selected physoclistous species.**

   i. **Focus on the time and frequency domain characteristics of pressure pulses required for lethal injury. To selected fish species and age groups.**

      1. **Time domain important for amplitude, frequency domain important for rise time and other pulse shape and duration features.**
      2. **Duration of exposure important (1 strike, 10 strikes, etc. to produce injuries).**

         a. **Address issue of "dose" for controlled studies.**

   ii. **Approach: Laboratory testing using hydraulically driven hyperbaric chambers. Program hydraulic drive to create pressure pulses that exactly simulate those generated by pile driving.**

1. **Laboratory testing is the easiest to control and will be the most definitive. However, expect "suggestions" to conduct field cage tests as well.**

iii. **Deliverable: Research report of sound signal characteristics necessary to cause barotrauma in selected test species and to identify the pile-driving conditions that result in the creation of the hazardous sound signals. Expect direct impact of results on criteria to be used for pile-driving work permits.**

d. **Research objective 3: Investigate effects of pile-driving sound on the inner ear of fish (hearing and vestibular senses).**

  i. **Focus on hearing sensitivity threshold shifts given representative "dose" of sound. Expect the issue of dose to require development and may be critical factor in establishing any linkage between sound exposure and consequence. Also expect the biological significance of any observed threshold shifts to be an issue.**

  ii. **Approach: Laboratory determination of threshold shifts using ABR (auditory brainstem response) techniques following exposure to "representative" pile-driving sounds. In cases of severe threshold shift (if observed) preparation of photomicrographs of hair cell beds may be helpful to assess physiological consequences of sound exposure. While ABR is proven for evaluation of hearing thresholds shift and, while it appears theoretically possible to evaluate vestibular function using ABR, the use of ABR to evaluate vestibular function has not been proven. Other laboratory tests of vestibular function may be necessary.**

  iii. **Deliverable: Research report clarifying linkage between exposure to sound and sublethal impact on inner ear function.**

e. **Research objective 4: Investigate the design of mitigation measures (primarily bubble curtains) to eliminate or significantly reduce the levels and/or characteristics of sound propagated away from a pile being driven. Criteria for success are to be derived from the findings of Research Objectives 1-3.**

  i. **Focus on low pass designs that also attenuate low frequencies. The objective is to modulate both the amplitude and rise time of sound pulses that propagate beyond the mitigation device's effective field.**

  ii. **Approach: Laboratory and field small scale experiments to evaluate tradeoffs between bubble size, displaced volume, and bubble field dimension (primarily thickness) on the attenuation and filtering of pile pulse sounds. While the theory for sound attenuation by bubbles is well developed, the application of this theory in efficient and cost effective bubble curtains is not well developed.**

iii. Deliverable: Research report with criteria for effective bubble curtains written to provide guidance to engineers designing bubble curtains.

f. Research objective 5: Investigate the behavioral response of salmonids and one selected physoclistous species to mitigated and unmitigated pile-driving sounds.

i. Identify behaviors, such as migratory delay, that present a risk to fish.

ii. Approach: Expect many fish of interest to be too small, too fragile, or otherwise not available for techniques such as tagging and tracking. However, some species and sizes f fish of interest can probably be tracked using these techniques. Overall, the approach to behavioral response to pile driving will require assessment of typical behavioral patterns for potentially impacted fish followed by development of metrics to assess deviations from typical behavior which indicate responses to pile-driving activity. Examples in the peer reviewed literature are for the behavioral response of rockfish aggregations and cod shoals to seismic survey activity. These studies used active acoustics to map fish distribution before, during, and following pile-driving activity. Visual observations, such as those described by Feist, are also possibilities.

iii. Deliverable: A report describing "normal" and "affected" behaviors for target species of fish as a function of underwater sound variables where these variables are linked to pile-driving variables such as pile type, hammer, etc.

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APPENDIX D: Puget Sound Background Information

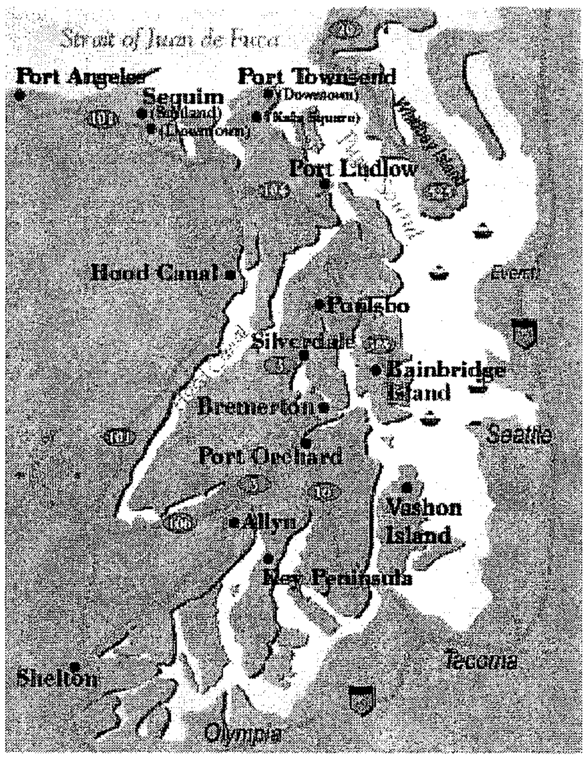
Prepared by the
Washington State Department of Transportation

Pile-driving Workshop
Puget Sound Background Information

Puget Sound

Puget Sound is a saltwater estuary connected to the Pacific Ocean by the Strait of Juan de Fuca, entered through Admiralty Inlet and extending approximately 100 miles to the south. Puget Sound is created by a series of deep underwater valleys and ridges with an average depth of 450 feet. This diverse topography results in a diverse land-water mosaic with 2,500 miles of shoreline and consisting of multiple bays, peninsulas, and inlets, and hundreds of islands of varying sizes. Puget Sound's shorelines are comprised of a mosaic of beaches, bluffs, deltas, mudflats and wetlands.

More than 10,000 streams and rivers drain into Puget Sound. However, nearly 85 percent of the basin's annual surface water runoff comes from only 10 rivers: Nooksack, Skagit, Snohomish, Stillaguamish, Cedar, Green/Duwamish, Puyallup, Nisqually, Skokomish, and Elwha.



Puget Sound

Puget Sound Wildlife

Puget Sound's diverse and unique geographic composition supports a range of productive marine habitats occupied by a wide variety of birds, mammals, and fish. Many of these species are year-round residents, while others are seasonal migrants. Each season, Puget Sound is occupied by numerous species of wildlife that rely on its habitats for wintering, breeding, rearing, or as a migratory stopover.

Marine Birds. Puget Sound supports a wide variety of marine birds including: loons (*Gavia* spp.), grebes (Family Podicipedidae), cormorants (*Phalacrocorax* spp.), alcids (Family Alcidae), gulls (*Larus* spp.), shorebirds (Family Scolopacidae), and ducks (Family Anatidae) (http://www.pacificseabirdgroup.org/gallery.html). Species diversity and populations are greater in winter when many species of ducks and seabirds that nest further north overwinter in Puget Sound's relatively calm and protected waters. However, a variety of marine birds remain throughout the year and breed in and around Puget Sound. Many gull, cormorant, and alcid species are among these local breeders.

Marine Mammals. Puget Sound is utilized by eight marine mammal species. Five of these species are residents and include: harbor seal (*Phoca vitulina*), Dall's porpoise (*Phocoenoides dalli*), harbor porpoise (*Phocoena phoceona*), orca (*Orcinus orca*), and Minke whale (*Balaenoptera acutorostrata*). The remaining three species occur seasonally and include California sea lion (*Zalophus californianus*), Steller sea lion (*Eumetopias jubatus*), and gray whale. The harbor seal is most common and occurs throughout Puget Sound. The porpoises and whales primarily occupy the deeper waters within Puget Sound and are most common in the north Sound and Strait of Juan de Fuca. After breeding elsewhere, California and Steller sea lions venture into Puget Sound in pursuit of forage fish. California sea lions are more common of the two species in Washington and more likely to venture further into Puget Sound. Most Steller sea lion occurrences are on the outer coast and few venture into Puget Sound. When present, they most often occur in northern Puget Sound near the San Juan Islands and Vancouver Island.

Fish. Puget Sound supports a wide variety of fish life including numerous species of rockfish (*Sebastes* spp.), flounder (Family Pleuronectidae), salmon and trout (Family Salmonidae), smelt (Family Osmeridae), shark (Family Squalidae), and cod (Family Gadidae), and Pacific sand lance (*Ammodytes hexapterus*) and Pacific herring (*Clupea pallasi*). Many of these fish provide the primary food source for many of the marine birds and most of the marine mammals (http://wdfw.wa.gov/fish/forage/forage.htm). Most are classified as game fish and are harvested through commercial and/or recreational fishing.

Protected Species

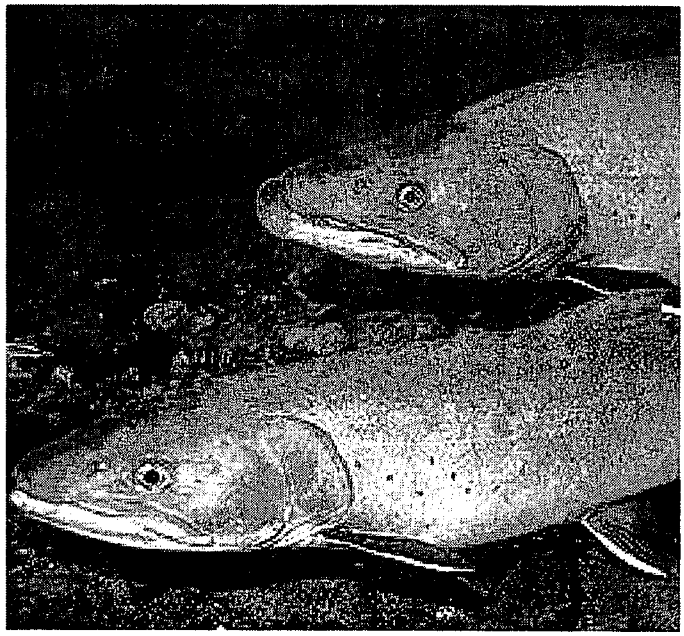
Virtually all birds that occur within Puget Sound are protected under the Federal Migratory Bird Treaty Act and are also classified as protected species under state law. The marbled murrelet (*Brachyramphus marmoratus*) is afforded additional protection as a "threatened" species under the Federal Endangered Species Act (ESA). Marbled murrelets are unique, in that they nest at inland forest sites and feed and winter in marine areas. Nest sites are typically established on platforms such as moss-covered limbs and deformities most commonly provided by old growth conifer forests. During the nesting season, marbled murrelets fly each day between their salt water feeding areas and inland nest sites that can be located over 50 miles away. Marbled murrelets feed on small schooling fish such as sand lance and herring, and marine invertebrates. Feeding primarily occurs in shallow marine waters between 70 and 250 feet deep, typically within one mile from shore. Puget Sound supports a large percentage of the marbled murrelets that remain in Washington. Marbled murrelet density is greatest in the northern portion of Puget Sound, both during winter and summer. Loss of old growth forests is the primary factor that has influenced the decline of marbled murrelets, but other factors, such as disturbance in feeding areas, could also be contributing to their decline.

Marbled Murrelet

All of the marine mammals are protected under the Federal Marine Mammal Protection Act. In addition, the Steller sea lion is listed as "threatened" under the ESA.

Most of the fish are regulated by the State as game species. However, the bull trout (*Salvalinus confluentus*), Chinook salmon (*Oncorhynchus tshawytscha*) that spawn in tributaries to Puget Sound, and chum salmon (*O. keta*) that spawn in tributaries to Hood Canal within Puget Sound are listed as "threatened" species under the ESA. Like the salmon, the bull trout that occur in Puget Sound are anadromous, they spawn in freshwater streams and live a portion of their adult life in marine waters. Bull trout typically spawn in the cold, headwater portions of streams. Not all bull trout migrate to sea. Those that do may swim a considerable distance from their spawning grounds in search of prey species, which typically include smaller fish. They are often attracted to outmigrating runs of juvenile salmonids in freshwater streams, and a variety of small fish that occupy the shallow margins of the marine waters.

Chinook salmon spawn in rivers and larger streams after spending several years in the marine environment. Chum salmon most often spawn in the lower reaches of streams and frequently within the tidal zone. Chinook salmon rear in freshwater streams for up to one year before migrating to salt water as smolts, whereas juvenile chum salmon migrate to sea soon after hatching. Chinook salmon typically spend 3 to 5 years in the marine environment, while most chum salmon spend 3 to 4 years before returning to their natal streams to spawn. Juvenile salmon rear in near shore marine waters then move to deeper waters when they mature.

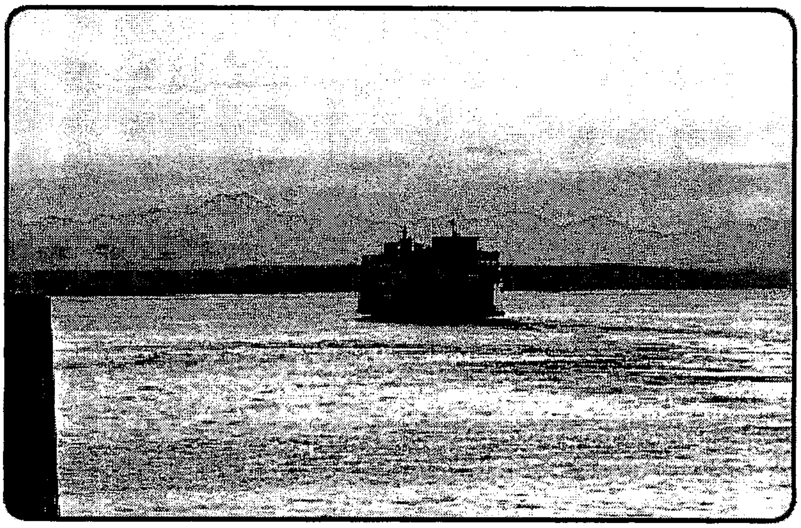


Adult Bull Trout

Essential Fish Habitat (EFH) which includes habitat that supports groundfish, coastal pleagics, and Pacific salmon is protected under the Magnuson Stevens Act (http://www.pcouncil.org/facts/habitat.pdf). Within Puget Sound, EFH includes habitat that supports numerous groundfish species and Chinook, coho (*O. kisutch*), and pink (*O. gorbuscha*) salmon, which covers virtually all of Puget Sound.

WSDOT In-Water Work

Within Puget Sound, the Washington Department of Transportation (WSDOT) operates a ferry system for the transport of automobiles and passengers across the many waterways within the Sound. The Washington State Ferry system currently services 10 routes from 20 terminals supported by a fleet of 29 vessels (http://www.wsdot.wa.gov/ferries/index.cfm). WSDOT also maintains thirty-seven bridges over marine waters and many miles of state highway that boarder Puget Sound.



Washington State Ferry in Puget Sound

WSDOT's repair and maintenance of these facilities often requires work within Puget Sound's waters. Among these activities, pile driving is often a necessary component of WSDOT's facility repair and maintenance. Similar to the above water effects, in-water pile driving generates a high level of noise (acoustic pressure) impulses capable of traveling considerable distance from the source. However, the acoustic pressure generated from pile driving under water has the potential of inflicting physical damage to aquatic organisms. This is of particular concern to WSDOT given the number of protected species that occur in proximity to their many facilities located throughout Puget Sound.

APPENDIX E: Washington State Department of Transportation (WSDOT) Problem Statement and Goals

Prepared by
Washington State Department of Transportation

Pile Driving Workshop
April 29, 2004

- WSDOT Problem Statement
- WSDOT Research Goals
- WSDOT Workshop Goals

Problem Statement

Impact driving of large steel piles generates underwater sound that may have adverse effects on salmonids, other fish species, marine mammals and diving sea birds. While fish kills have been documented at several pile driving sites at ferry terminals in Washington State, bridge construction sites in California and at the Port of Vancouver, very little information is available to allow transportation and regulatory agencies to accurately predict impact levels that will occur during a pile driving project. It is also unclear what the appropriate methods are to avoid or reduce the impacts. Since there is a lack of scientifically valid information, regulatory agencies must rely on conservative interpretations of the available data, which may not directly correlate to the impacts caused by pile driving, to protect species under their jurisdiction. This conservative approach has resulted in increased project costs and delays while the benefit to protected species is unknown. There is a real need to obtain scientifically valid information on the effects of pile driving on salmonids and other species of interest.

Prepared April 2004 by the Washington State Department of Transportation and Battelle Memorial Institute
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Research Goals

Currently our Research Goals are focused on the impacts of pile driving in and adjacent to marine waters on salmon and physoclistous species. We recognize that impacts to diving birds and impacts to fish in freshwater are also areas that have major informational gaps. Goals include:

- Identify the characteristics of sound impacts that WSDOT projects, which occur in or adjacent to marine waters, have or potentially have on salmonids and other species of interest.
- Identify the necessary conditions for barotrauma of salmonids and physoclistous species (e.g. hammer energy, substrate, duration of exposure, etc.).
- Investigate the effect of pile driving sound on the inner ear of salmonids or physoclistous species (hearing and vestibular senses).
- Identify methods that will eliminate or significantly reduce the level and/or characteristic of sound propagated away from piles.
- Determine the bioeffect radius for selected species of pile driving as a function of pile driving and biological variables.
- Investigate the behavioral response of salmonids and physoclistous species to mitigated and unmitigated pile driving sounds.

Prepared April 2004 by the Washington State Department of Transportation and Battelle Memorial Institute
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Workshop Goals

1. Evaluate the Research Strawman Outline.
2. Review the research program objectives for completeness.
3. Determine the type of information each approach will provide and evaluate the utility of the information to address the problem as described in the Problem Statement.
4. Estimate the time for completion (e.g., field seasons) and relative cost for selected approaches.
5. Assess the experimental risks (e.g., probability of successfully providing desired information within estimated time for completion and relative costs) of selected approaches.
6. Prioritize the order in which the research objectives should be investigated.
7. Identify the "best" approaches for each objective in their order of priority (Research objectives 1-5).

Prepared April 2004 by the Washington State Department of Transportation and Battelle Memorial Institute
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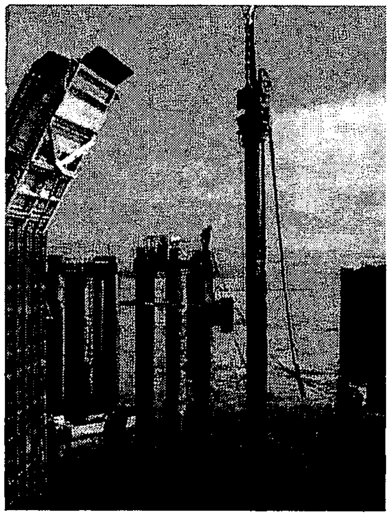
APPENDIX F: Washington State Ferries Programs, Projects, and Schedules

Prepared by
Washington State Ferries

WSF Pile Driving Workshop



Presented by Joel Colby

April 29, 2004

Prepared April 2004 by Washington State Ferries
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Outline

1. Capital Program
2. Major Capital Projects
3. Major Preservation Projects
4. Typical Project Schedule
5. Questions

Prepared April 2004 by Washington State Ferries
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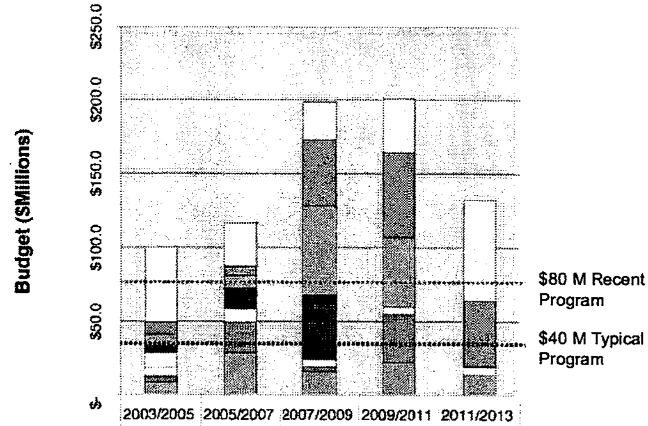
Terminal Engineering Major Projects



	2003/2005	2005/2007	2007/2009	2009/2011	2011/2013
Preservation	$50.6	$28.8	$25.4	$36.7	$68.4
Seattle	$8.8	$6.7	$45.1	$57.1	$45.4
Mukilteo	$7.6	$8.5	$60.7	$47.2	$-
Keystone/PT	$4.5	$13.9	$43.2	$-	$-
Edmonds	$10.0	$-	$-	$-	$-
Eagle Harb	$6.2	$8.8	$5.0	$5.0	$5.0
Bainbridge	$4.0	$21.0	$3.7	$32.5	$-
Anacortes	$8.3	$28.6	$15.6	$22.1	$13.8

Prepared April 2004 by Washington State Ferries
06_WSF_Colby.ppt

Washington State Ferries

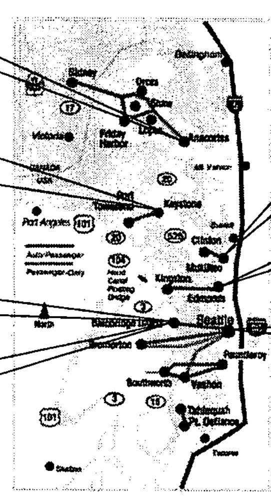
UPCOMING MAJOR TERMINAL CONSTRUCTION PROJECTS

ANACORTES
Terminal upgrade and multimodal expansion
$88 Million, 2005-2013

KEYSTONE/PORT TOWNSEND
Enhancement/relocation of Keystone terminal and reconstruction of Port Townsend terminal
$61 Million, 2005-2008

BAINBRIDGE ISLAND
Terminal upgrade and multi-modal expansion
$61.4 Million, 2007-2011

EAGLE HARBOR
WSF Maintenance facility rehabilitation/relocation
$30 Million, 2005-2007



MUKILTEO
Terminal relocation and multi-modal expansion
$131 Million, 2008-2010

EDMONDS
Terminal relocation and multi-modal expansion
$163.2 Million, 2006-2009

SEATTLE
Terminal upgrade and multi-modal expansion
$157 Million, 2008-2012

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06_WSF_Colby.ppt

Washington State Ferries

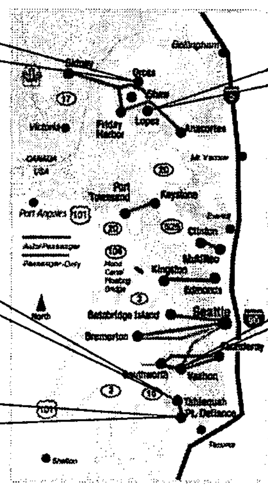
UPCOMING MAJOR PRESERVATION PROJECTS

ORCAS
- Dolphin Replacement
  $7.7 Million, 2011-2015
- Trestle Replacement
  $2.6 Million, 2011-2015

LOPEZ
- Dolphin Replacement
  $3.5 Million, 2005-2007
- Trestle Replacement
  $2.2 Million, 2009-2013

TAHLEQUAH
- Trestle Replacement
  $5.2 Million, 2005-2007

VASHON
- Dolphin Replacement
  $8.1 Million, 2007-2009
- Trestle Preservation
  $19.2 Million, 2011-2015



POINT DEFIANCE
- Trestle Replacement
  $5.4 Million, 2005-2007
- Dolphin Replacement
  $3.5 Million, 2013-2015

Prepared April 2004 by Washington State Ferries
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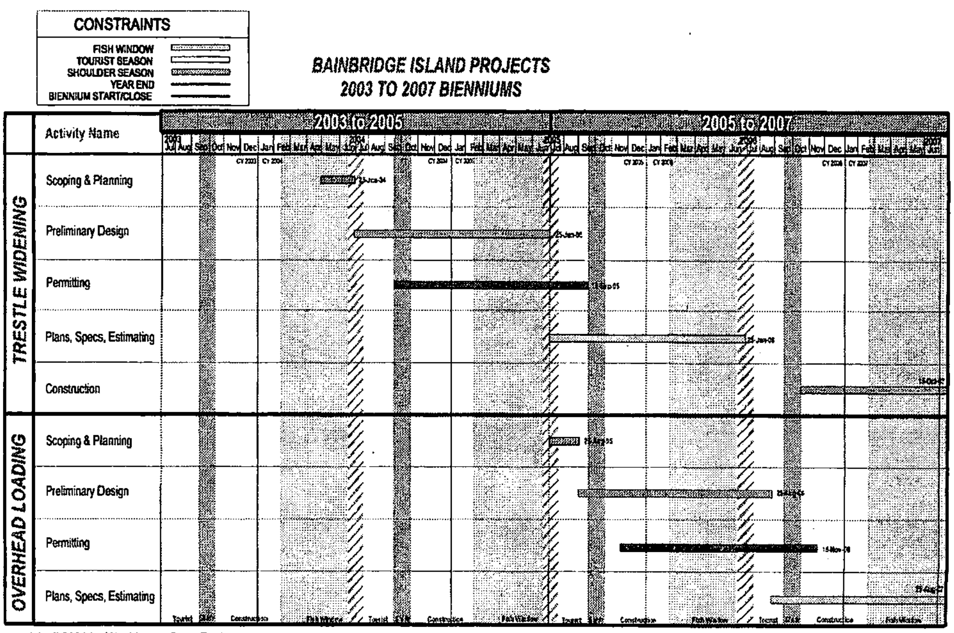
Typical Project Schedule



Prepared April 2004 by Washington State Ferries
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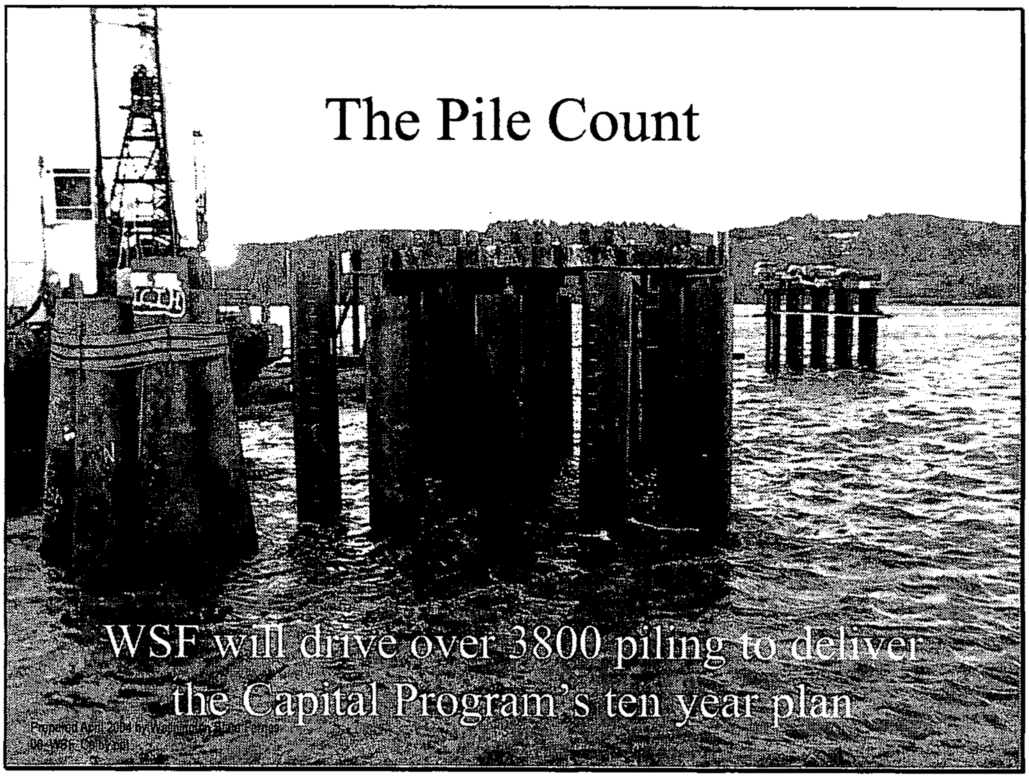
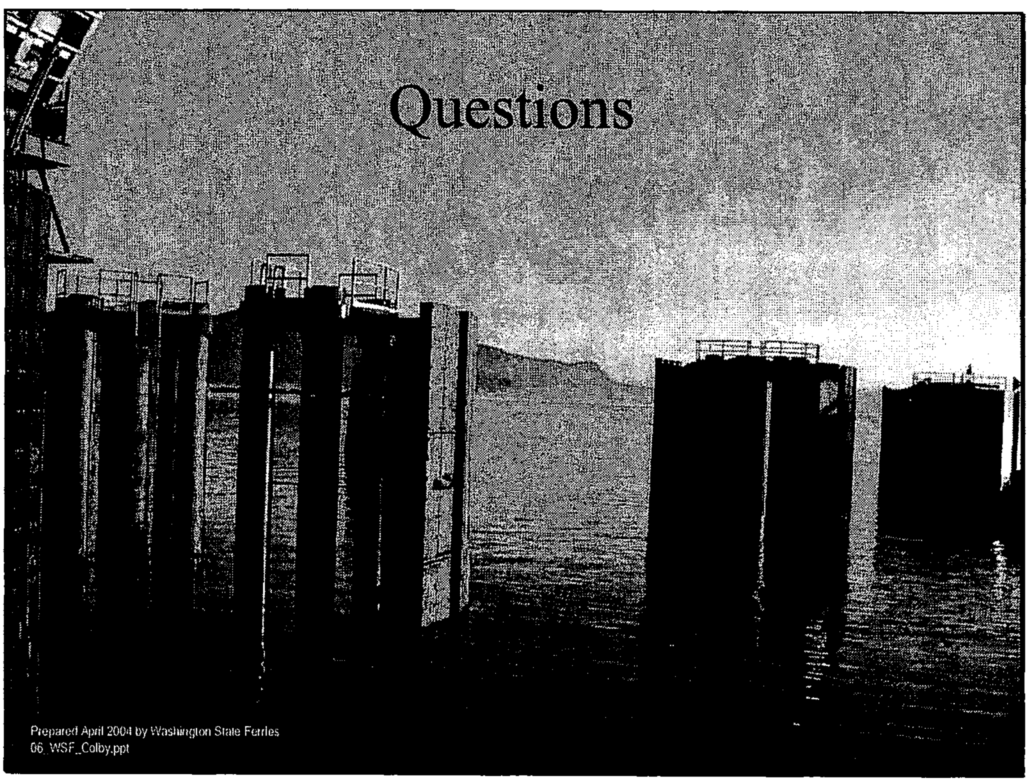

The Pile Count
WSF will drive over 3800 piling to deliver
the Capital Program's ten year plan


Questions
Prepared April 2004 by Washington State Ferries
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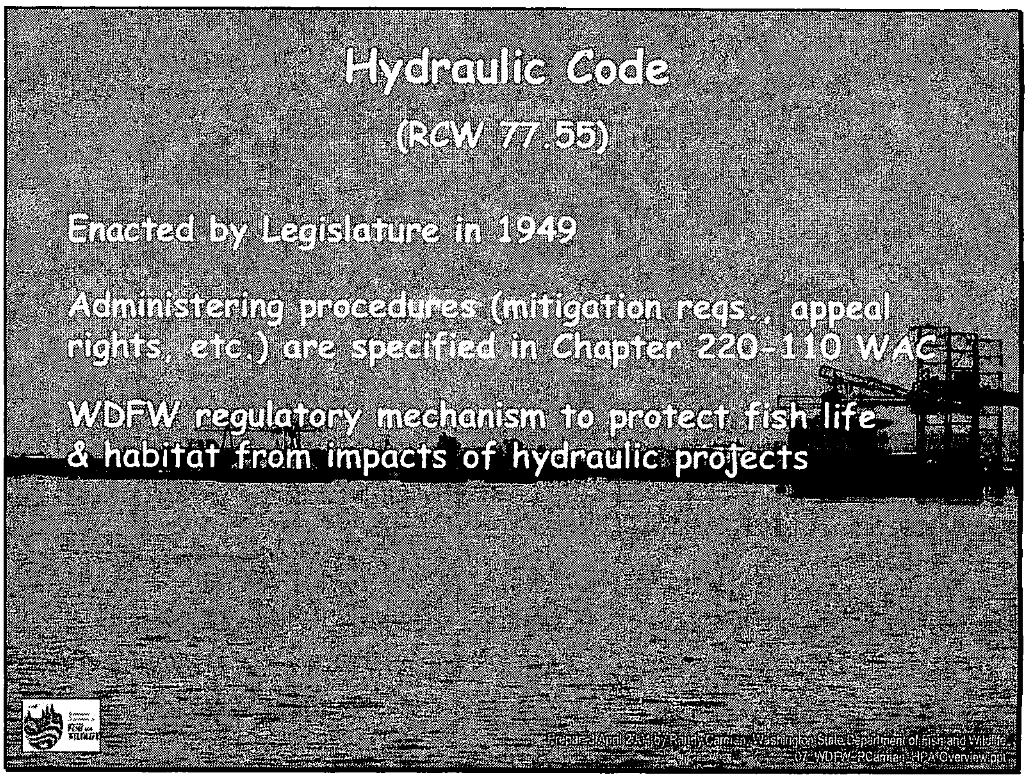
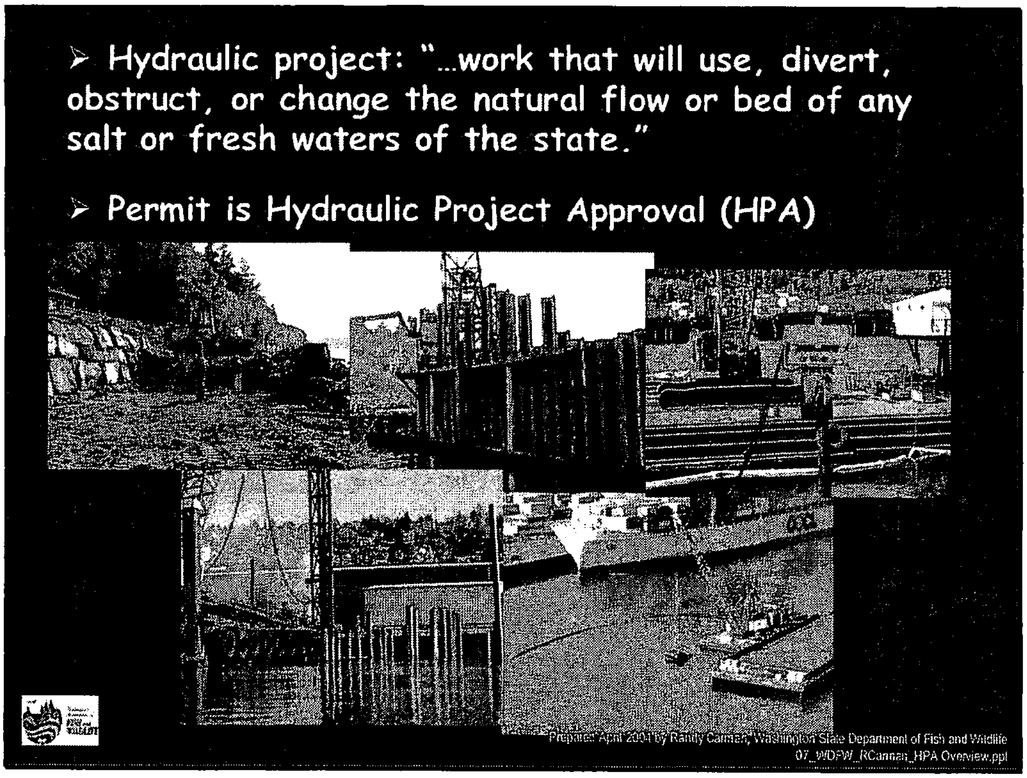
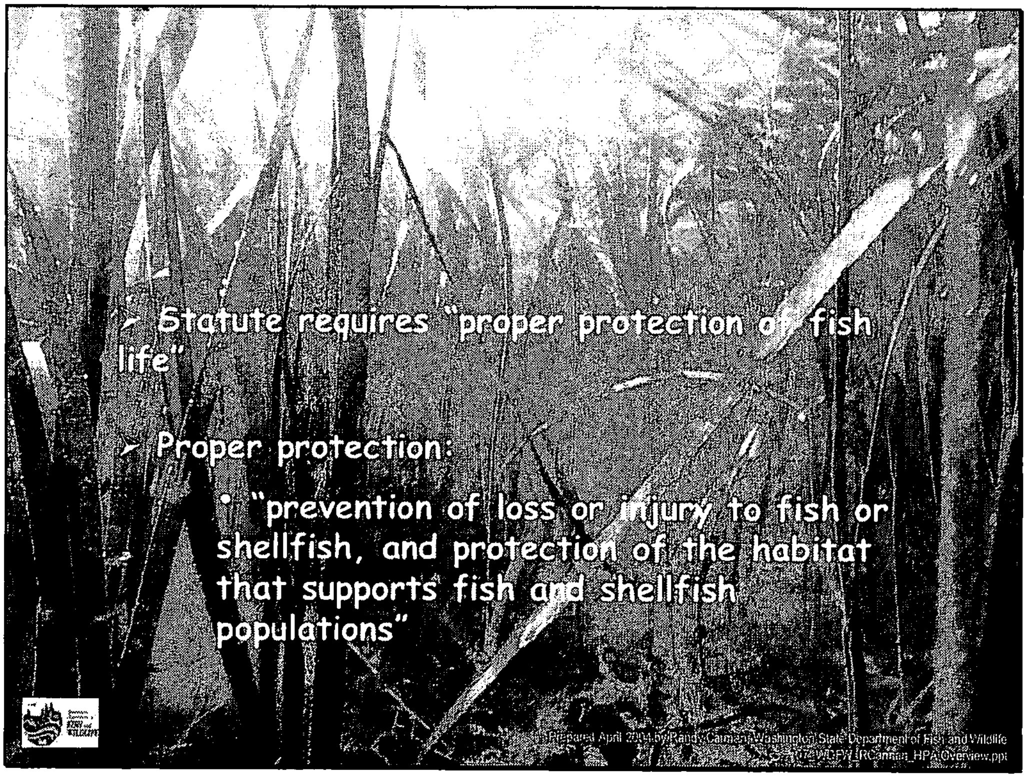
APPENDIX G: Hydraulic Project Approvals – Overview

Prepared by the
Washington Department of Fish and Wildlife

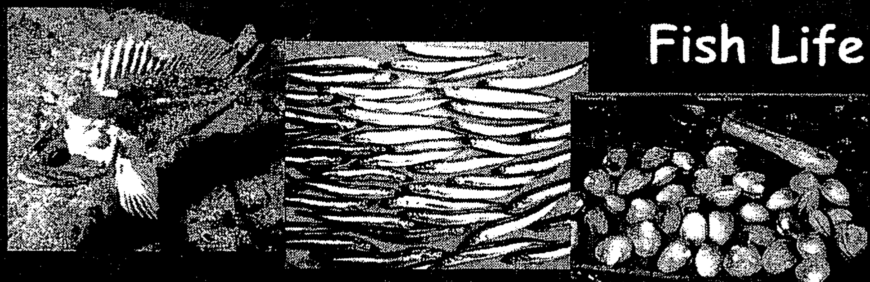

Hydraulic Project Approvals
WSDOT Pile Driving Workshop
April 29, 2004
Washington Department of FISH and WILDLIFE
Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife
07_WDFW_RCarman_HPA Overview.ppt


Hydraulic Code
(RCW 77.55)
Enacted by Legislature in 1949
Administering procedures (mitigation reqs., appeal rights, etc.) are specified in Chapter 220-110 WAC
WDFW regulatory mechanism to protect fish life & habitat from impacts of hydraulic projects


➢ Hydraulic project: "...work that will use, divert, obstruct, or change the natural flow or bed of any salt or fresh waters of the state."
➢ Permit is Hydraulic Project Approval (HPA)
Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife
07_WDFW_RCarman_HPA Overview.ppt


➢ Statute requires "proper protection of fish life"
➢ Proper protection:
• "prevention of loss or injury to fish or shellfish, and protection of the habitat that supports fish and shellfish populations"
Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife
07_WDFW_RCarman_HPA Overview.ppt

Fish Life

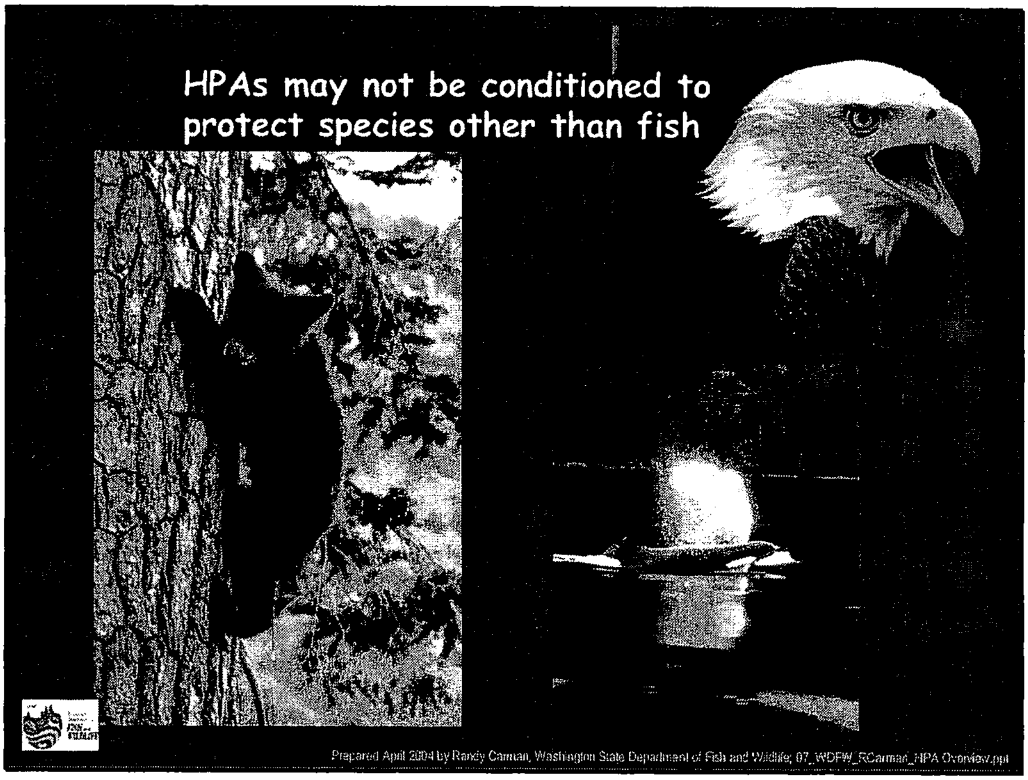


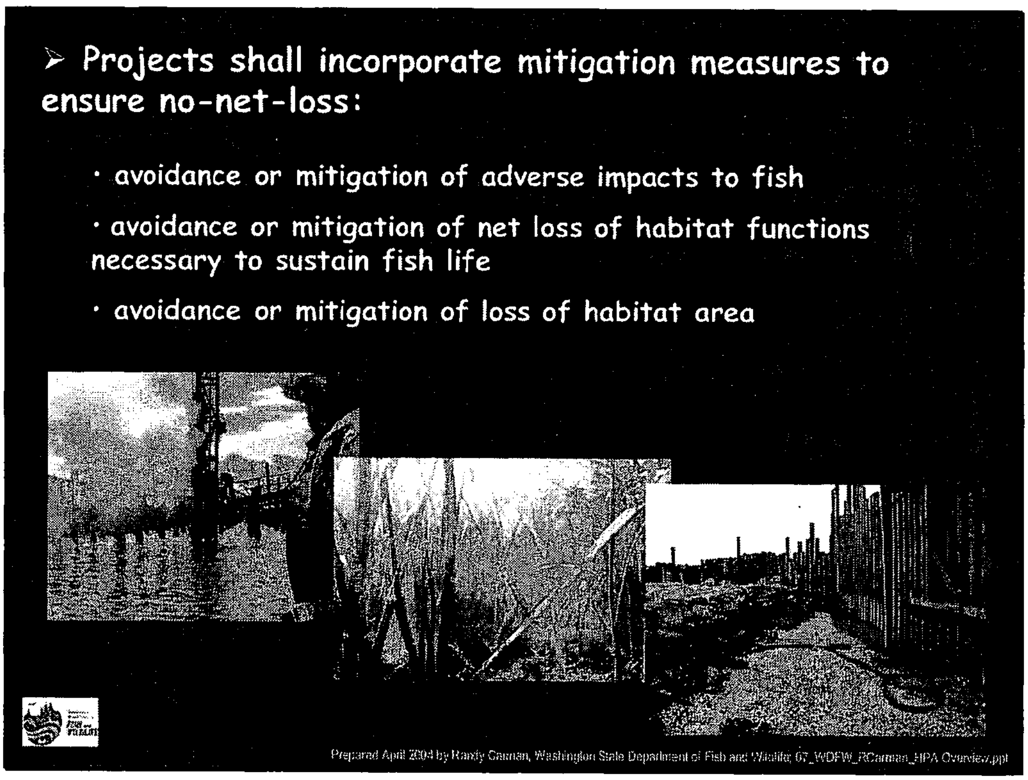
"all fish species, including but not limited to food fish, shellfish, game fish, and other non-classified fish species and all stages of development of those species"

Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife; 07_WDFW_RCarman_HPA Overview.ppt

- Includes all fish life in Washington whether:
  - native or not,
  - wild or hatchery, or
  - listed as threatened or endangered (federal or state)

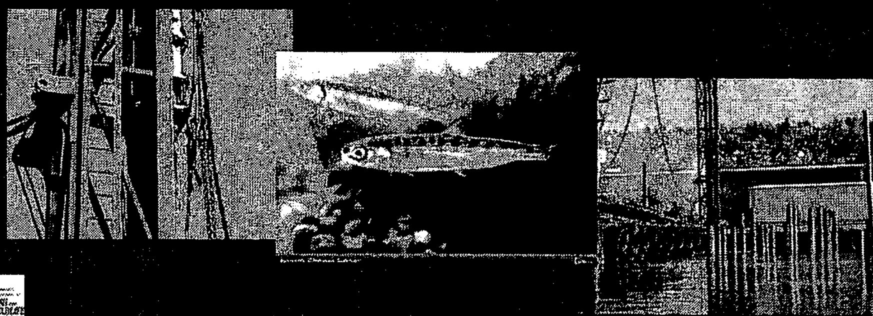
Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife; 07_WDFW_RCarman_HPA Overview.ppt


HPAs may not be conditioned to protect species other than fish
Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife; 07_WDFW_RCarman_HPA Overview.ppt


➢ Projects shall incorporate mitigation measures to ensure no-net-loss:
• avoidance or mitigation of adverse impacts to fish
• avoidance or mitigation of net loss of habitat functions necessary to sustain fish life
• avoidance or mitigation of loss of habitat area
Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife; 07_WDFW_RCarman_HPA Overview.ppt

- Mortalities associated with steel pile driving necessitated inclusion of avoidance and minimization measures in HPAs for impact driving in Puget Sound

- WDFW worked in concert with NOAA & USFWS to review existing information and develop consistent & appropriate mitigation measures



Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife; 07_WDFW_RCarman_HPA Overview.ppt

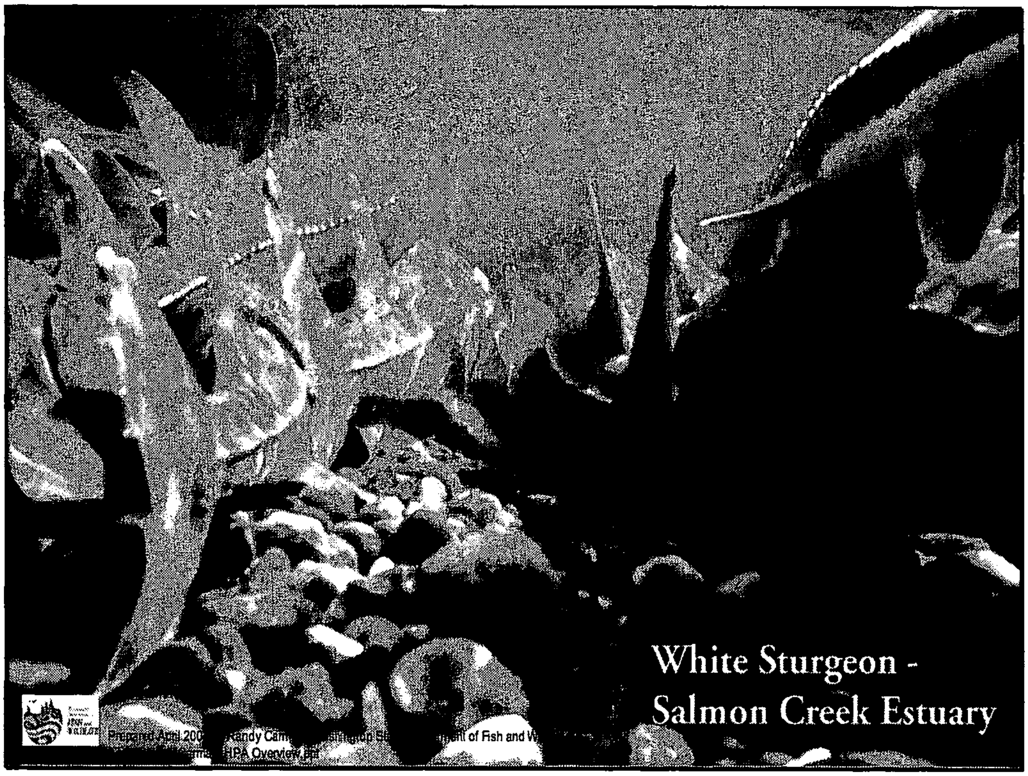
- Overall intent is to minimize risk to fish based on use of best available data

- High uncertainty of impacts increases level of potential risk

- In the face of uncertainty WDFW must apply Precautionary Principle approach

- New data from research should decrease uncertainty

Prepared April 2004 by Randy Carman, Washington State Department of Fish and Wildlife; 07_WDFW_RCarman_HPA Overview.ppt


White Sturgeon -
Salmon Creek Estuary

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APPENDIX H: Pile Driving - USFWS & NOAA Fisheries Concerns Regarding Protected Resources

Prepared by the
U.S. Fish and Wildlife Service and NOAA Fisheries

Pile Driving: USFWS & NOAA Fisheries Concerns Regarding Protected Resources

April 29, 2004, WSDOT Pile Driving Workshop
Seattle, Washington

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service
08_USFWS_JQuan.ppt

U.S. Fish and Wildlife Statutory Responsibilities

- Endangered Species Act (ESA)
- Migratory Bird Treaty Act
- Fish and Wildlife Coordination Act

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

ESA - Species of Concern
Bull Trout (*Salvelinus confluentus*)

- Adults and subadults most likely exposed to WSDOT pile driving projects.
- Length 150mm to 800mm
- Weight 0.03 kg to 5kg

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

ESA - Species of Concern
Marbled Murrelet (*Brachyrampus marmoratus*)

- Adults and juveniles most likely exposed to WSDOT pile driving projects.
- 0.22 kg (adults birds)

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

Avian Species and Underwater Impacts

- Underwater Explosions
  - Yelverton *et al.* 1973, 1981
  - Richardson *et al.* 1995
- Common to the fish, bird, and mammal species exposed to the blasts were injuries to gas/air filled organs and eardrums.

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

Underwater-blast Criteria for Birds Diving Beneath the Water's Surface

(Yelverton *et al.* 1981, Richardson *et al.* 1995)

Impulse, Pa•sec	Criteria
310	50% mortality - Survivors seriously injured and might not survive on their own.
248	1% mortality - Most survivors had moderate blast injuries and should survive on their own.
138	No mortality - Slight blast injuries and a low probability of eardrum rupture.
69	Low probability of trivial lung injuries and no eardrum rupture.
41	Safe level. No injuries.

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

	Weight (kg)	Impulse (Pa•sec) No Injury	1% Mortality	50% Mortality
Juvenile Chum Salmon	0.005	12	34	62
Anchovy	0.006	13	36	66
Juvenile Chinook Salmon	0.01	16	43	78
Sardine	0.06	28	76	138
Filefish	0.1	32	89	162
Rats	0.2	26	*60*	*90*
Adult Marbled Murrelet	0.22	?	?	?
Chub Mackerel	0.3	46	127	230
Blackthroat seaperch	0.4	51	139	253
Mallard	1.16 (0.89-1.49)	41	248	310
Rouen	2.3 (1.92-2.84)	41	248	310
Yellow tail	3.2	98	270	491
Spanish mackeral	3.2	98	270	491
Adult Chum Salmon	5	113	312	567
Adult Chinook Salmon	10	142	389	708

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

ESA Thresholds

"May Affect, not likely to Adversely Affect" (NLAA)

- **Insignificant** – relates to the size of the impact
  ...Would not be able to meaningfully measure, detect, or evaluate....

- **Discountable** - are extremely unlikely to occur
  ...Would not expect discountable effects to occur...

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

ESA Thresholds

"May Affect, Likely to Adversely Affect" (LAA)

Harm - includes significant habitat modification or degradation that results in death or injury to listed species by significantly *impairing essential behavioral patterns*, including breeding, feeding, or sheltering.

Harass - intentional or negligent actions that create the likelihood of injury to listed species to such an extent as to significantly *disrupt normal behavior patterns* which include, but are not limited to, breeding, feeding, or sheltering.

Prepared April 2004 by Jennifer Quan, US Fish and Wildlife Service; 08_USFWS_JQuan.ppt

APPENDIX I: NOAA Fisheries Statutory Responsibilities

Prepared by
NOAA Fisheries

NOAA Fisheries Statutory Responsibilities

- Endangered Species Act (ESA)
  - PS chinook
  - Hood Canal summer-run chum
- Magnuson-Stevens Fishery Conservation and Management Act (MSA)
  - Essential Fish Habitat (EFH)
  - Conservation *recommendations*

Prepared April 2004 by John Stadler, NOAA Fisheries
09_NMFS_JStadler.ppt

What is EFH?

Definition (50 CFR 600.10)

"Essential fish habitat means those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity."

Includes chemical, *physical* and biological characteristics of the habitat.

- Prey species

What Species of Fish Have EFH?

- Only those species that are managed under a Federal Fisheries Management Plan (FMP)
- FMPs in the Pacific Northwest (PFMC):
  - Groundfishes – rockfishes, flatfishes, etc.
  - Coastal Pelagics – anchovies, sardines, etc.
  - Pacific Salmon – chinook, coho, PS pinks

Why is pile driving a concern to NOAA Fisheries?

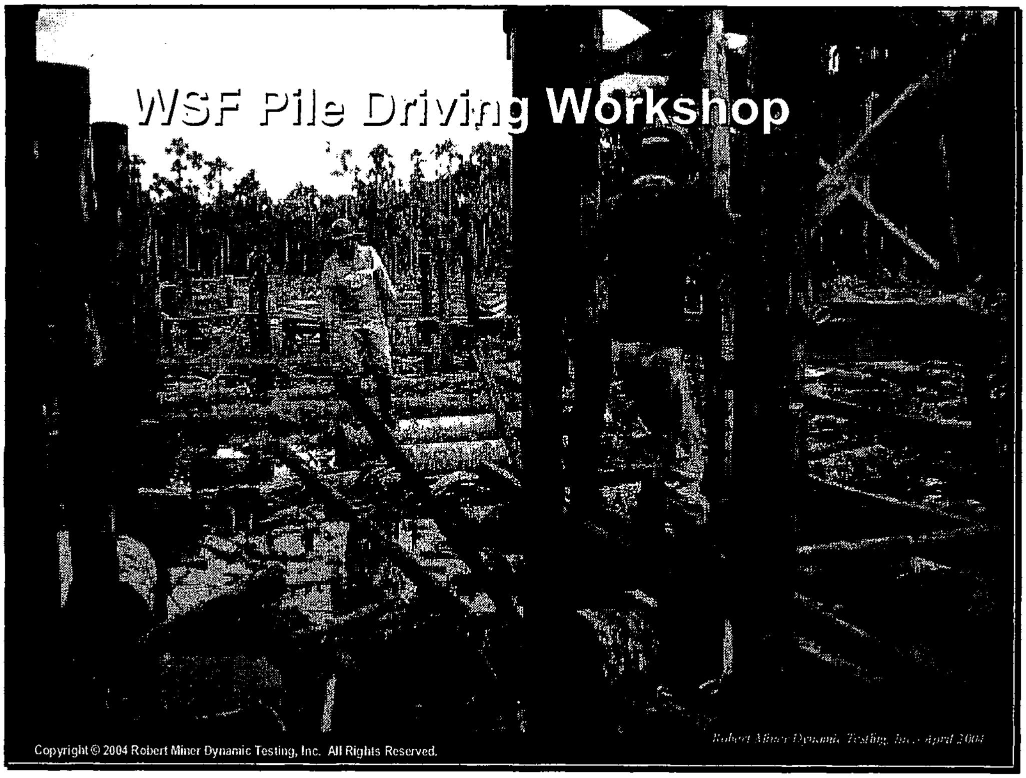
- Direct effects to ESA-listed fishes and habitat
- Effects to the physical properties of EFH
- Has resulted in deaths of many species covered by ESA and EFH
  - Salmonids – ESA and EFH
  - Rockfishes – EFH
  - Anchovies – EFH, prey for salmonids
  - Sardines – EFH, prey for salmonids
  - Herring – Prey species for ESA and EFH
  - Smelt – Prey species for ESA and EFH
  - Surfperches – Prey species for EFH

Resource Agency Needs

1. What characteristics of pile driving sounds are most important?
2. What are the thresholds for these characteristics?
    - Physical injury and behavioral disruption
        - Cumulative effects
3. What are most useful characteristics?
    - Easily measurable
    - Protective of species of concern
4. How effective are mitigation measures (e.g. bubble curtains)?
    a) Sufficient for NLAA or "No Effect" determination (Services)?
    b) If LAA, how much is "take" reduced?
    c) Sufficient for "Protection of Fish Life" (WDFW)?
5. To raise current thresholds, data must be scientifically sound
    - *Precautionary Principle*

APPENDIX J: An Introduction to the Mechanics of Pile Driving

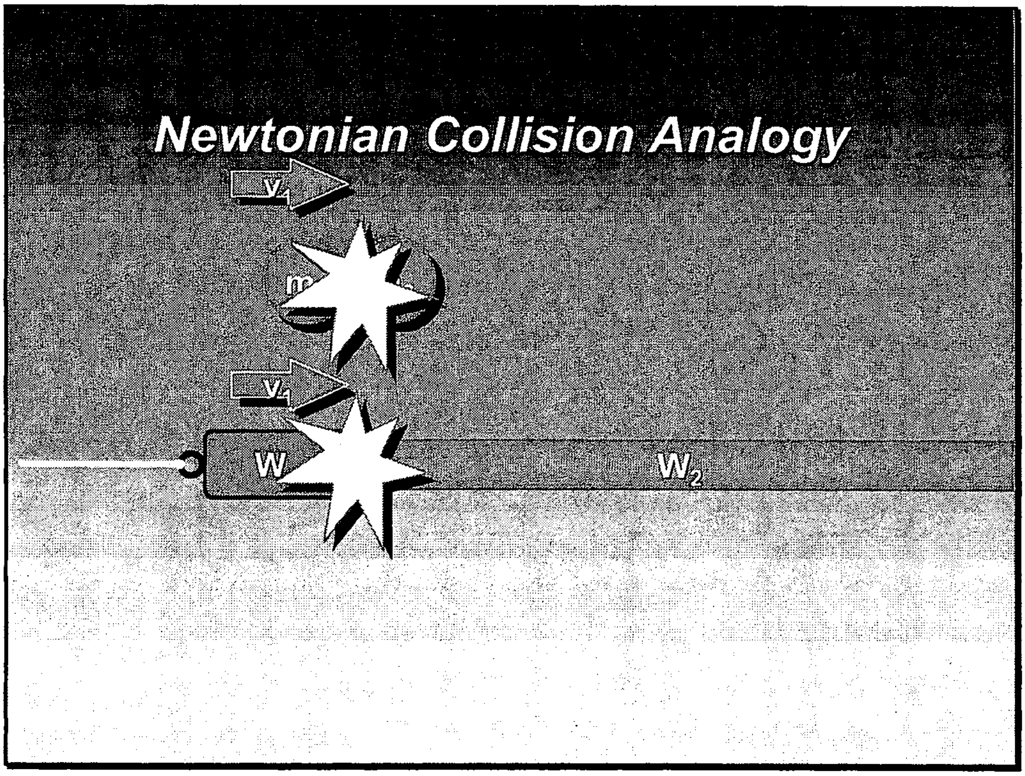
Prepared by
Robert Miner Dynamic Testing, Inc.

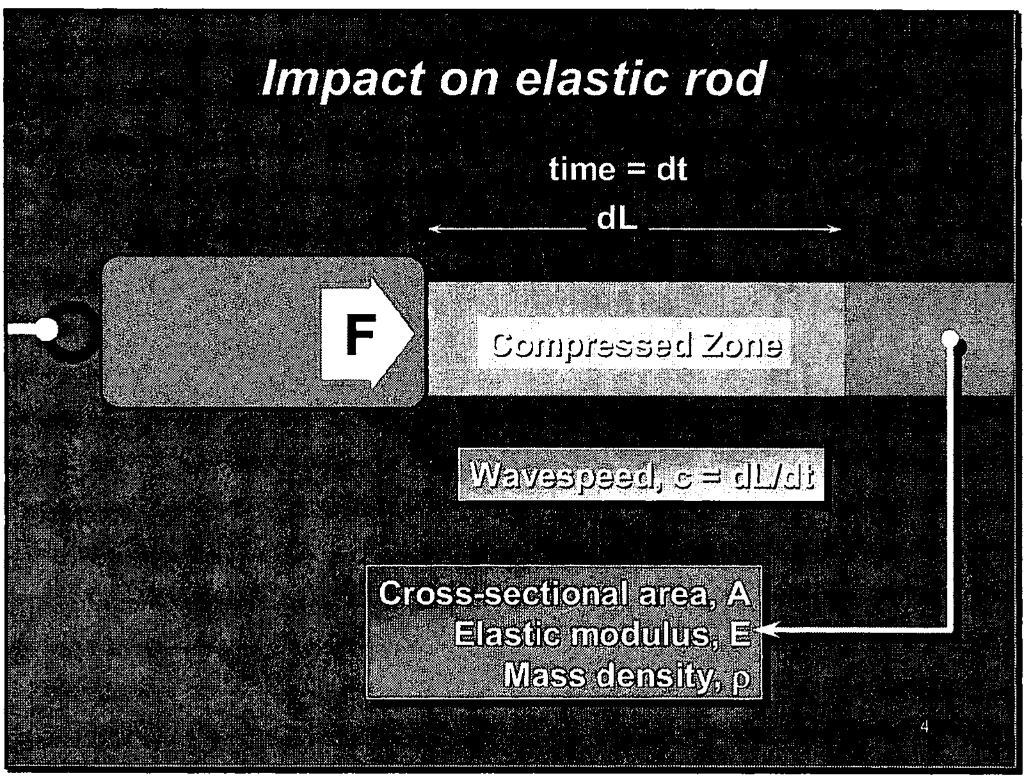


An Introduction to The Mechanics of Pile Driving

- Axial (1D) Wave Propagation
- Axial Strain vs Transverse Strain
- Measurement and Analysis Tools
- Key Parameters Effecting Strain
- Summary

2


Newtonian Collision Analogy
W2

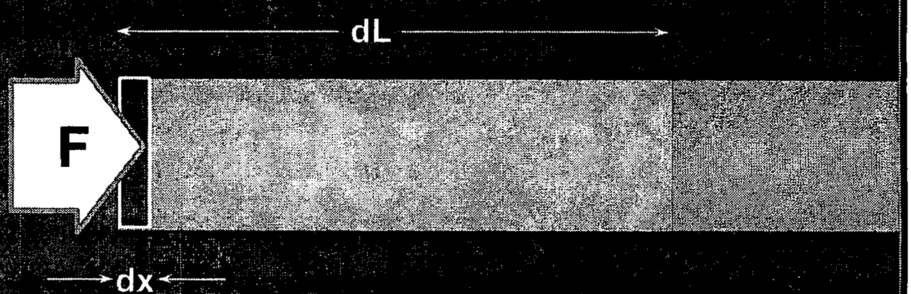

Impact on elastic rod
time = dt
dL
F
Compressed Zone
Wavespeed, c = dL/dt
Cross-sectional area, A
Elastic modulus, E
Mass density, ρ
4

Material Wavespeeds

- Steel 16,800 ft/s
- Concrete Piles 12,000 to 15,000 ft/s
- Timber Piles 11,000 to 14,000 ft/s
- Air approx. 1,100 ft/s
- Water approx. 5,000 ft/s

5

Particle Velocity



6

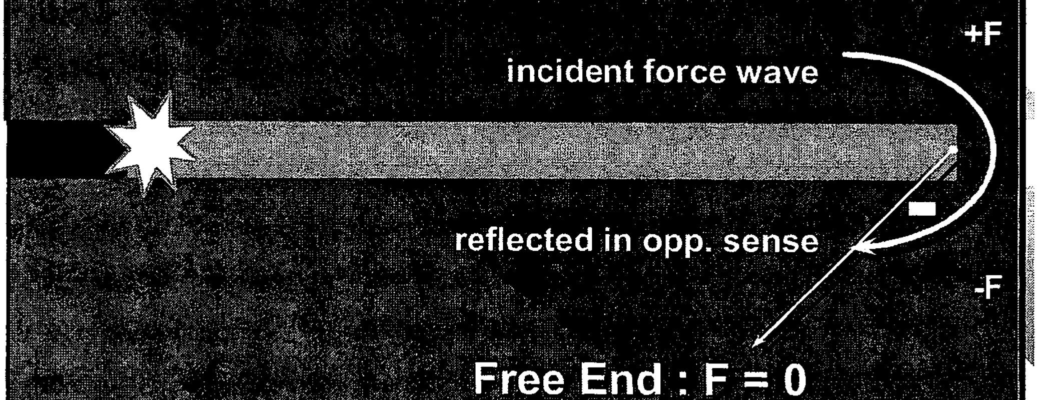
1. *Ram impact causes a Downward Wave.*

2. *A reflection from the pile end, or any other pile discontinuity causes an upward wave.*

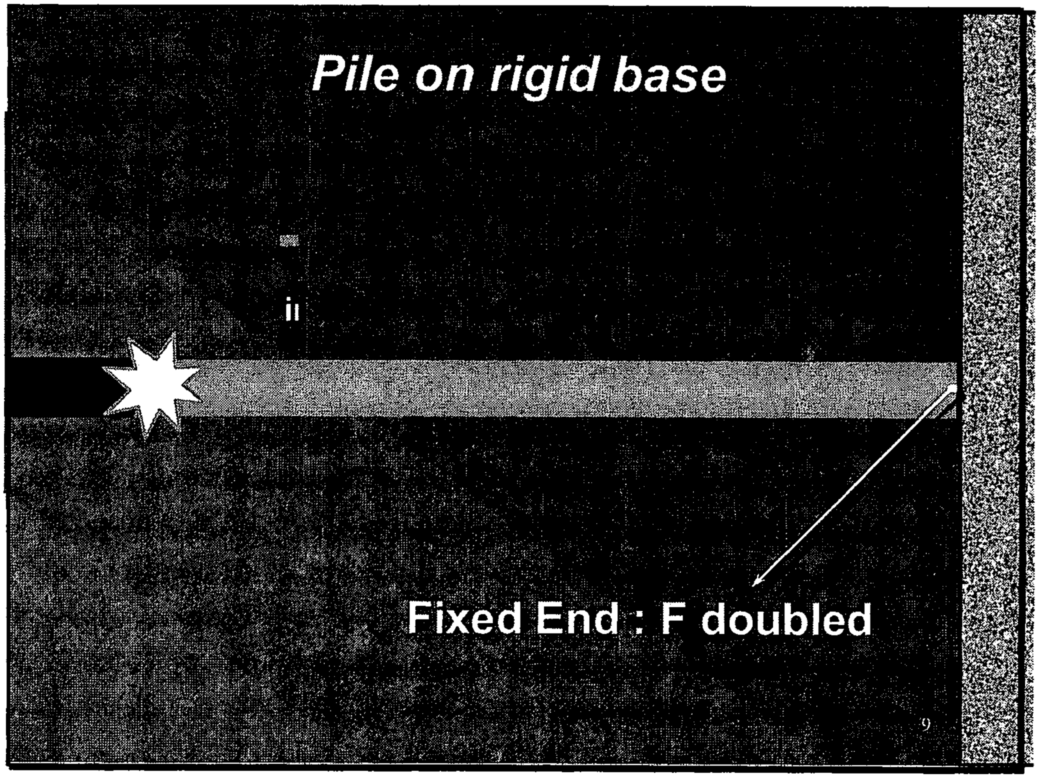
3. *Soil resistance causes an upward wave.*

7

Pile with free end



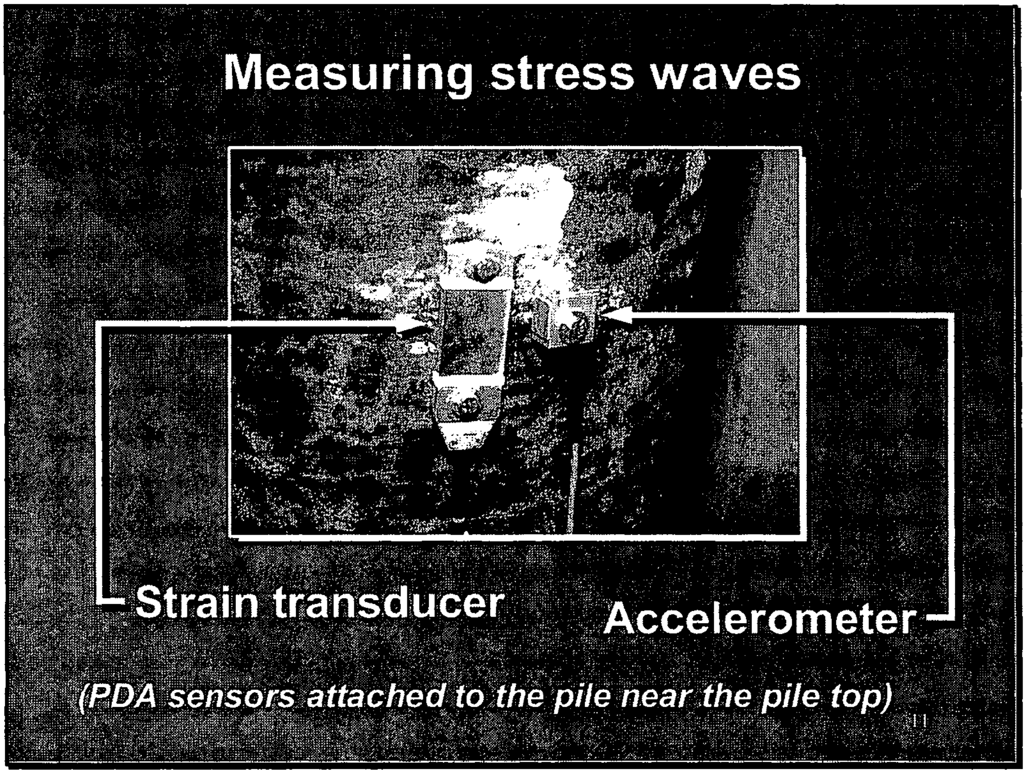
8

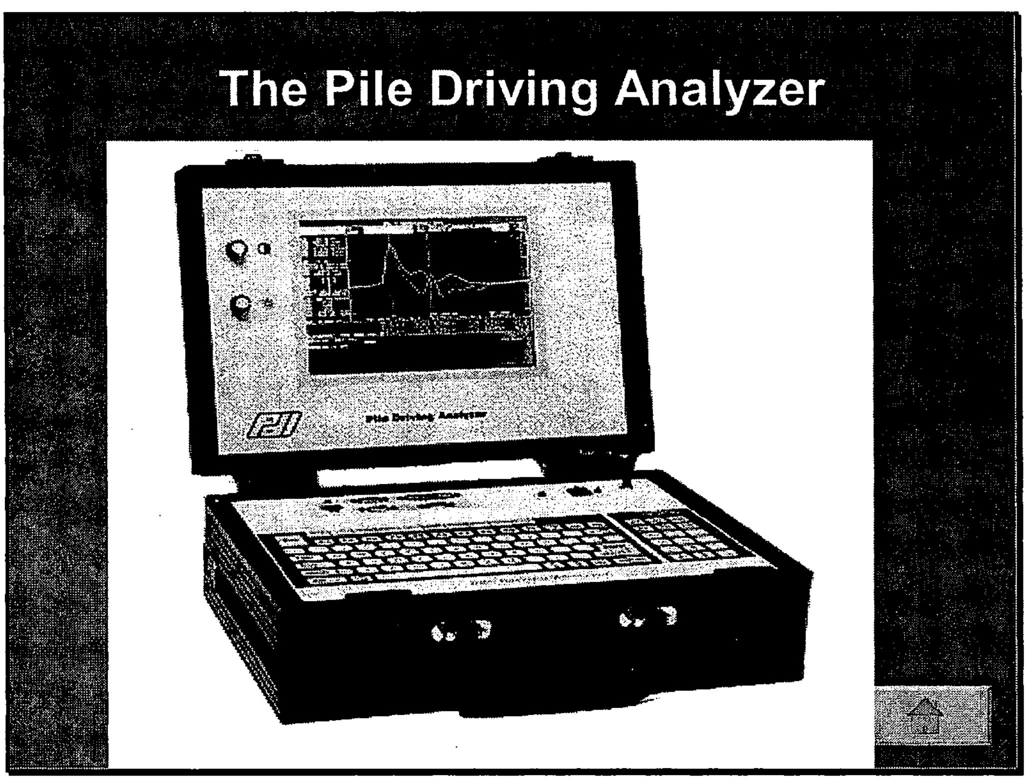


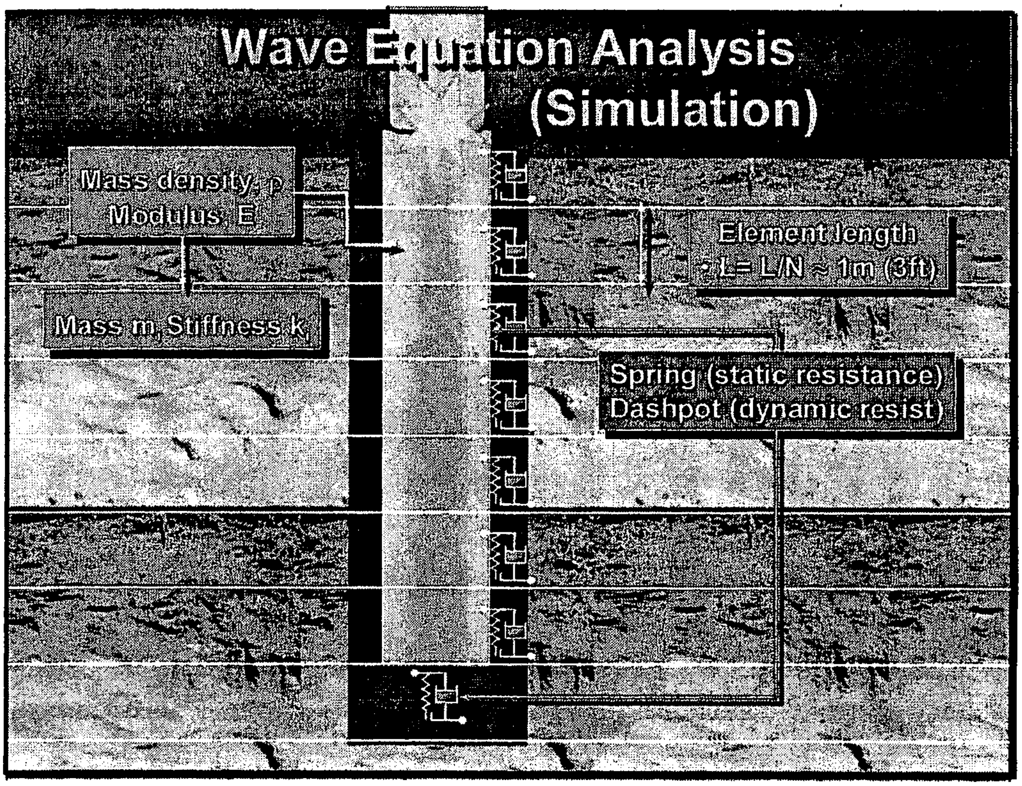
(Poisson's Ratio)

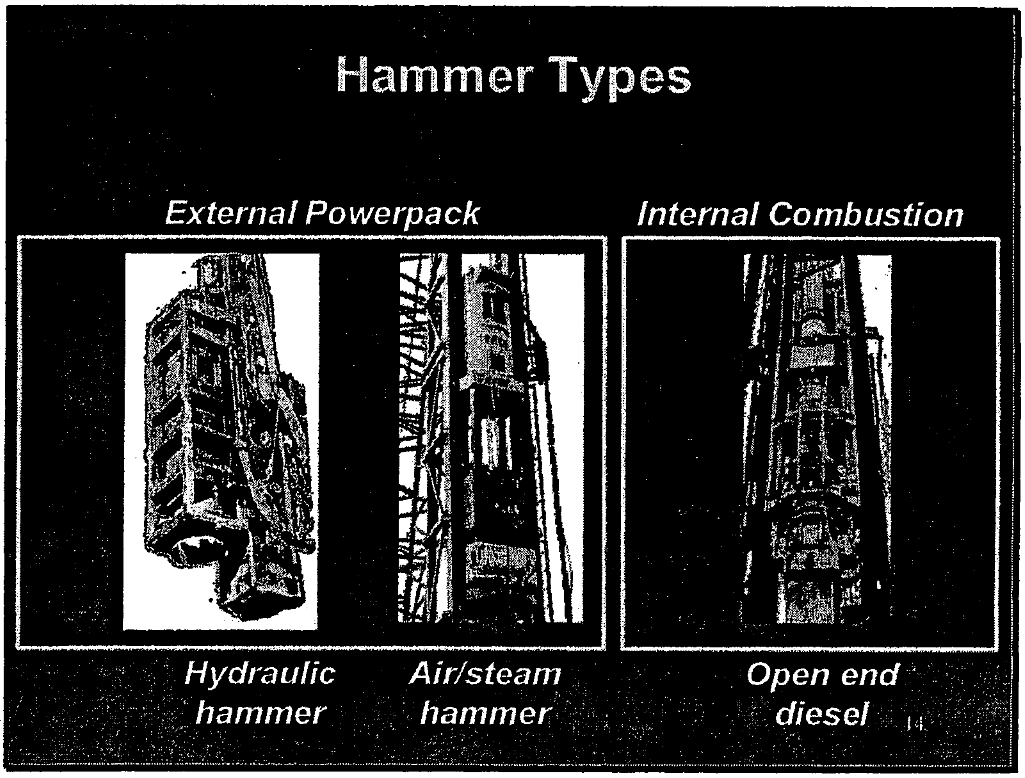
S. D. Poisson – a French mathematician with a fishy name.

An axial force that causes an axial compression will result in a directly proportional lateral expansion.


Measuring stress waves
Strain transducer
Accelerometer
(PDA sensors attached to the pile near the pile top)


The Pile Driving Analyzer


Wave Equation Analysis
(Simulation)
Mass density, ρ
Modulus, E
Mass m, Stiffness k
Element length
L = L/N ~ 1m (3ft)
Spring (static resistance)
Dashpot (dynamic resist)


Hammer Types
External Powerpack
Internal Combustion
Hydraulic hammer
Air/steam hammer
Open end diesel
14

Hammer Energy

Hammers are typically sized by reference to the ram's maximum potential energy.

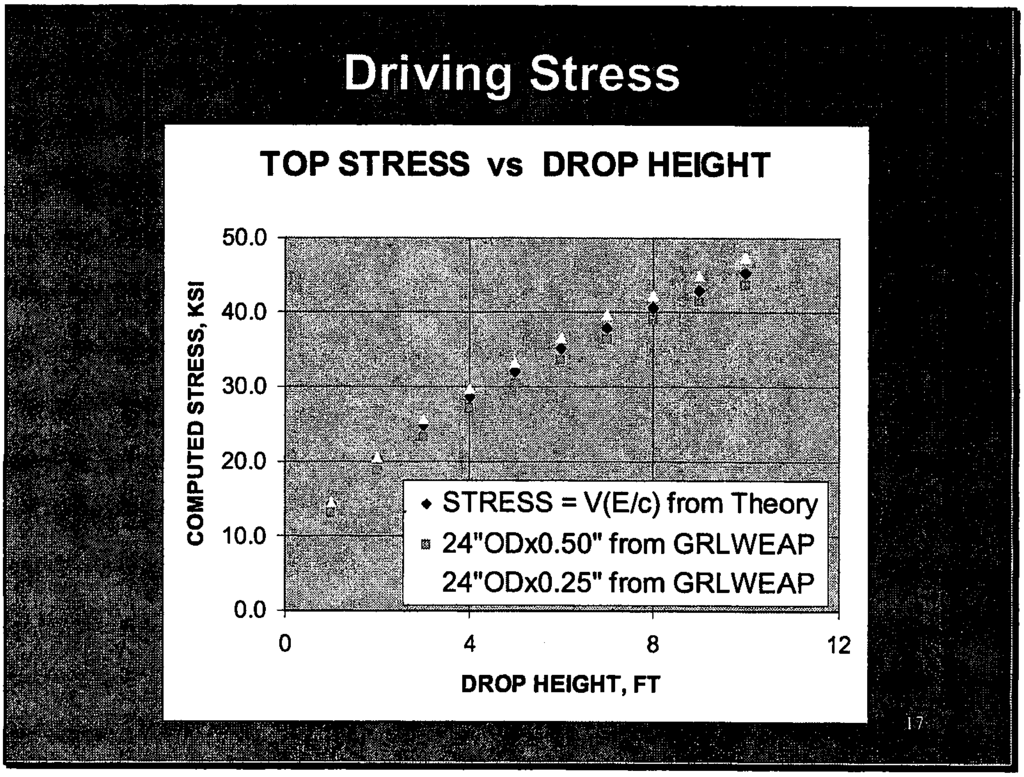
The potential energy is the product of the ram "drop height" and the ram weight.

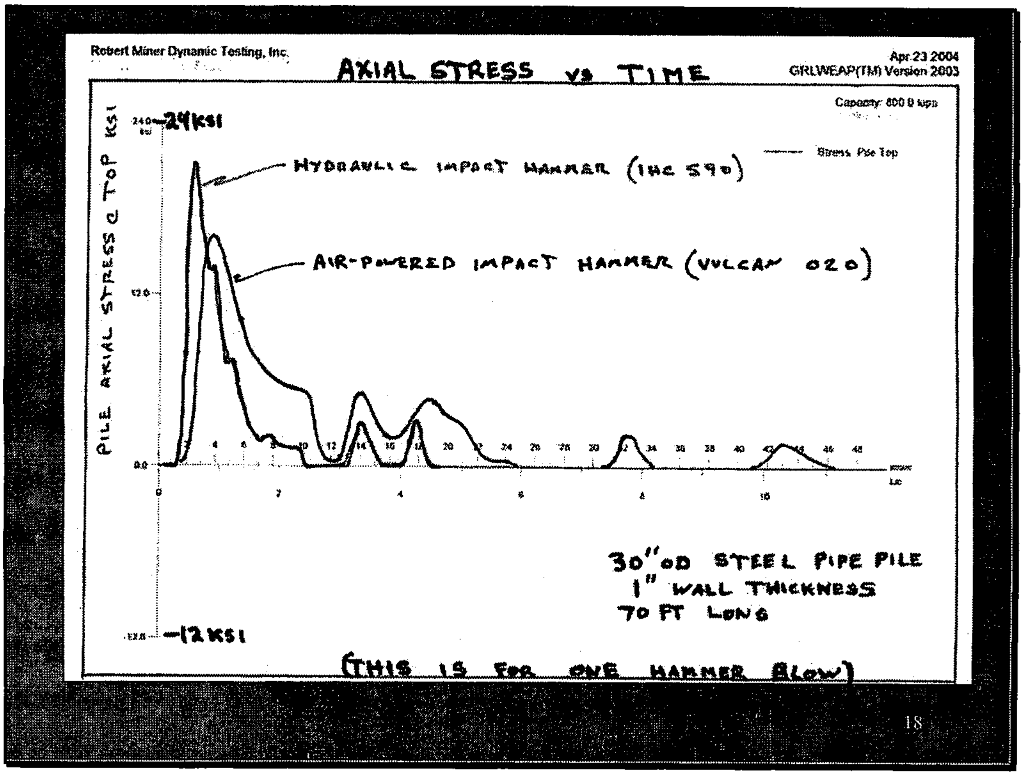
15

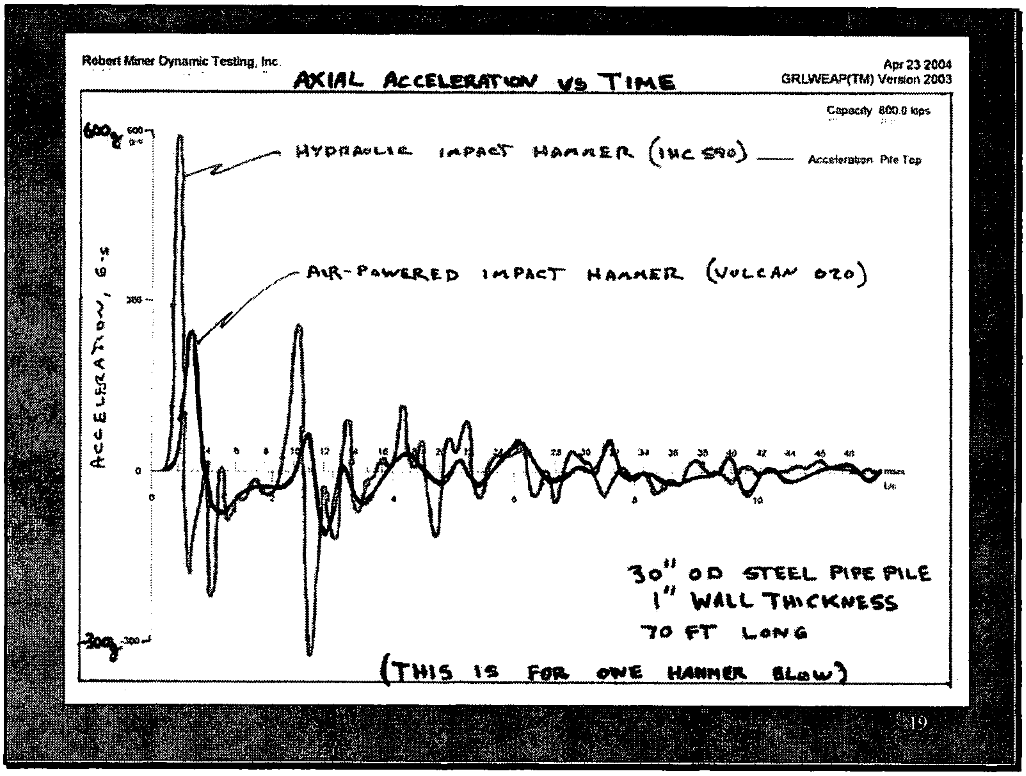
Peak Velocity and Peak Stress

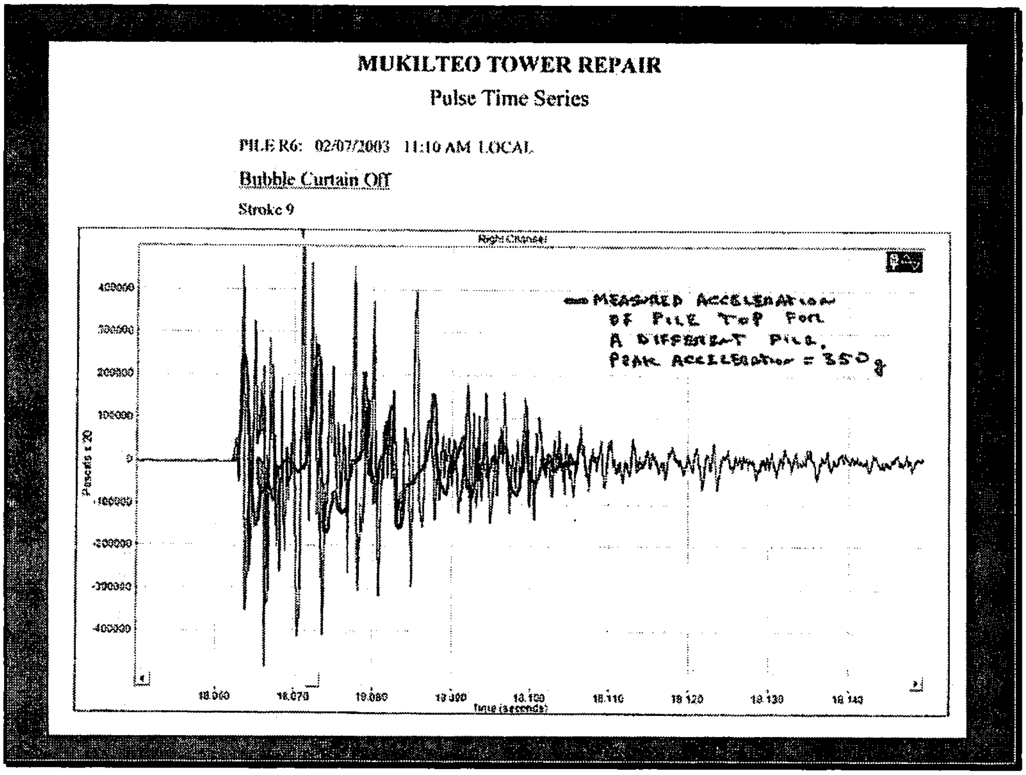
Axial stress, is proportional to particle velocity and pile properties:

16


Driving Stress
TOP STRESS vs DROP HEIGHT
COMPUTED STRESS, KSI
50.0
40.0
30.0
20.0
10.0
0.0
0
4
8
12
DROP HEIGHT, FT
STRESS = V(E/c) from Theory
24"ODx0.50" from GRLWEAP
24"ODx0.25" from GRLWEAP
17


Robert Miner Dynamic Testing, Inc.
AXIAL STRESS vs TIME
Apr 23 2004
GRLWEAP(TM) Version 2003
Capacity: 800.0 kips
Stress, Pile Top
PILE AXIAL STRESS @ TOP KSI
24KSI
HYDRAULIC IMPACT HAMMER (IHC 590)
AIR-POWERED IMPACT HAMMER (VULCAN 020)
-12KSI
30" OD STEEL PIPE PILE
1" WALL THICKNESS
70 FT LONG
(THIS IS FOR ONE HAMMER BLOW)
18


Robert Miner Dynamic Testing, Inc.
AXIAL ACCELERATION VS TIME
Apr 23 2004
GRLWEAP(TM) Version 2003
Capacity 800.0 kips
HYDRAULIC IMPACT HAMMER (IHC S90)
Acceleration Pile Top
AIR-POWERED IMPACT HAMMER (VULCAN 020)
ACCELERATION, G-s
600g
-300g
30" OD STEEL PIPE PILE
1" WALL THICKNESS
70 FT LONG
(THIS IS FOR ONE HAMMER BLOW)
19


MUKILTEO TOWER REPAIR
Pulse Time Series
PILE R6: 02/07/2003 11:10 AM LOCAL
Bubble Curtain Off
Stroke 9
Right Channel
MEASURED ACCELERATION OF PILE TOP FOR A DIFFERENT PILE. PEAK ACCELERATION = 350 g
400000
300000
200000
100000
0
-100000
-200000
-300000
-400000
Pascals x 20
18.060
18.070
18.080
18.090
18.100
18.110
18.120
18.130
18.140
Time (seconds)

Vibratory Hammers

Vibratory hammers operate in a "steady state", typically with 10 to 30 Hz excitation. Axial pile strain is usually modest.

Observations of vibratory driving seldom provides "proof " or evidence of soil resistance.

21

Summary

1. Wave propagation theory is powerful tool for understanding pile driving.

22

Summary

2. *Dynamic Measurements and Wave Equation Analysis can measure or predict quantities that are closely tied to a pile's transverse strain and which are thus probably closely tied to a pile's acoustic emmission.*

23

Summary

3. *Pile acceleration, strain and strain-rate are predictable, measurable and controllable by reference to hammer details, hammer operation, pile type, and soil conditions. These same factors may have important direct or subtle effects on acoustic emission.*

24

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APPENDIX K: Mitigation Approaches

Prepared by
Battelle

Mitigation Approaches

- Regulatory
  - Seasonal work periods
- Behavior
  - Repelling charges – etc.
    - Generally believed ineffective
  - Behavioral barriers
    - Sound, lights, bubbles, etc.
    - Wide range of effectiveness based of fish species, local conditions, etc.

Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon

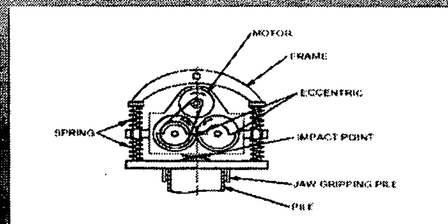
Mitigation Approaches

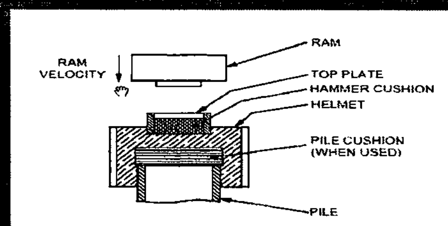
- Physical Barriers
  - Cofferdams or other barriers
    - Various sizes and configurations

Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon

Mitigation Approaches

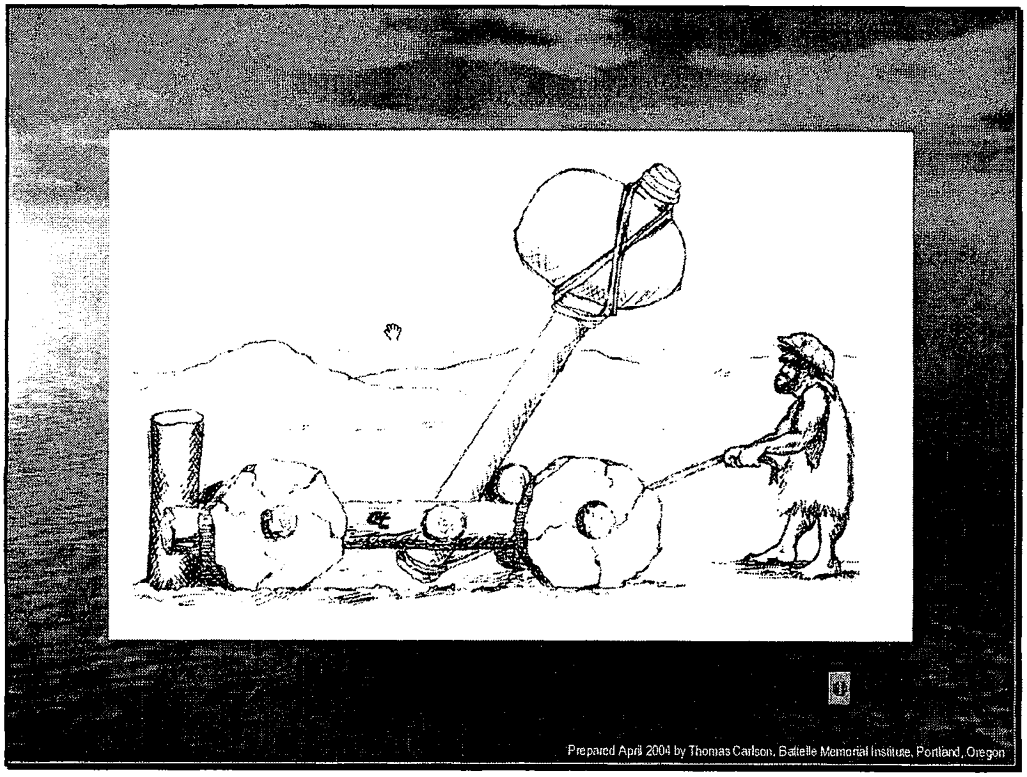
- Pile Driving Mechanics
  - Hammer type and operation
    - Vibratory
      - Often equivalent peak pressure but less rapid rise times due to less high frequency energy
    - Impact
      - More rapid rise times, peak pressure values dependent on many variables

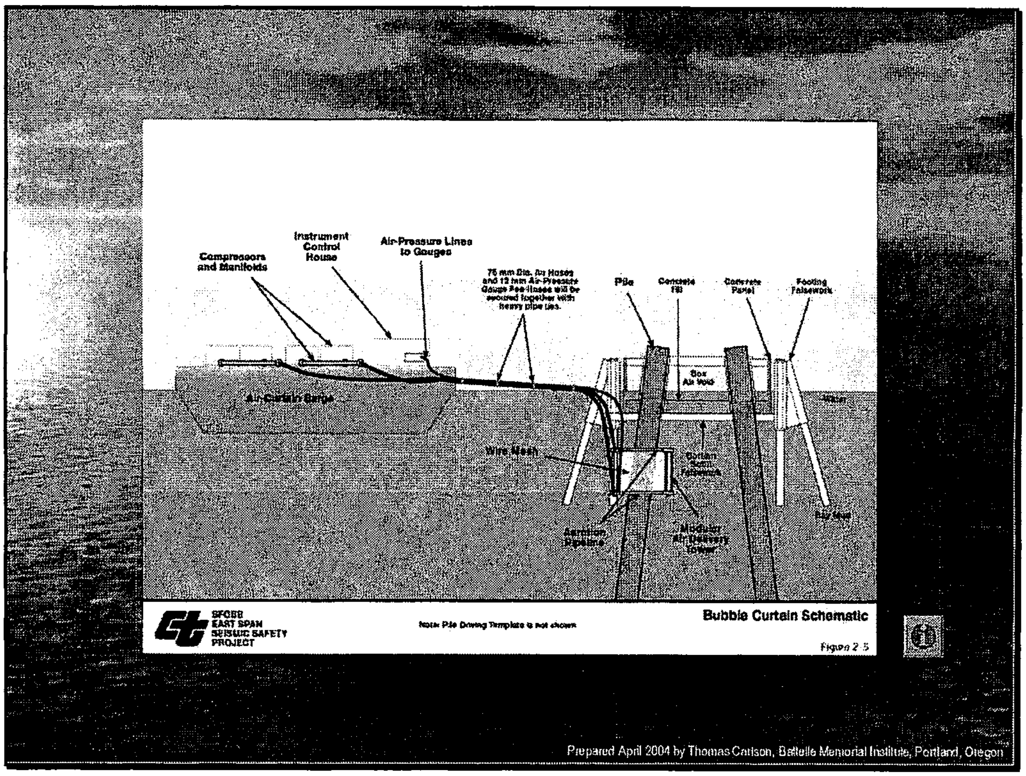


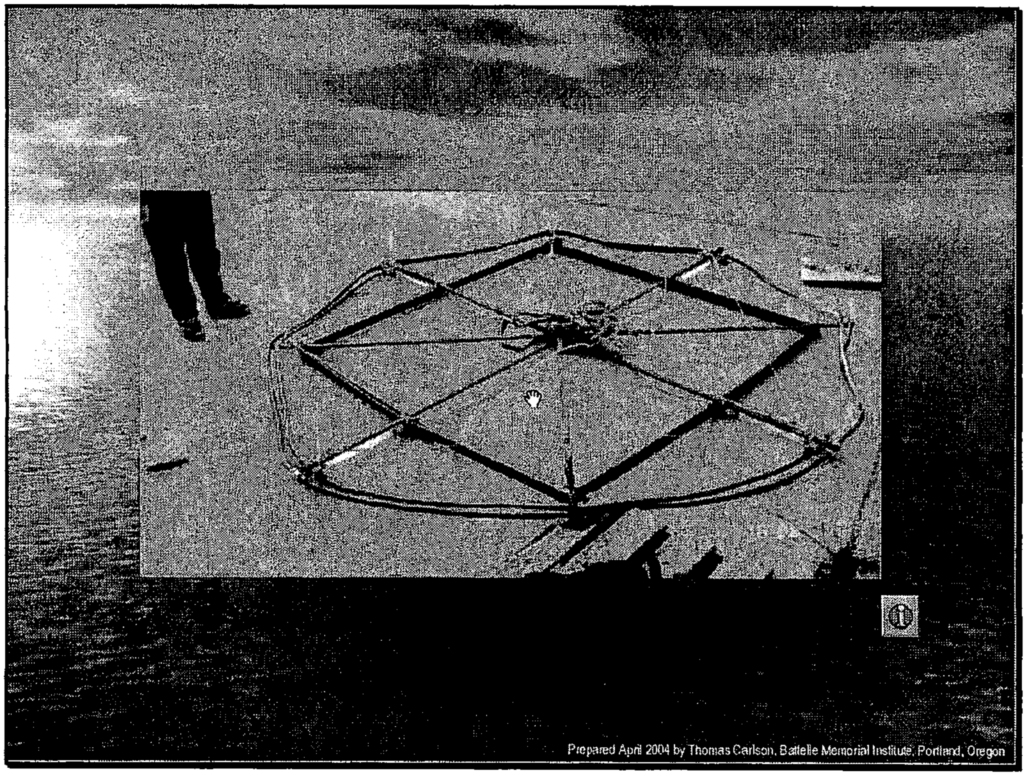


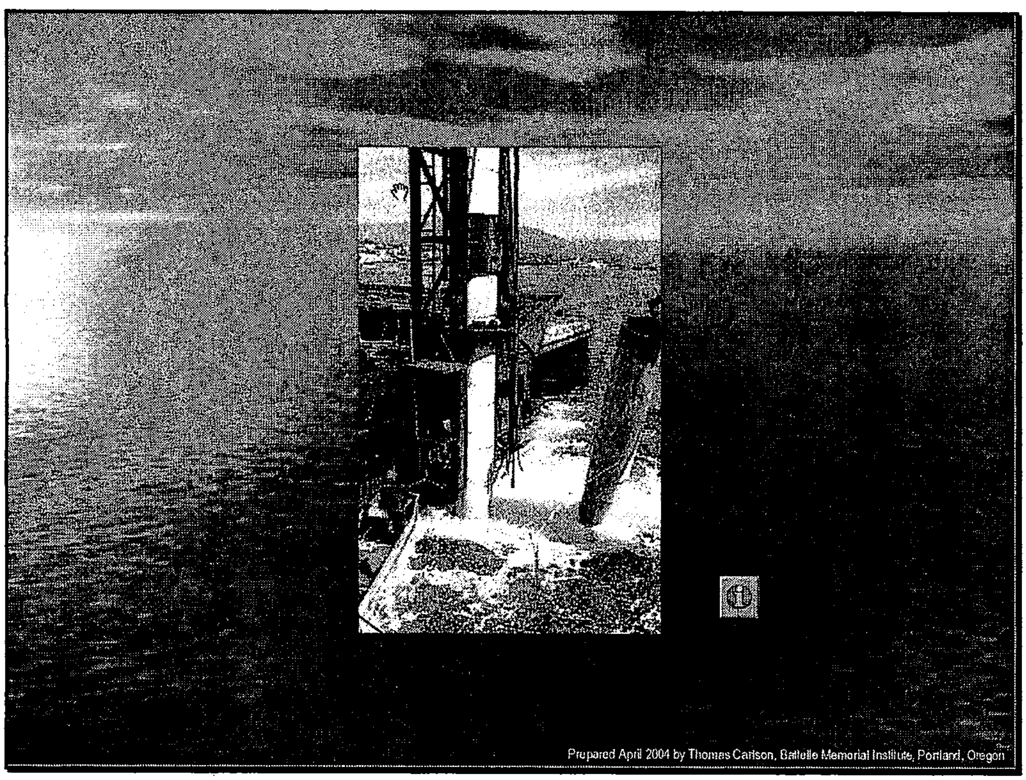
Mitigation Approaches

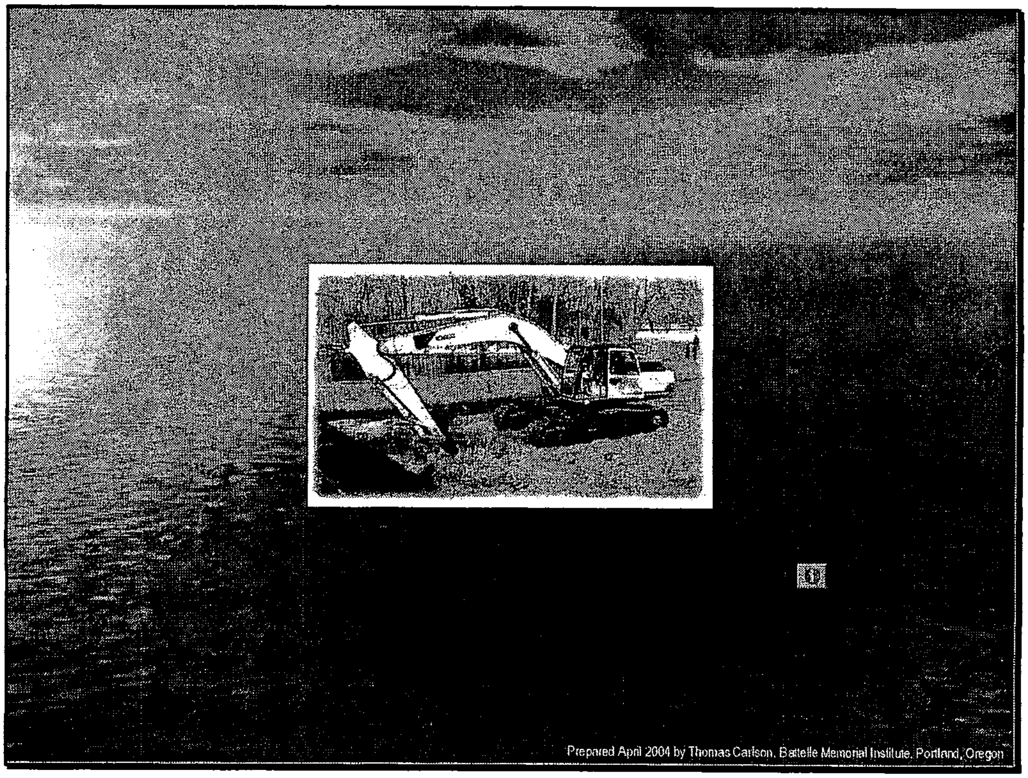
- Bubble Curtains
  - Originally used to mitigate use of underwater explosives
    - Documented reduction in peak pressure, impulse, energy flux density, and fish mortality
  - Designs and effectiveness vary
    - Movement toward multiple ring assemblies to help assure adequate volume of air in cloud of small bubbles completely surrounding a pile.
    - Most effective are containment + bubbles
      - Gunderboom

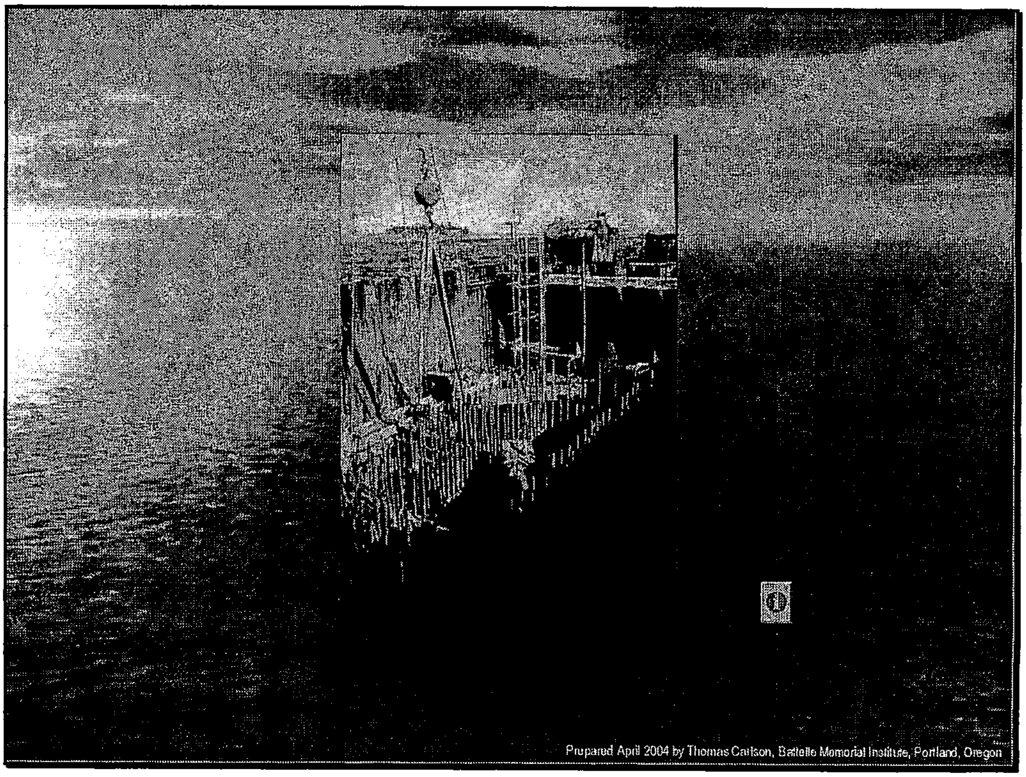

Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon


Compressors and Manifolds
Instrument Control House
Air-Pressure Lines to Gauges
Pile
Concrete Fill
Concrete Panel
Footing Falsework
Box Air Void
Wire Mesh
Aeration Pipeline
Modular Air Delivery Tower
SFOBB EAST SPAN SEISMIC SAFETY PROJECT
Note: Pile Driving Template is not shown
Bubble Curtain Schematic
Figure 2.5
Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon


Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon


Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon

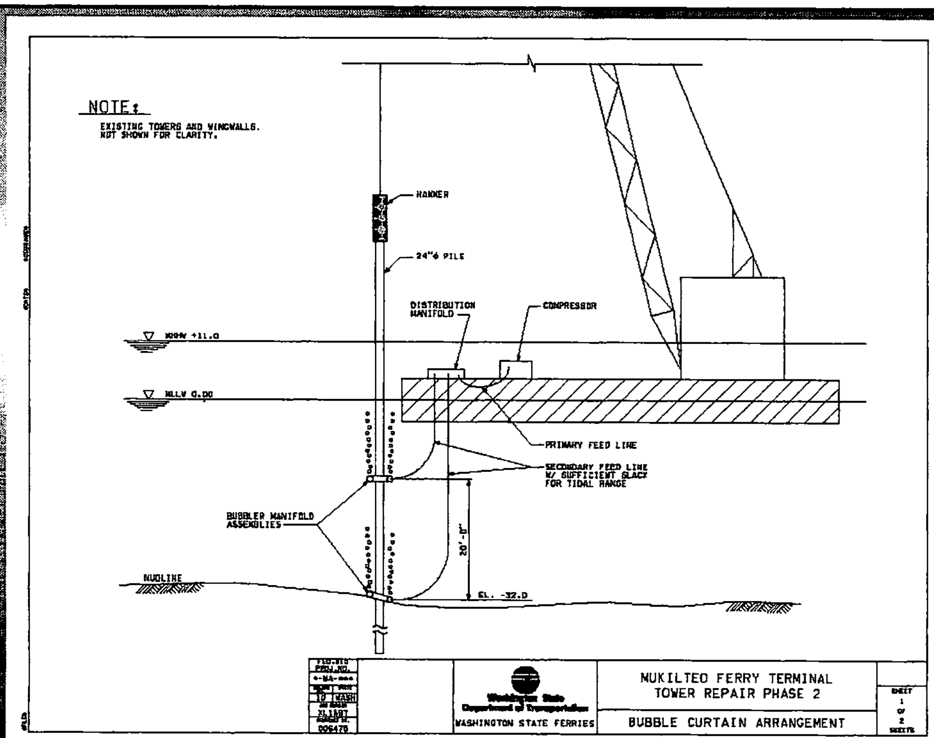

Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon

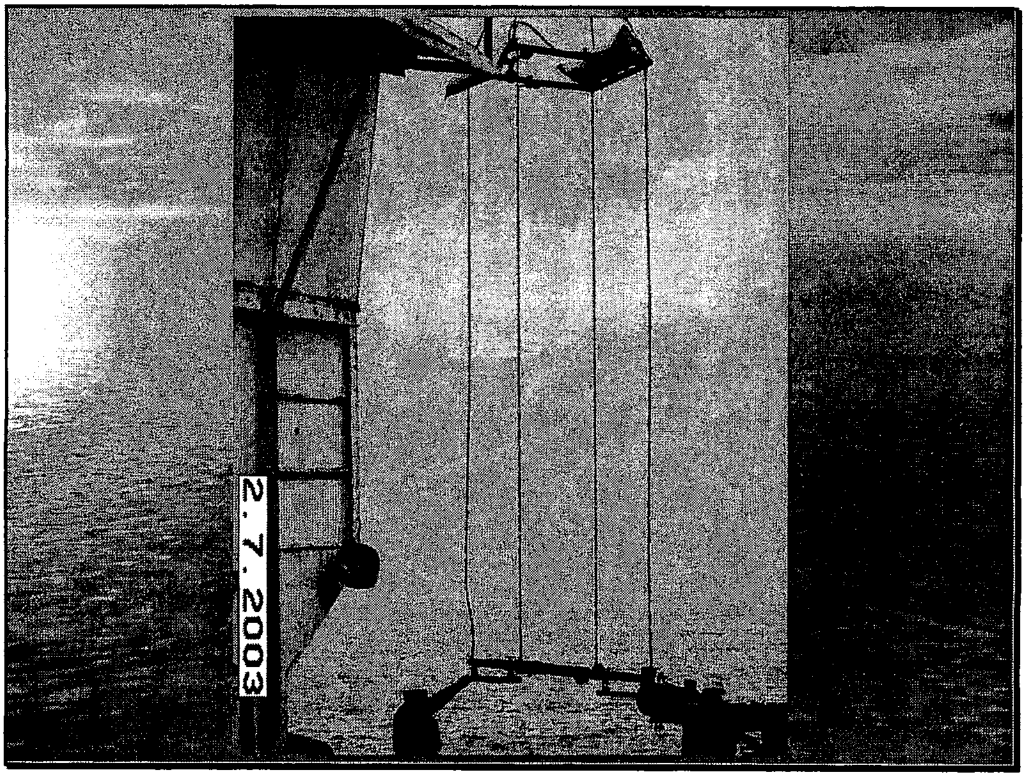

Prepared April 2004 by Thomas Carlson, Battelle Memorial Institute, Portland, Oregon

Mukilteo Tower Repair Phase 2

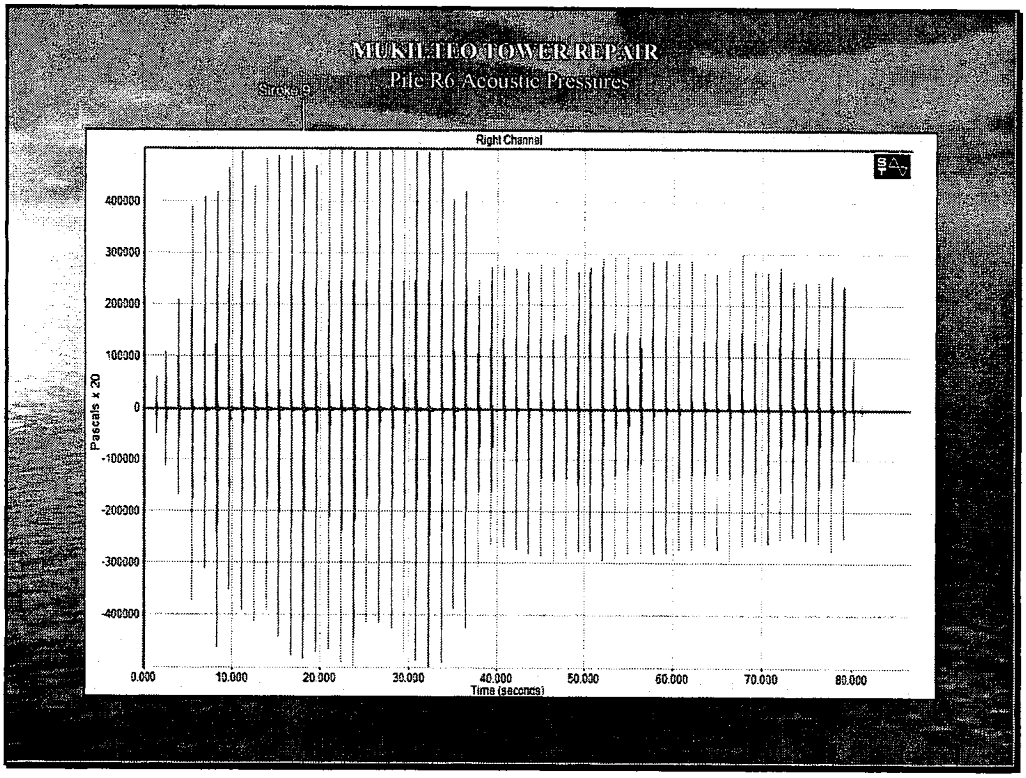
Application of Bubble Curtain to Mitigate Effects of Pile Driving On Fish

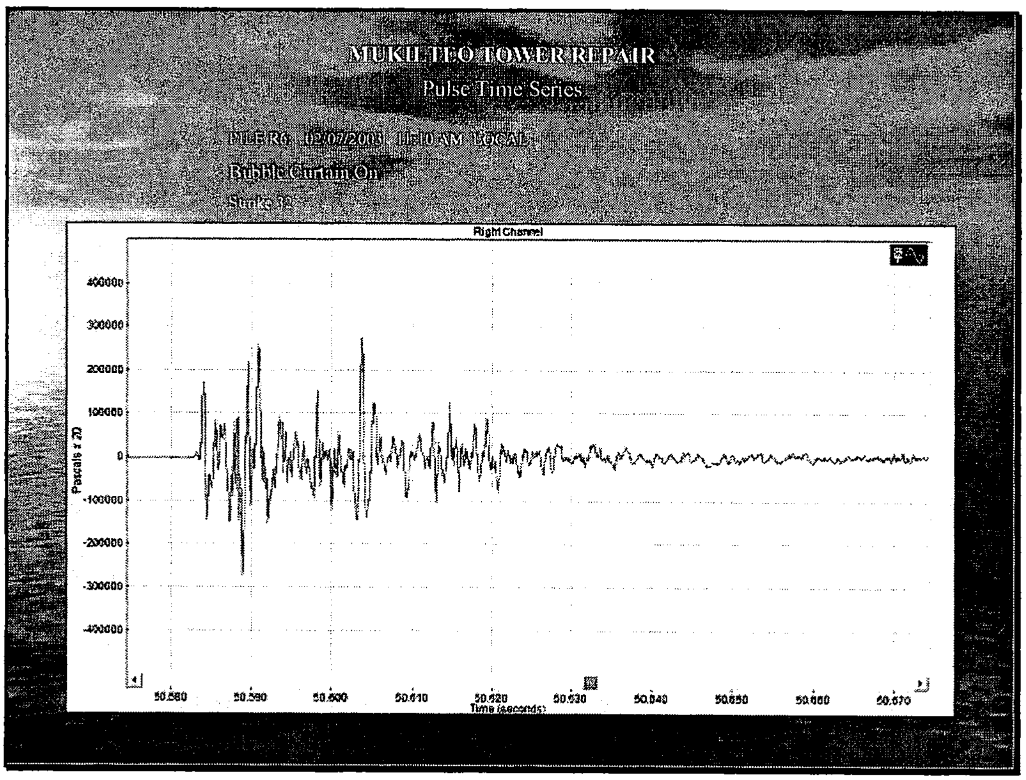
Frank S. Petrie, PE
KPFF Consulting Engineers
for
Washington State Ferries

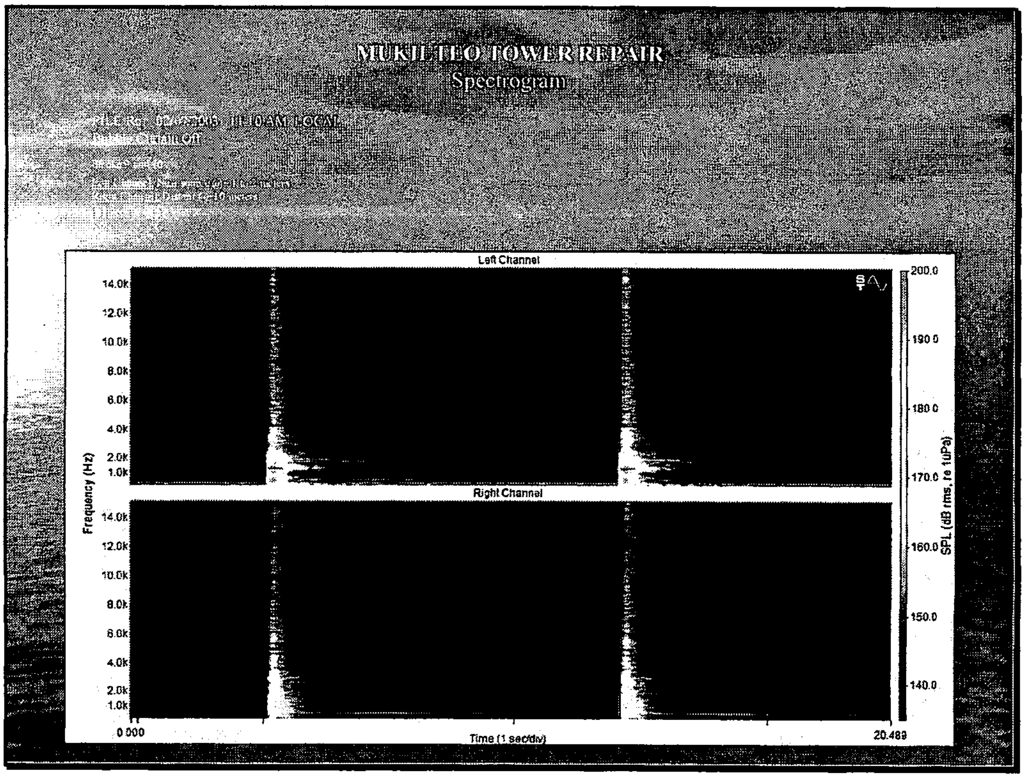


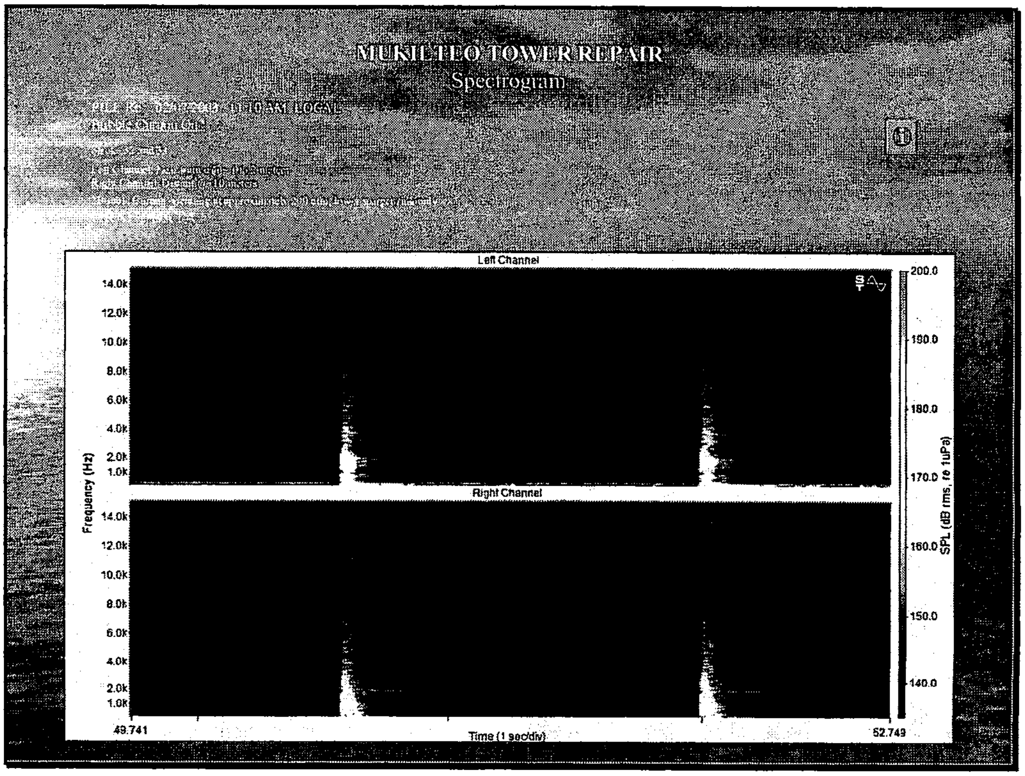

2.7.2003


2.7.2003


MUKILTEO TOWER REPAIR
Pile R6 Acoustic Pressures
Stroke 9
Right Channel
Pascals x 20
400000
300000
200000
100000
0
-100000
-200000
-300000
-400000
0.000
10.000
20.000
30.000
40.000
50.000
60.000
70.000
80.000
Time (seconds)


MUKILTEO TOWER REPAIR
Pulse Time Series
PILE R6: 02/07/2003 11:10 AM LOCAL
Bubble Curtain On
Stroke 32
Right Channel
Pascals x 20
400000
300000
200000
100000
0
-100000
-200000
-300000
-400000
50.580
50.590
50.600
50.610
50.620
50.630
50.640
50.650
50.660
50.670
Time (seconds)


MUKILTEO TOWER REPAIR
Spectrogram
Left Channel
Right Channel
Frequency (Hz)
14.0k
12.0k
10.0k
8.0k
6.0k
4.0k
2.0k
1.0k
0.000
Time (1 sec/div)
20.489
SPL (dB rms, re 1uPa)
200.0
190.0
180.0
170.0
160.0
150.0
140.0


MUKILTEO TOWER REPAIR
Spectrogram
Left Channel
Right Channel
Frequency (Hz)
14.0k
12.0k
10.0k
8.0k
6.0k
4.0k
2.0k
1.0k
49.741
Time (1 sec/div)
52.749
SPL (dB rms, re 1uPa)
200.0
190.0
180.0
170.0
160.0
150.0
140.0