Destructive Water-Borne Pressure Waves

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ABSTRACT

Many energetic sources (blasting, pile-driving, seismic exploration, …) near or within a water body may produce destructive, water-borne pressure waves. Pressure waves of sufficient amplitude can impact water-side structures and aquatic fauna. Such energetic sources produce pressure waves and cavitation that can cause concrete to spall, deform metal sheets that are near to the source, kill aquatic organisms, and/or damage hearing of marine mammals at large distances.

Any program (energetic systems) that causes pressure waves within the water layer may be conducted in a manner that reduces the pressure waves' severity. The methodology to reduce pressure waves does not need to reduce the efficiency of the energetic source. Basic physical laws govern the transmission and attenuation of the pressure waves. Exploration of the site's geology and assessment of potential adverse impacts should be conducted before the specifications for the project are written. Reduction of the pressure waves without other added mitigation differs for each class of sources. Additional mitigation varies by source class, the site's geology, the water depth at the source and at the protected zone, potential adverse impacts from the pressure waves, needed pressure-wave reduction, and the range of azimuths from the source region requiring protection.

INTRODUCTION

Energetic sources, such as blasting and pile-driving, near or within a water body may produce destructive, water-borne pressure waves. These energetic sources include not only blasting and pile-driving, but also seismic exploration and more obscure sources, like aquatic organism investigations, military testing and warfare. (Military action can also cause adverse pressure waves, but it would be naïve to suggest that those directing war efforts would consider such effects.) Resulting pressure waves have caused adverse effects to water-side structures and have been documented to cause aquatic fauna mortality or injury. Such sources produce pressure waves and cavitation that can cause concrete to spall, kill organisms with air-containing organs, and damage hearing of marine mammals at distances that do not cause other injuries.

Water-borne pressure records are difficult to obtain consistently and precisely. Recording difficulty has affected evaluation of the sources of these pressure waves and of mitigation procedures to limit the adverse effects. Making consistent and precise records is made more difficult when the Contractor utilizing the energetic source has no responsibility for obtaining accurate water-borne pressure records.

Mitigation of water-borne pressure waves is not encouraged by Owners because the effects are not well understood. Chiefly, mitigation efforts are considered either when the Owner has a previously recognized potential project effect or when there may be (has been) a community outcry or when an environmental issue causes a regulatory action. Any program with an energetic source that causes pressure waves in the water layer's wave guide may be conducted in a manner that reduces the pressure waves' severity. The methodology to reduce pressure waves does not need to reduce the efficiency of the energetic source. Basic physical laws govern the transmission and attenuation of the pressure waves. Reduction of the pressure waves without other added mitigation differs for each source class. Additional mitigation may be accomplished when the source, site geology, wave transmission, and recognized adverse effect are considered in detail.

This paper will use the general term of pressure waves and typically refer to peak-to-peak compression-wave pressures. Many scientists refer to noise or sound (compression waves) in terms of Sound Pressure Level (SPL). SPL is the logarithm of root-mean-square of pressure over a period of time as a ratio to a reference pressure. The period of time is not standard. The reference pressure is different for compression waves traveling through air (20 microPascal, µPa) and through water (1 µPa). SPL, while a useful designation for noise, is a complication that will not be used within this paper, as it may be unfamiliar to the casual reader.

ENERGETIC SOURCES

The dominant sources of blasting and pile-driving, as well as the more special source classes of seismic exploration and military testing, will be considered. Aquatic organism testing will not be considered as its purpose is to resolve the lethality to exposed species.

Blasting

Explosives and blasting agents are used for removal of massive units of structures or rock. [While blasting agents differ from explosives, the term "explosives" will be used collectively herein to refer to any materials that may be detonated.] For many situations blasting may be the only method of removal that is both feasible and cost effective. Blasting must remain a viable tool for removals within or near water bodies. Loss of the blasting source class use will cause most removal projects to have much longer durations for mechanical removal.

Explosives are used because high explosives detonate instead of burning (Keevin & Hempen, 1997). [Keevin & Hempen, 1997, is an easily obtained web document that covers several topics of underwater blast mitigation.] Work is accomplished in two phases, the detonation and gaseous phases. Brisant shock energy emanates from the detonation front. The shock energy moves through any medium and is transmitted into the ambient environment. Not far from the detonation front in the far-field, the expanding wavefront falls below the elastic range of dense solids and within the incompressible range of water. The chemical reaction of the detonation releases large amounts of heat and produces various gasses under great pressure. The gasses will continue to expand until equilibrium is established. Both the detonation and gaseous phases may produce pressure waves.

Some blasting programs will contribute their explosive energy directly into the water column. Blasting within bridge piers surrounded by water contributes nearly as much energy into the water as an equivalent charge weight in open water. The key criteria for lessening the energy into the water layer are: 1- containment of the charge; 2- radiation of the energy into a massive structure within which the explosives are contained. For the bridge pier the detonation shock energy passes into the water because the energy is not radiated into a massive subsurface, even though the charge may have been contained well.

As a source, explosives are unique in their typical use. Hempen *et al.* (2005 and 2007) both show that efficient blasting techniques reduce water-borne pressures when the removal is being conducted within a massive structure or continuous rock formation. If the blasting is not being conducted with consideration of the pressure waves, there may be shots that produce excessive adverse effects relative to those with proper consideration.

Some of the terrestrial measures to reduce blasting vibrations are useful for mitigating explosive use within or near water bodies. Some terrestrial measures that may be used for efficient removals and reduce water-borne pressure waves are blast initiation, explosive type, reduction in charge weight, delays, and confinement by stemming.

Blast Initiation. An explosion can be initiated (set off) in a number of ways including (but not limited to): use of electric blasting caps to a primer; use of electric blasting caps to a detonating cord; or use of non-electric shock tubes to a detonating cord. A long, narrow kill zone in water occurs with the use of detonating cord. Use of detonating cord should be limited, except directly within the blast-hole pattern's area. [Electric blasting caps are limited in their use overwater because stray currents and radio frequency induction may cause sufficient current in the lead wires to shoot the blasting caps. This charging of the blasting cap circuit may lead to misfires.] In blasting overwater, shock tubing is typically used to reduce lethal effects of the detonating cord.

Explosive Type. Selection of the explosive by the Blaster is an art. Blasters work from experience. All elements considered, an explosive that has a lower detonation velocity (Keevin & Hempen, 1997) will have less shock energy to transmit into the water layer. The explosive with less effect on the environment (and perhaps more effective in the removal project) will have a lower detonation velocity and relatively larger gas production relative to other explosives or blasting agents.

Reduction in Charge Weight of Explosives. The mass (weight) of explosives determines the total energy content placed into shock, thermal and gaseous energy components. There is a nonlinear relationship that a larger mass of the same type of explosive will produce larger amplitude pressure waves. So the Blaster will usually design the charge weight per hole for the burden and spacing intended. The Blaster can reduce the adverse effects and optimize the removal effectiveness by having a test blasting program for large projects. The purpose of the test blasting program is to determine the smallest charge weight, and other optimum criteria, for an effective program.

Delays. The charge weight of a shot-hole pattern blast may be reduced if the Blaster uses delays or decking. The use of delays is customary. Several authors, including Hempen *et al.* (2005 and 2007), have shown that the use of delays effectively reduces a pattern shot into a series of small distinct explosions. Any group of explosives within the pattern initiated within nine milliseconds (ms) of one another are considered a single charge for purposes of computing their pressure wave and vibration effects. It is preferable to have 25 ms between delays for underwater blasting to mitigate the pressure wave effects. Pressure-wave amplitudes are directly related to the size of the charge within each delay interval, rather than the summation of charges detonated in all holes (Munday *et al.* 1986). This statement has been supported during pressure measurements at the Kill van Kull Harbor Deepening Project and the Miami Harbor Deepening Project (Hempen *et al*. 2005, 2007).

Confinement by Stemming. Confinement within a dense material, concrete or rock, is obtained with the use of stemming. Confinement is created when angular rock and gravel are placed a minimum length within the drill hole's exposure to the dense material being removed above the explosive charge. Stemming is commonly used by the blasting industry to contain the explosive force and increase the amount of work done to the surrounding strata (Konya and Davis 1978; Moxon et al. 1993). This technique decreases the amount of blast energy that is lost out of the drill hole and thus reduces the impact to the aquatic environment. The U.S. Army Corps of Engineers' contracts typically require the use of angular rock stemming in boreholes.

Results from the Miami Harbor Deepening Project (Hempen *et al*. 2007) showed that loss of confinement, whether due to thin or weak rock layers or to poor stemming placement, allows significantly greater pressure-wave amplitudes. Both peak pressure and impulse are significantly reduced with average confinement. Well-confined shot holes produce very low pressure wave effects. A corollary to proper confinement is proper logging of the drilling, knowledge of the geology or structure, and use of the logging and structure data when loading the holes and placing the stemming.

Vibration Source. Explosive charges may act as point, line, area or volume sources depending upon the distance to the position of interest and upon the array of charge placements and their delay timing. The representation of the source is important is appraising wavefronts and attenuation of the pressure wave, other ambient conditions, and mitigation measures.

Various wave types develop from an explosion in a solid medium. Terrestrially, shear waves and surface waves cause more adverse effects than compression waves, also called pressure or sonic waves. In water only compression waves exist. [Fluids, including gasses, cannot support shearing so only compression and tensile displacement is possible.] At solid-fluid interfaces only pressure waves pass into the fluid regardless of the wave type incident upon the interface.

The distance to the point of interest is pertinent, because as the distance becomes very large relative to the lateral area of charge placement, the explosive source acts equivalent to a point source. Individual explosive charges and short lengths of explosives charges delayed in initiation timing from other charges both act as point sources. Pressure waves attenuate the greatest with distance from point sources as spherical wavefronts.

For most blasts where each shot hole is delayed in initiation timing from other shot holes, the explosive is a line source. Pressure waves attenuate moderately with increasing distance from line sources as cylindrical wavefronts.

Different source conditions result from those occasional instances of simultaneous shots without delays or inadequate delay timing between shot holes. Both of these inadequate delay scenarios are exacerbated by the close position of interest. Under these conditions the explosive pattern acts as area or volume sources. Area sources result when a partial or entire row of shot holes are initiated simultaneously or over very short delay times. Volume sources emanate energy from multiple rows of shot holes initiated simultaneously or over very short delay times. Pressure waves attenuate least from area and volume sources as planar wavefronts.

Pile-Driving

Pile-driving sources may produce pressure waves in the water and substrates before significant pile resistance develops. Pressure waves are more efficiently produced with higher side-friction loads or end-bearing loads on the pile. Hannigan *et al.* (1997b) describes the components of a pile driving system and their energies delivered by the hammer.

Not only do hammer energies, lead systems, pile caps, end- or friction-bearing piles, pile lengths, and types of piles affect the pressures entering the water column, but also the water depth and physical properties of the subbottom units (Site Geology) need to be considered.

Lead Systems. Lead systems align the pile's placement direction and allow the hammer to strike "a truly concentric blow" (Hannigan *et al.*, 1997b). The lead system allows transverse modal energy of the pile to enter the support system and ring with noise. This sound is transmitted to the barge or vessel or structure and radiated into the ambient environment.

Hammer Type. The type of hammer and its energy is designed for effective use at that site. (Vibratory hammers, often limited to sheet pile installation, usually do not cause as large of a pressure-wave effect as other impact hammer types.) In general, larger hammer energies can transmit much greater energy into pressure waves. Thus, large-energy impact hammers (Hydraulic and single-acting Steam or Air Hammers) have the capacity, depending upon a number of factors to cause more adverse pressure-wave effects. Hammer energy is transmitted through the pile cap (with its cushion) to the pile. The several components of the pile cap are selected to avoid damage to the top of the pile and effectively drive the pile to its design capacity.

Many factors are involved with the selection of the pile type, hammer, and pile cap. Most of these system designs and operational decisions should be assessed without consideration of potential pressure-wave damage. Yet, minor field revisions in the pile-driving system may make significant differences in effective pile installation or minimizing pressure-wave effects. The problem is the variability of possible pile-driving systems, of required pile capacities, and of the site geology. These complexities do not offer easy solutions to be both effective in pile installation and minimizing effects.

Terrestrial measures to reduce pile-driving ground vibrations are mostly limited to: setting responsibilities within the specifications, monitoring with attendant driving technique alteration, trenching barriers and either predrilling or jetting. "… ground vibrations of some magnitude are almost always induced to the surrounding soils during pile installation" (Hannigan *et al.* 1997a). Hannigan *et al.* (1997a) properly recommends specifications that control damaging ground vibrations by the pile-installation Contractor. Woods (1997) provides an excellent reference for understanding pile-installation ground vibrations. Woods (1997) cites only wave barriers and "alternative pile installation techniques" to reduce ground vibrations. These alternative techniques include: "jetting, predrilling, cast-in-place or auger cast piles, nondisplacement piles," and changing the type of hammer or "pile cushioning" (Woods 1997). The document suggests use of the alternative techniques, as the wave barrier may be expensive and not easily made effective.

Oriard (2002) suggests two other important factors of terrestrial pile-driving upon ground vibration are: distance to the source and soil-structure interaction. Distance to the source is not the lateral distance but the true three-dimensional distance from the energy source to the position of effect. This distance to the source does not usually approach zero. In the case of pile driving across a given site to very near the wall of a structure, one could improperly use the lateral distance of the pile at the ground surface to the wall at the ground surface. Instead, the relevant distance is from the dominant location of friction-bearing or end-bearing resistance to the entire footing or foundation of the structure. Soil-structure interaction suggests that ground vibrations must affect the entire mass of the structure. Recording ground vibration in the free field is not equivalent to how the structure or organism may respond to the same energetic source within the same ambient environment at the same distance.

<u>Vibration Source</u>. The vibration source is partially a point source and partially a line source for pile driving. Woods (1997) provides excellent discussion and figures of wavefronts for terrestrial creation of ground vibrations.

As per the discussion above (under Blasting), fluids only support pressure waves, also called compression or sonic waves. Easily illustrated, end-bearing energy is translated into pressure waves that radiate spherically from the pile's end. What may be less obvious are the conical, or nearly cylindrical, wavefronts that emanate as shear waves (in a medium supporting shear) from the friction-bearing portions of the soil. These shear waves are converted to pressure waves as the waves cross a boundary into a fluid. Still less obvious is that noise as pressure waves flows into the water both from the pile and from the lead supporting system through the barge. The pile oscillates in its modes of freedom as it is struck. Those transverse displacements pass as conical pressure-wave wavefronts into the water. All the wetted solid surfaces of the barge/vessel pass noise into the water as planar pressure-wave wavefronts with every hammer impact. Other oscillating and vibrating machinery on the deck or within the barge/vessel also radiate their noises into the water along the wetted surface.

The end-bearing energy converted to pressure waves attenuates more as a spherical wavefront compared to the other forms of pressure-wave creation. Friction-bearing energy and mode-shape pile-displacement energy attenuate moderately as spreading conical wavefronts. The noise emanating from wetted surfaces has the least attenuation as planar wavefronts. The latter, fortunately, has typically the least amount of energy.

<u>Seismic Exploration</u>

Overwater mineral exploration, chiefly for petroleum products, originally used explosive charges. These were small point-source charges that would be considered equivalent to blasting as previously discussed.

It is much more common for the seismic-exploration's energetic source to be a repeating mechanical pulse towed behind a vessel. Such sources range from low energy pingers, to boomers, sparkers and airguns with the latter being higher energy sources. The dominant amount of energy from these mechanical sources is released downward within a narrow cone. These mechanical sources act as point sources.

Mechanical sources of seismic exploration have focused beams of much lower energy content than most blasting removal programs and pile-driving programs. The energy content and directionality of the seismic exploration sources reduce their ambient environmental effect relative to the original source of explosives. As seismic exploration is conducted by geophysicists who are able to grasp these topics when it is pertinent to their own needs, there will not be more discussion to mitigate seismic exploration.

<u>Military Testing</u>

Military testing has energetic sources most equivalent to blasting. [There are military sources both in testing and operational uses that produce sonic pressure waves. These sonic sources regardless of their purpose or use are so specialized as to be well outside the scope of this document.] Military energetic sources similar to explosives may be used above the water surface, within the water column, or at, or just below, the bottom surface of the water body. Sources in military testing are rarely confined.

Some military explosions will act as volumetric sources. Most sources of military testing will be point sources, but may have very large energies.

Military testing sources that are similar to explosives should consider those appropriate conditions that may be applied under the blasting sections of this paper.

PRESSURE-WAVE FACTORS FOR MITIGATION

There are three important factors of Site Geology, Wave Transmission and Adverse Impacts, besides the Energetic Source Class.

Site Geology

The ambient environment controls how waves pass and how the energy is attenuated or guided. All geotechnical programs for construction or removal programs should have a good understanding of the Site Geology. The structure being built or removed will depend upon adequate knowledge of the subsurface.

The geology of a site is very complex. This complexity is attributed to the depositional environment of the rock in the subsurface, the erosional period since the placement of the rock, and subsequent soil development. The subsurface media should be considered as variable in all directions even over short distances. Important parameters include assuring knowledge of the top-of-rock surface and of the thicknesses and lateral continuity of the uppermost rock units.

Besides proper exploration to understand the units in the subsurface, the geophysical velocity model of the subsurface should be resolved. The actual velocity section will govern how waves are passed, attenuated and focused through the subsurface. An approximate compression-wave velocity model can usually be obtained by knowing the type and extent of soils and rock below the water body where the work will be conducted. In most cases an approximate velocity model is all that is required.

The Medium of Water. This paper only relates to pressure waves within water, whether fresh or saline. Water has several unique qualities. Water is very uniform in its properties relative to soil and rock. Although water cannot be sheared, water's compression-wave velocity may be higher than that of soils above the ground-water surface. Water's sonic velocity is dependent only upon depth, temperature and salinity, and may be predicted by formula. Water is compressible near the detonation front of explosives. Water may be considered incompressible when a wave passes at its normal sonic velocity.

Shallow water is defined herein as water bodies with average depths of less than 25 meters (m). This depth is particularly reserved for construction and demolition in most US harbors and rivers. [Shallow water could be resolved on other bases. Yet this 25-m depth definition is smaller than other authors suggest for issues related to thermoclines or wave transmission. So the 25-m definition is certainly acceptable and for the most part meets the requirements of construction and demolition activities.] Bodies of shallow water have increased wave attenuation. Bodies of shallow water with undulating bottom depths or large areas of very shallow depths (less than 1-m depths) have still greater attenuation of pressure waves.

Water acts as a wave guide. Pressure waves get trapped in the shallow water horizon accepting energy back into the water by refraction from lower high-velocity units. Raypaths with large angles of incidence to the bottom surface cannot refract into the bottom material and are reflected back toward the water. The air-water interface is a good reflector. So pressures waves trapped in the wave guide only have spherical or cylindrical wavefront spreading losses of shallow water.

Wave Transmission

Cole (1948) in his assembly of earlier research and in his own pioneering work develops the passage of energy through water for open-water explosive sources. Wave transmission from other solid media into water is an important aspect that may be resolved by geophysical procedures regardless of the source type.

Pressure Waves. There are no shear and surface waves in water as in ground displacement from terrestrial energetic sources. Only pressure waves exist in water. Water acts as a wave guide diminishing the passage of energy into the subbottom.

Pressure waves incident upon the air-water surface change from compression to tension, since the wave cannot pass stress into the air. While water is nearly incompressible, it has very little tension capacity. The low tension capacity results in cavitation occurring where the incident wave's compression amplitude is greater than atmospheric pressure on the water surface. The reflected pressure wave has heat and gas losses from the cavitation created close to the water surface.

The wavefront at several wave lengths (or three to five water depths) laterally from an energetic source within the water column, or within the water's depth below the bottom, become nearly vertical cylindrical or planar waves in shallow water. This occurs as a function of the shallow water depth and wave guide effect. The wavefront is either nearly cylindrical or planar depending on the energetic vibration source type.

Distance to the Source. The exact distance is measured along the raypath that wave transits from the source to the position of potential effect. A conservative (always smaller or equal to the exact distance) distance estimate is the straight line three-dimensional distance from the source to the position of potential effect. Usually the lateral distance, the map or surface distance, is a poor estimate of the exact distance.

The distance estimate should originate at the closest location of the energetic source. This source position varies with the source class of energetic disturbance. The position of potential effect may be assumed.

Disturbance in a Solid. Well-confined explosions in rock radiate the energy dominantly into the solid. Less energy is available to reach the nearby or overlying water body as pressure waves. When poorly confined near the solid/soil interface, both the shock energy and rifling of the gas energy combine to increase the energy entering the water body.

End-bearing piles on a stiff surface that may be penetrated by the pile radiate less energy into pressure waves than a pile being deformed by the solid that it cannot easily penetrate. The deformed pile causes greater amplitude pressure waves in the water column.

Adverse Impacts

The adverse impact of the energetic source may be to the built environment and/or to aquatic organisms. The energetic source may need to be greatly reduced or may need only minor operational adjustment depending upon what is being impacted and the distance of the energetic source to the position of potential effect. The impact will be significantly different for structures than aquatic organisms.

Effect upon the Built Environment. Adverse impacts from energetic sources cause relatively minor damage to structures. Some types of damage may hasten maintenance or cause some operation problems depending upon the structure being protected. Oriard (2002) notes that structures are usually not effected more than "a few tens of feet" (10 to 15 m) from the energetic source.

Effect upon Aquatic Organisms. Aquatic species may be killed or harmed in a manner leading to their death from energetic sources in either stream or marine environments. The Endangered Species Act limits "take" of threatened or endangered species within the United States. "Take," which ranges from any form of disturbance to death, is absolutely forbidden. Take of a *single* threatened or endangered species can be grounds to terminate or suspend operations of a project of any size. Marine organisms may be affected (constituting a "take") hundreds of meters from an energetic source.

MITIGATION

Measures to mitigate pressure waves from energetic sources within or near water bodies vary by the source class. Consideration of the energy source class, site geology, wave transmission, and recognized adverse impact should be accounted for the most effective mitigation. Only the two most prominent source classes, Blasting and Pile-Driving, will be discussed. Seismic Exploration should be resolved for its own conditions and requirements. Military Testing may be analogous in part to Blasting.

Measures that reduce pressure waves from all forms of energetic sources will be noted before specifically addressing the specialties of Blasting and Pile-Driving.

Specifications

Specifications provide background data, design requirements, and divide responsibilities. The specifications should clearly provide the Site Geology, potential Adverse Impacts, and suggested or required Mitigation Measures. The Contractor must be responsible for actions that are under his control. Specifications for any use of an energetic source should make the awarded Contractor responsible for adverse impacts from terrestrial vibrations and water-borne pressure waves. The Contractor should not conduct the compliance monitoring, but should be required through the specifications to be cooperative in obtaining the compliance monitoring (planned down time or making available vessels or laborers to help with monitoring).

Special Studies. Specialty contracts may be needed to determine any of the issues not readily understood before completion of the specifications. A complex or deep site may require a special site investigation for the site geology. Potential adverse impacts due to the energetic source may not be well understood by the Owner or Designer. If there is a nearby water-side structure, an assessment of whether the structure may be impacted could be conducted. Environmental considerations may need to be appraised before the specifications are completed.

Environmental Considerations. Environmental-compliance reporting is required by and must be submitted to U.S. federal authorities, if the project is being conducted for the federal government or if any federal funding is compensating for the project's costs or if any federal permit is required for the project (Keevin, 2007). Environmental-compliance reporting may be required by state or U.S. federal authorities, depending on the regulations and laws of the state within which the project is being conducted or depending upon other occurrences (for example, an aquatic-organism take during the project's span of work).

An evaluation of the project should be conducted with a tiered approach for aquatic organisms (Keevin & Hempen, 1995) for nearly all projects with the use of moderate to large energetic sources, This tiered approach was written for blasting programs, but would be comparable for those projects employing pile installations. The tiers develop from the easiest actions ("I. Blast Design Parameters & Biological Parameters" Review or Pile Installation Design Review) to moderate measures ("II. Blast Design Parameters & Biological Parameters" Modifications or Pile Installation Design Revisions) to lastly the more encompassing and expensive "III. Compensation and/or the Use of bubble curtains or other barriers" (Keevin & Hempen, 1995).

Mitigation for Water-side Structures

Mitigation for structures will typically involve an assessment of whether a potential for damage exists through the water from nearby energetic sources. [This document will not develop fracture and vibration damage to structures from the energetic sources.] The two main types of potential damage from pressure waves are the worse effects on thin metal surfaces and the lesser effects of spalling of concrete and damage to riprap. Thin metal surfaces (like turbine blade, gates, sheet piling, …) can have positive or negative pressure distortions from pressure waves. The ambient loading upon the metal surfaces and the proximity to the energetic source (or to cavitition or gas-bubble products of explosions) will have sufficient energy to cause reforming of the metal surface. Spalling of concrete and damage to riprap occurs from cavitation, or expansion of existing gasses, within fine cracks in the concrete or rock.

Barriers for Built-Environment Protection. If assessment determines too great a risk of structure damage, usually a barrier is developed between the energetic source and the structure being protected. The barrier most often takes one of two forms for protecting structures during blasting: sheet-pile protection that may or may not be unwatered; and, air curtains. [The air curtains, also called air screens and bubble curtains, will be discussed under Mitigation for Blasting below. Barriers for pile installations will be developed under Mitigation for Pile-Driving below.] Sheet-pile installation is typically conducted with a vibratory hammer that usually has low impact on nearby structures. Sheet-pile protection may not be feasible: over the short distance between the closest approach of the energetic source and the structure being protected; or, because the apron, floor or founding medium of the structure is a dense solid that sheet piling could not penetrate.

Mitigation for Aquatic Organisms

Aquatic organisms are sensitive to, live within, and utilize to their advantage, the ambient sounds, noise and pressure waves in nature and caused by man. Energetic sources that increase pressure waves from merely perceptible to annoying (the initiation of "take") to harmful or lethal should be considered for mitigation. Some of the mitigation procedures may easily be conducted. When the simple procedures are not applicable or appropriate or when the energetic source is extreme, detailed and extensive (usually expensive) mitigation plans are required.

Use of Construction Noise to Protect Aquatic Species. Fish and marine mammals use sound and pressure changes to survive and to communicate. Aquatic organisms will, if capable to do so, move away temporarily from an offending noise when the energetic source may be annoying or disturbing. The key is the short-term nature of the aquatic organisms' displacement. Once an operation begins that is associated with the energetic source, there will be the least harm to aquatic organisms if the activity and its noise is continuous. The work should be as continuous as possible associated with blasting, like the drilling of shot holes, or with pile installations. Operations should be on a 24-hour basis when practical or feasible. Quiet periods should be grouped together when there are relatively few. Ten 24-hour days working followed by four days off is preferable to five 24-hour days working followed by two days off. Short down times of one noise source should be filled by other sources continuously working. Multiple drill barges or pile installation systems would be preferred to single systems.

By reducing quiet periods, the "recovery time" may be eliminated for more mobile aquatic organisms to move back into the area and be exposed to pressure waves from the energetic source. Required short downtimes should be made as short as practical. The normal operating procedure is to drill the shot holes, load the explosive, load the stemming, connecting the initiation system as each hole is completed, provide authorities with information for shot initiation clearance, sound the warning, and then initiate the blast. From the time the Blaster finishes loading the shot to the time of initiation can often be thirty minutes or more. Drilling, loading, and movement of boats in the project area all produce loud noise. The intention is to reduce the thirty minutes, quiet delay period by conducting alternate activities simultaneously, except for a very short period at the shot's warning and initiation.

Seasonal Restrictions. Seasonal restrictions on the use of energetic sources during biologically sensitive periods can be extremely effective in reducing or eliminating adverse impacts to migrating or young aquatic organisms (Keevin, 1998). Usually the work to be conducted with energetic sources can be accomplished easily between the end of one restricted period and the beginning of the next. Seasonal restrictions are in Tier II of the tiered approach (Keevin & Hempen, 1995) advocated in Environmental Considerations above.

Seasonal restrictions can be a very effective mitigation for some locations. In other locations of great diversity or lack of migrating species, there may be no period or only a short period that one of several species is not endangered. So, seasonal restrictions are highly dependent upon the location of the project.

Development of Mortality Modeling, Exclusion Zones and Watch Programs**.** Assessment of aquatic resources and mortality modeling are in the first tier of the tiered approach (Keevin & Hempen, 1995) advocated in Environmental Considerations above. Each specific mortality model appraised for a project's details suggests whether the volume of water where a species would likely be fatally injured is relatively large or small. Further, the mortality modeling enables a Watch Program to be developed for any species that surfaces or that may be tracked in shallow waters by boat or helicopter observers. The Watch Program assures that those species being observed are not within a harmful distance of the energetic source. Watch Programs are in Tier II of the tiered approach (Keevin & Hempen, 1995) advocated in Environmental Considerations above.

Keevin & Hempen (1997) assembled research literature on mortality models for classes of aquatic organisms. Mortality models are approximations in the case of marine mammals and sea turtles where anecdotal observations have been made on only a few individuals. Mortality modeling of some fishes may be statistically quite accurate, because of the repetitive testing upon a large number of caged individuals. Most aquatic organisms have not been tested to have a mortality model. [Keevin *et al*. (1999) recommended needed research for protection of aquatic organisms.] In some cases, a surrogate may be chosen that already has a mortality curve for the species needing protection that does not have a model.

Jordan *et al*. (2007) explain the considerations for, and the development of, a particular Watch Program. Safe Distances for a specific protected species may be developed from the project's details when an acceptable mortality model exists for that species. The largest Safe Distance of all species to be protected is the radius of the Exclusion Zone around the extreme bounds of an energetic source's deployed area. Observers in boats and/or helicopters assure that none of the protected species are cited within the Exclusion Zone. Watch Programs can only operate during daylight hours. Thus, blast shot initiations and pile installation may only occur during daylight hours to allow Watch Program observation of species that may be harmed by these sources. For pile-driving particularly, a Watch Program during only daylight hours may be counter to continuous operations that keep organisms at tolerable distances of their own choosing.

<u>Barriers for Aquatic-Organism Protection</u>. Barriers for mitigation of harm to aquatic organisms from energetic sources may be required by environmental authorities or may be appropriate. It may be appropriate because using a barrier: is the proper action to conserve a living resource; curries favor with environmental regulators and/or the public; is less expensive than other alternatives; and, is less risky than termination or suspension of the project if a single "taking" were to occur without a barrier.

Barriers to the passage of pressure waves from an energetic source may take several forms depending upon the location of the energetic source and the protected species. Barriers include sheet-pile walls, earthen or stone levees around the work zone, and air curtains. [The air curtains, also called air screens and bubble curtains, will be discussed under Mitigation for Blasting below. Barriers for pile installations will be developed under Mitigation for Pile-Driving below.]

<u>Mitigation for Blasting</u>

Explosive sources for removal of massive units have less energy transferred as pressure waves in the water layer compared to the severity of pressure waves from water-column explosions. Pressure-wave records of actual rock removal programs have corroborated theories from other authors' laboratory testing (Hempen *et al*. 2005, 2007). Radiational damping reduces the energy entering the overlying water layer's wave guide when the blasting is properly confined within a competent continuous medium. The terrestrial methods to lessen adverse impacts from vibrations, cited above for Blasting under the topic of Energetic Sources, should be followed. Many of this author's recommendations to the State of Florida, and as cited herein, have been incorporated into Florida's blasting regulations (State of Florida, 2006).

<u>Site Geology</u>. The project's structure and site geology must be understood to predict the type of pressure-wave energy release. Individual shots can radiate much of their energy away from the water layer or allow most of the energy into the water layer, like an open-water shot.

Removal of both, 1- piers (surrounded by water) of small diameters relative to their submerged depth and 2- submerged thin rock lenses (or concrete slabs) overlying soils units, will radiate pressure waves into the water, as if the explosion had been in open-water. Most of the energy remains in the water layer and little is lost entering the subbottom media. While it is important to confine the solid medium with stemming, such confinement for these surrounded-by-water cases does not allow energy loss into the subbottom. Lack of confinement will only make the shot less efficient. When the shot-hole collar is below the water surface, lack of confinement will allow the explosion to rifle and increase the energy of the pressure wave.

Removal programs of massive structures or rock with proper confinement by stemming will greatly reduce the pressure-wave energy entering the water layer. Radiational damping is the mechanism that allows the energy to travel into the massive unit away from the water layer.

<u>Blasting's Recognized Adverse Impact</u>. Mitigation for structures from blasting damage will differ from mitigation for aquatic organisms. The feature to be mitigated must be recognized before the completion of the specification.

<u>Barriers for Blast Mitigation</u>. Many physical barriers will reflect, refract, diffract, and attenuate pressure waves. Sheet-pile walls and either earthen or stone levees built around the work zone are effective. These barriers may allow unwatering which eliminates the passage of pressure waves. These solid barriers are usually too expensive, unless their placement would be used later in the project. Air curtains are physical barriers that may easily be placed and removed. Barriers of any type should not be quickly accepted without careful evaluation of risk reduction for their added expense.

Air curtains, also called air screens and bubble curtains, have been required on many projects for protection of either a structure or aquatic organisms. Air curtains can be highly effective at energy reduction by reflecting and attenuating pressure waves. Hempen (1993) provides technical information about barriers in general and the testing and design of air curtains specifically. Grogan (2005) and Keevin *et al*. (1997) developed the design and effectiveness of air curtains for aquatic organisms' protection.

Air curtains have been required by regulatory agencies. Anecdotal assessment of some air curtains has suggested that the systems failed to offer adequate protection in certain cases. Air curtains must be properly designed for the site, project, and required reduction of the pressure wave. Systems are not necessarily properly designed if "an air curtain" is furnished by an operator that has not previously used the technology. The design, operation and maintenance of the system should be cited in the specifications, when air curtains are required for a project.

Mitigation for Pile-Driving

The impact energy of pile installation differs markedly from the energy from explosives. The pile-driving system radiates some energy through the lead system and floating platform. Most of the radiated energy is from the point and line sources along the entire length of the pile from end-bearing resistance, side-friction resistance, and lateral displacement of the pile in its lower mode shapes. The purpose of piling is to create a stiff medium which is opposite of the purpose of blasting, to remove a massive medium.

Pile-driving impacts places less energy with each impact into the environment than a blasting program for each shot. Yet depending upon a great many variables, pressure waves emanating from the source may be greater for pile-driving than for blasting. The variables include the hammer energy, the cushion and pile cap, pile type, the operation of the driving system, and the soil stratigraphy at the project site. ATM (2004) cites various other works and shows that impact–driven steel pipe piles produce the most adverse impacts relative to concrete and timber piles.

Most of the terrestrial measures for mitigating pressure wave radiating from pile driving are less or not applicable for overwater programs. A vibratory hammer produces much less energy as pressure waves than an impact hammer. A vibratory hammer should be used, if the vibratory hammer is applicable for the pile type chosen and if adequate design capacity will be achieved. Containment barrier mitigation is discussed in Barriers for Pile-Driving Mitigation below.

Site Geology. Pile foundations are required for sites that have poor and/or deep soils. There is little radiation of pile-driving energy into rock, because most of the impacts occur before end-bearing on rock is reached. Further, as end-bearing resistance increases, displacement of the pile in its mode shapes increases. Much of the energy from mode-shape noise enters the water layer directly.

Sites with great depth to dense rock will have side-friction resistance. Loose mud and soil near the water-subbottom surface will transmit energy at velocities similar to the overlying water. So these poor soil sites release larger amounts of pressure-wave energy as a percentage of the total energy of their source relative to blasting.

Pile-Driving's Recognized Adverse Impact. Mitigation for structures from pile-installation damage will be similar to mitigation for aquatic organisms. The feature to be mitigated must be recognized only for compliance monitoring of the potential adverse impact from pile-driving. The monitoring program should be developed before, and included within, the specifications.

Barriers for Pile-Driving Mitigation. A containment barrier wall and a containment pipe pile are the only mitigation measures that are appropriate for reducing pressure-wave effects from pile driving. The important factor to be resolved for either type of containment is the required depth of the containment wall or pipe pile. The containment mitigation must be placed with adequate depth to greatly increase the distance from the line source along the pile to the zone of protection within the water column. There will be little reduction in pressure waves if the base of either system is not deep enough. The base of the containment, to be effective for reducing pressure waves, may be approximated as the greatest or most applicable of: twice the depth of the water; the depth to a moderately dense or stiff soil horizon; or, one quarter of the total pile depth.

Another factor in choosing to use a containment wall or pipe pile is the loosening affect of removing the containment pipe pile. The containment wall could be a permanent feature and thus would not need to be removed. Containment walls only surround the pile field at the perimeter. The installed piles often are less affected when a containment wall is removed.

Containment walls may be vibratory driven sheet-pile walls. The advantage of sheet-pile walls is that they may be left in place permanently or removed for reuse or for salvage income. The wall reflects the pressure wave back toward the source to the base depth of the wall and also reflects the energy downward. Containment walls do not use an interior-facing air screen, as may be used with a containment pipe pile.

The containment pipe pile is usually a larger steel pipe pile jetted into position. The installed pile will be driven, usually by impact, within the containment pipe pile. The equipment to jet the containment pipe pile into place may be used to supply interior compressed air in the annulus of the larger pipe pile. The rising air screen enhances the reduction of pressure waves that reach the water layer when the containment pipe pile is sufficiently deep. Noting again, containment pipe piles are typically removed. This removal after placement of the designed pile may reduce the final load capacity of the designed pile.

CONCLUSION

Sufficient advance study should be conducted to determine if there is the potential for adverse impact from the project's energetic source. Once the potential adverse impact(s) is(are) determined, the risk of not mitigating the pressure waves may be appraised against the cost of mitigation.

There may be no alternative to extensive mitigation. Mitigation may be required by the Owner of a nearby structure or by an environmental regulating authority for protection of one or more aquatic species.

Adequate studies and exploration should be conducted in advance of writing the specifications. A tiered approach may be considered for aquatic organism impacts. The specification should be written only after the Owner and Designer comprehend all the factors to allow the proper approach to the potential impact. The specifications should provide background information, design requirement of the main duties, and plainly cite the mitigation measures (in design, operation, maintenance and compliance monitoring) that will be taken to reduce the potential adverse impacts. The specification should clearly make the Contractor responsible for actions taken with the use of the energetic source. The Contractor should not conduct the compliance monitoring, but should be required through the specifications to be cooperative in obtaining the compliance monitoring.

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