UNDERWATER BLAST PRESSURES FROM A CONFINDED ROCK REMOVAL DURING THE MIAMI HARBOR DEEPENING PROJECT

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ABSTRACT

Water-borne blast pressures from confined blasts were recorded as part of a submerged blasting program in Florida for channel deepening. The blasting was confined within the rock floor by stemming. Shot patterns of stemmed borings were recorded, as were two open-water shots. One hole of one shot was not confined properly, which allowed comparison of confined and a poorly confined larger charge weights per delay. The pressure data were intended to gain information on typical pressure measures from the rock removal program relative to impacts on marine organisms. Water-borne pressures from actual confined, rock-removal shots validate the hypothesis of lessened impacts to aquatic and marine biota.

INTRODUCTION

Blasting was part of the ongoing Miami Harbor Channel Deepening for the Dodge Island Widening (and Turning Basin). The blasting was confined within the rock floor to remove rock for channel deepening. Jacksonville District funded the study to take data from actual confined blasts to compare with open-water blasts. The project area is home to a number of protected, threatened, and endangered species including the Florida manatee, five sea turtle species, American crocodile and the bottlenose dolphin. Safety zones for these species were established around the blast area (Jordan et al. 2007). Pressure data were collected with the intention of demonstrating that pressures did not exceed safe levels previously established and that confined blasting produced much smaller kill radii than “open water” safety models predicted. Blast monitoring was conducted from 6 to 12 August 2005.

Explosives shot in open water will produce both higher amplitude and higher frequency shock waves than contained detonations. Thus, the use of blasting in rock removal during channel or harbor deepening projects should result in reduced pressures and lower aquatic organism mortality than the same explosive charge weight detonated in open water (Nedwell and Thandavamoorthy 1992; Marine Technology Directorate Ltd. 1996). This is important because most mortality models used to compute aquatic organism mortality by natural resource agencies were developed using open-water shot data that will overestimate demolition or embedded shots. However, published field verification of the pressure reductions during production blasting is nonexistent. The deepening project provided the opportunity to conduct pressure measurements during rock removal and compare those data with computed peak pressures for open-water explosions.

MATERIALS & METHODS

Types of Explosives and Initiation

The blasting agent used for the rock removal project was Pourvex PHD, a water slurry, manufactured by ETI Canada Ltd. The slurry has a specific gravity of 1.34, a detonation velocity of 20,000 feet/second (fps) [6,100 meters/second (mps)], and it is not cap sensitive, requiring a booster initiated by a blasting cap. The placed charges were 5.6 pounds (lb) per ft [8.3 kilograms(kg)/m] of the 4.5-inch (11-cm) diameter shot holes. The charges monitored during the study varied from a low of 17 lb (7.7 kg) to a maximum of 134 lb (60.8 kg) of charge weight per delay, depending on the height of rock relative to the dredge depth, decking, and the pattern's layout. Two High Detonation Pressure (HDP) boosters, distributed by ETI Canada Ltd., were used in each shot hole. Each booster had a weight of 1.0 lb (0.45 kg), a specific gravity of 1.60, and a detonation velocity of 26,000 fps (7,900 m/s).

The initiation system deployed a Detaline system dual path, precision delay, non-electric initiation cord and components. The system utilizes a fine, extruded detonating cord with a PETN explosive core of 2.4 grains per ft (0.51 g/m). The timing and delay sequence to the shot holes were achieved with "Detaslide Delays" detonators. The detonators were used in each booster and were connected via Detaline to "Detaline Surface Delays." The surface delays were connected to a dual trunk of Detaline. All the shot holes were drilled, loaded and connected to the dual trunk line. The shot was initiated using a "Noiseless Lead-in-Line." An instantaneous detonator was attached to a length of hollow shock tube that contains explosive dust. The entire shot was initiated by a blasting cap, which was fired into the shock tube connected to the trunk line delay system to the individual shot holes. By using a non-electric initiating system the shot was safely initiated and connected without concern for radio silence. Radios can initiate primary electrical initiation systems.

Shot Patterns

A typical section of material to be removed consisted of a foot of silty clay overburden, 6 to 8 ft (1.8 to 2.4 m) of the competent Miami Oolitic Limestone, over a low strength marl. The take elevation was -48 ft (-15 m) Elevation (EL), tidally corrected.

The August 2005 work was the closing removal near the port's south pier face. A planned pattern deployment positioned the drilling barges by surveying. Rock above the pay grade was drilled and shot. When rock was not encountered on the pattern above the pay grade, there was no need to place any blasting agent. This caused the shot pattern to be variable in size. The number of holes per row (termed ranges) and the number of ranges varied with the remaining high-rock surface topography. The spacing of shot holes along the ranges and between the ranges varied.

Stemming was used to confine the charge in each 4.5-in (11-cm) diameter shot holes to reduce blast pressures by restricting riffling into the water channel above the shot hole. The stemming was 5/8 to 3/4 inch (16 to 19 mm) particle size, crushed limestone. The stemming length was variable; the minimum stemming length was 3.5 ft (1.1 m) in the Miami Oolitic Limestone.

Pressure Recording and Analysis

The pressure transducer system consists of the arrayed transducers, cabling, timing, analog to digital conversion, and storage. The raw transducer voltage data and the previously acquired transducers' calibration allow calculation of the pressures at the location of the transducer.

There were two systems recording the pressures of Miami Harbor Rock Removal. The two deployed systems allowed the recordings to be more versatile to meet the needs of recording. One system was purchased by Contract Drilling and Blasting (CDB) and the second system was configured by St. Louis District (SLD), Corps of Engineers. Both systems used PCB Piezotronics transducers and constant-current source. The CDB system had a deck of analog to digital conversion and storage cards. The SLD system used a digital recording oscilloscope to accomplish the conversion and storage.

The transducers were suspended below buoys or off the side of a barge and referenced in position by surveying to the blast-hole pattern. CDB used three tranducers suspended by rope from a buoyed line at three regular positions 50-ft (15-m) apart. The CDB transducers were located approximately 5 ft (1.5 m) off the bottom (b), mid-water column (m) of about 20-ft (6-m) depth, and 5 ft (1.5 m) below the surface (t – top). The CDB m and t positions were taped to the rope, only the b transducer was free. The CDB system was capable of recording nine transducers and was triggered by a blasting cap at the start of the shot. The SLD system used four transducers and was triggered by exceeding a threshold pressure of the detonation cord leading to the loaded holes. The SLD transducers each were freely suspended a short distance apart hanging by the transducer cable with a weight attached below the transducer.

All the transducer data was corrected for the individual transducer's calibration. Pretest calibration was conducted by PCB Piezotronics. The pressure time history could then be analyzed. The pressures should be accurate to ± 5% to 8%. While the pressure data may be given with three digits, it is only accurate to one and a half significant digits.

Pressure Data for the Closest Holes

Pressure data by transducer are provided for four shots in Table 1. AP36, AP37 and AP38 are pattern shots with charge weights of 17, 32 and 32 lb, respectively. [Metric conversions are included when there are not multiple comparisons.] AP38 booster is the shot of an open-water (1 lb, 0.45 kg) booster shot at 20-ft (6-m) depth (midwater column). As may be noted in the table, AP36 had one shot that was very poorly confined. The reason for the lack of confinement is unknown, perhaps poor rock conditions or poor stemming placement. It is not known precisely which hole was poorly confined; it was likely the first or second hole furthest from the transducers.

Many holes were well confined by stemming and the strength of the rock in all three shots. A plume rose at the very poorly confined hole of AP36. Cavitation hats, high negative pressures at the water surface, occurred above holes that had less than full confinement. The closest holes, the last in time, for shots AP37 and AP38 may be used to develop an equation for well confined holes in this locale. Other rock locations are likely to have better confinement, but other rock stratigraphies would need to be investigated. Note in Table 1 the last column shows when the closest hole, best located and unambiguous for the data, has the maximum (1^{st}) or second maximum (2^{nd}) value of the entire record.

Table 1. Pressures and Parameters for Three Confined Shots and an Open-Water Charge.

					Entire Transducer Record				Closest Hole Values		
Blast	Max Charge Wt/Dlay (lb)	Transdr Des'gntn	Closest Lateral Apro'ch (ft)	Appro Dist (ft)	Max Pres (psi)	2nd Max Pres (psi)	Min Pres (psi)	2nd Min Pres (psi)	Max Pres (psi)	Min Pres (psi)	Sc Dis (fpp1/3
AP36 8 confined holes **less confined**	17	1, 50b	50	54	saturt'd	odd					
		2, 50m	50	62	saturt'd	odd					
		3, 50t	50	72	saturt'd	odd					
		4, 100b	100	104	263	84.4	-30.7	-24.2	obscr'd	obscr'd	
		5, 100m	100	112	207	50.7	-29.1	-26.9	obscr'd	obscr'd	
		6, 100t	100	122	saturt'd	odd					
		7, 150b	149	153	saturt'd	odd					
		8, 150m	149	161	201	36.2	-48.7	-28.1	obscr'd	obscr'd	
		9, 150t	149	171	saturt'd	odd					
		10, 100b	100	104	289	67.5	-30.0	-27.6	obscr'd	obscr'd	
		11,100m	100	112	274	58.3	-45.5	-29.3	obscr'd	obscr'd	
		12, 100t	100	122	275	69.5	-103.4	-54.7	obscr'd	obscr'd	
		13,100m	108	120	264	102	-70.3	-37.2	obscr'd	obscr'd	
AP37 12 confined holes	32	1, 50b	50	54	29.7	9.6	-14.4	-11.8	8.0	-11.8	17
		2, 50m	50	62	42.8	12.3	-22.9	-15.8	12.3	-10.9	20
		3, 50t	50	72	32.6	16.5	-20.4	-16.2	16.5	-20.4	23
		4, 100b	123	127	33.9	13.2	-9.4	-6.9	5.0	-6.6	40
		5, 100m	123	136	25.0	13.9	-9.1	-7.5	5.1	-5.0	43
		6, 100t	123	145	30.4	8.2	-17.7	-9.8	6.3	-5.7	46
		7, 150b	198	202	28.6	7.6	-5.9	-4.9	4.6	-5.9	64
		8, 150m	198	210	17.9	8.4	-6.8	-5.4	3.0	-4.8	66
		9, 150t	198	220	odd	displaced					
		10, Wb	159	163	41.6	9.4	-20.0	-7.0	2.6	-3.9	51
		11, Wm	156	168	23.9	13.4	-8.8	-6.3	3.2	-3.0	53
		12, Eb	164	168	18.3	5.6	-7.4	-4.9	2.1	-2.3	53
		13, Em	166	179	17.2	5.0	-13.1	-4.1	2.3	-2.2	56
AP38 **booster** 1 open water	1	1, Wb	85	87	46.3	16.9	-12.1	-5.2			85
		2, Wm	88	88	51.4	20.5	-34.7	-6.3			88
		3, Eb	62	64	61.2	15.1	-11.6	-8.4			62
		4, Em	64	64	66.9	11.8	-20.8	-11.1			64
AP38 12 confined holes	32	1, 50b	50	54	89.7	44.7	-24.3	-15.7	31.3	-24.3	17
		2, 50m	50	62	57.2	45.7	-26.7	-11.7	30.5	-26.7	19
		3, 50t	50	72	29.3	24.1	-21.4	-16.5	22.7	-21.4	23
		4, 100b	94	98	odd	cyclic					
		5, 100m	94	106	odd	cyclic					
		6, 100t	94	116	26.6	12.0	-13.6	-12.3	5.7	-13.6	37
		7, 150b	150	154	30.8	26.7	-16.2	-7.8	4.7	-16.2	48
		8, 150m	150	162	19.0	15.6	-12.5	-10.2	5.4	-12.5	51

	9, 150t	150	172	10.0	9.7	-10.0	-8.4	4.9	-10.0	54
	10, Wb	157	161	45.0	24.1	-14.0	-11.2	45.0	-11.2	51
	11, Wm	160	172	19.8	17.7	-19.2	-8.9	19.8	-8.9	54
	12, Eb	170	174	12.1	10.6	-9.9	-6.5	10.6	-9.9	55
	13, Em	168	180	11.3	10.4	-19.1	-7.2	11.3	-19.1	57

Des'gntn –Designation; Appro – Approximate; Sc Dist – Scaled Distance; fpp1/3 – ft/lb^1/3; saturt'd – saturated; obscr'd – obscured by a continuing cycle.

This Miami Harbor location shows that many holes were not as completely confined as desirable. Yet, every hole recorded in these confined shots had lower pressures than would have been recorded as an open-water shot of the same charge weight.

The closest hole of AP37 had no cavitation hat and clearly was well confined when shot. Figure 1.a shows the closest holes of AP37 in comparison the higher pressure at larger scaled distance for the open-water shot of a 1-lb (0.45-kg) booster (AP38 Booster). Note that the smaller charge (1 lb, 0.45 kg) from the further open-water shot produces greater pressures.

Sufficient data were available to produce a regression curve from the data of Figure 1.a. A modification of the regression curve to exceed all twelve points was determined. Following Cole's (1948) equation format, the maximum pressure, p_C, from the closest confined charge of the AP37 data is:

$$p_C \text{ (psi)} = 1{,}780\ SD_C^{\ -1.23},$$

where

SD_C = the confined scaled distance and $SD_C = d / (w_C^{\ 1/3})$,

D = the distance from the single confined blast to the point of pressure value, p_C, and

w_C = the maximum charge weight (in pounds) per delay of a single, confined blast.

The equation's values are plotted in Figure 1.a for values of confined scale distance.

The closest hole of AP38 was not as well confined. Figure 1.b includes all the data from the shots of AP37 and AP38 (all useable data) for the closest holes to the transducers. There is a single point that is an extreme outlier of AP38, SD_C of 50.8 feet per cube root of pounds (fpp1/3) of charge weight per delay and 45 psi [310 kiloPascals (kPa)]. A regression fit of the 22 points was adjusted until all the points, including the outlier, were beneath the curve. This conservative fit of the data is:

$$p_C \text{ (psi)} = 5{,}640\ SD_C^{\ -1.23}\ . \qquad [1]$$

This latter Equation 1 should give an upper bound to well confined charges for Miami Harbor. The Equation 1's values are plotted in Figure 1.b for values of confined scale distance.

Calculation of Mortality Radius

Cole's equation for open-water pressures was manipulated using Hubbs and Rechnitzer's (1952) lower bound of lethal pressure value of 40 psi (280 kPa). This equation was previously used by Hempen et al. (2005). The mortality radius for single, open-water shots, MR_{OW}, is:

$$MR_{OW} \text{ (feet)} = 260\ w_{OW}^{\ 1/3}, \qquad [2]$$

where

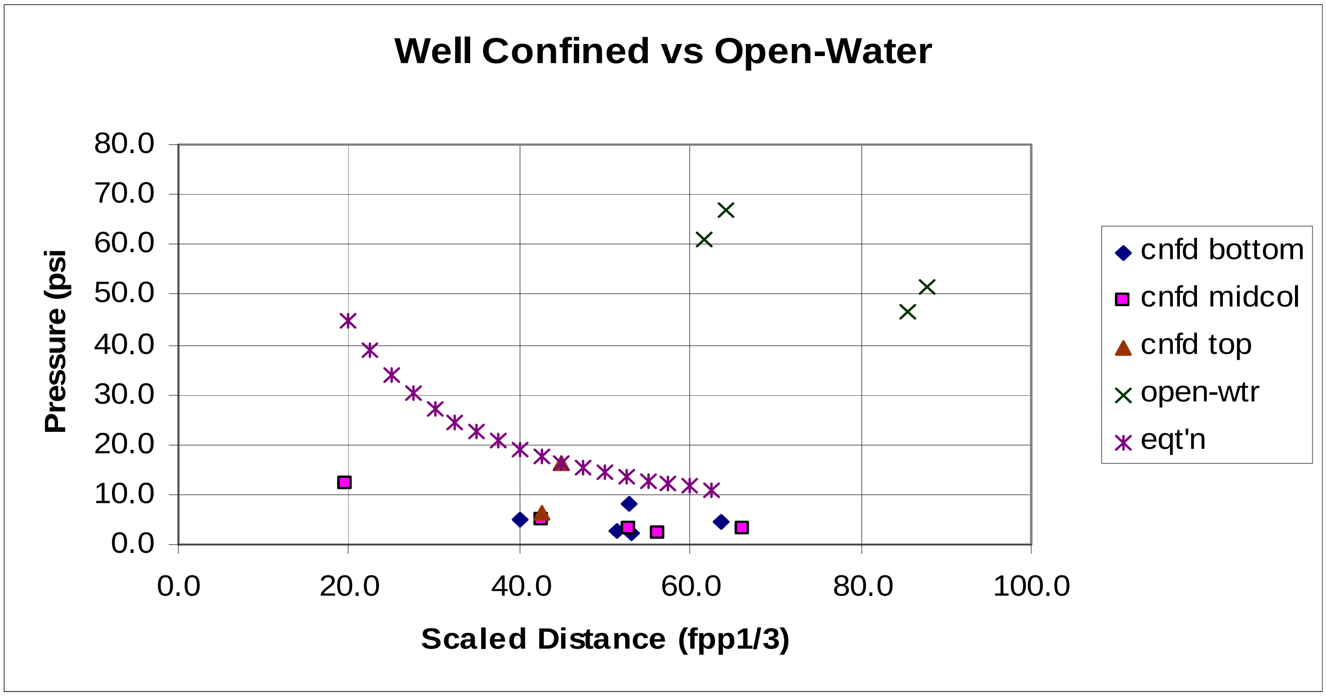
w_{OW} = the maximum charge weight (in pounds) per delay of a single, open-water blast.

Equation 1 was developed as a conservative estimate of pressure from the closest confined holes at Miami Harbor. The mortality radius for confined shots may be resolved from the confined pressure Equation 1 and using the low lethal pressure of 40 psi. The mortality radius for single, confined shots, MR_C, is:

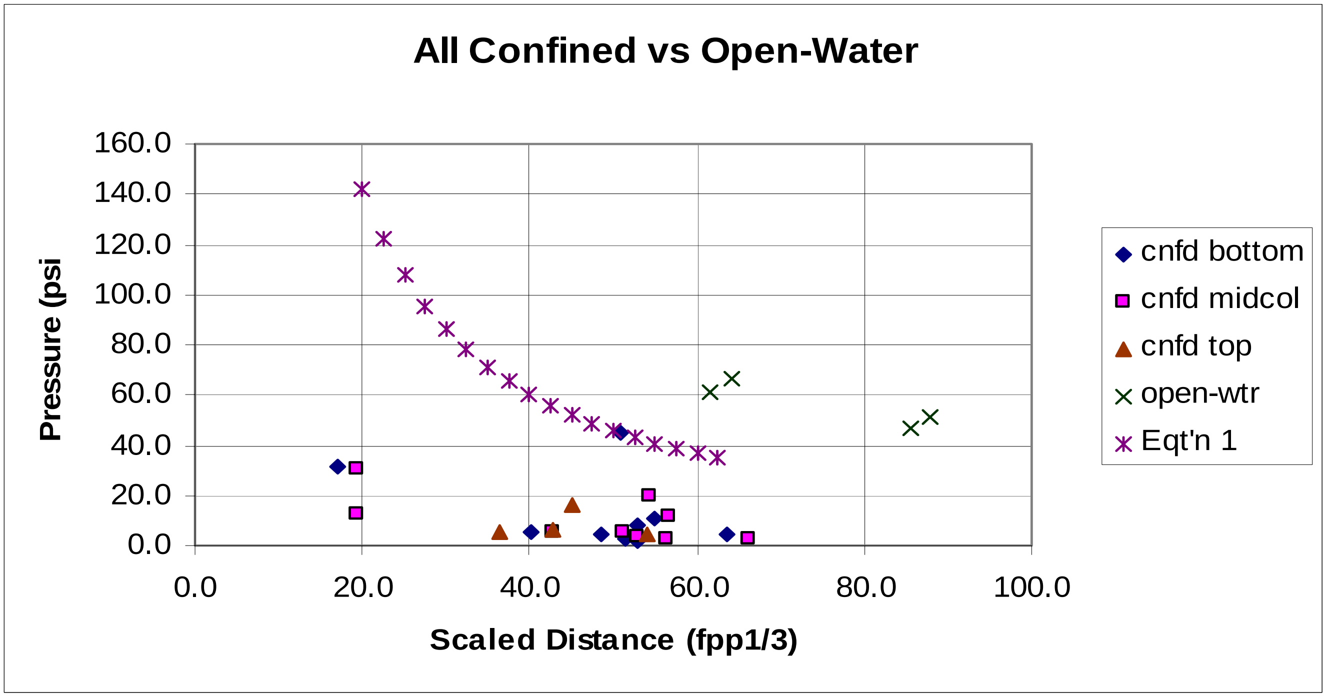
$$MR_C \text{ (feet)} = 56\ w_C^{\ 1/3}, \qquad [3]$$

where

w_C = the maximum charge weight (in pounds) per delay of a single, confined blast.



a. Graph of the Well Confined Holes of AP37 compared to the Open-water Booster shot.



b. Graph of Shots AP37 and AP38 Confined Holes compared to the Open-water Booster shot.

Figure 1. Graphs of the Closest Hole Parameters for the Transducer Locations.

If the equation for well confined shots had been used of AP37 and Figure 1.a, the coefficient would have been only 22. The coefficient of 56 in Equation 3 compares favorably with the mortality equation of Kill Van Kull (New York Harbor) Deepening Project, noted herein as KVK, of 80 (Hempen, et al. 2005). The KVK work had less data and its data was less well defined.

RESULTS

The pressures of the rock removal shooting have been well recorded. Quality, maximum pressures are provided in Table 1. The maximum pressures and their waveforms show very short duration peaks that may be related to the complex shot pattern and pathways of the waves. Impulse parameters of the better records were developed, but are not the subject of this paper**.**

DISCUSSION

The maximum pressures from the confined shooting were significantly lower than much smaller charges shot in open water. For Example, the kill radius of the 1-lb (0.45-kg) booster shot in open water, based on the results of Equation 2, was 260 ft (80 m). The kill radius would have only been 56 ft (17 m), as a conservative assessment, for a 1-lb charge that was confined by stemming within rock at Miami Harbor. The same charge may only have a kill radius of 22 ft (6.7 m) or smaller when confined within competent rock that was properly stemmed for confinement. The kill radii for the confined shots recorded at Miami Harbor of 17, 32, 67, and 134 lb/delay may have been calculated as 140, 180, 230 and 290 ft, respectively. Radiation of the wave energy into rock reduced the available energy reaching the water column. The pressures entering the water column were well below those pressures that typically propagate away from open-water (unconfined by solid media that may radiate the energy away with less harm) charges relative to charge weight per delay.

These study results corroborate previous laboratory studies and field studies that found reductions in peak pressure from confined shots. Nedwell and Thandavamoorthy (1992) compared the pressure time histories from the detonation of small explosive charges (1.8 g ICI Star detonator No. 8) in both free water and embedded in concrete blocks under laboratory conditions. They found that the peak pressure of the water-borne shock wave following the detonation of an explosive charge embedded in a borehole was about 6% (94% reduction) of that occurring for the same charge at the same distance, when it was freely suspended in water. Hempen et al. (2005) evaluated pressure reductions during channel deepening for the KVK. They compared pressures from four confined shots with computed open-water pressures and found that the confined pressures were only 19 to 41% (81 to 59% reductions) of open-water pressures. The mortality radius was 30% of the open-water shot and the mortality area of the confined shot would be only 9% of the mortality area for the open-water shot. Note that for the KVK, the largest calculated fish mortality was 350 ft (105 m) for a shot pattern containing 28 boreholes, with an 87 lb being the largest charge per delay shot. The mortality radius for moderately confined holes of Miami Harbor was 22% of the open-water shot and the mortality area of the confined shot would be only 5% of the mortality area for the open-water shot.

The maximum pressures recorded were related to the maximum charge weight per delay and clearly were unrelated to the total weight of blasting agents (e.g., sum of all the explosive weights in the bore holes detonated in a shot) that were detonated. The shot pressures were relatively uniform, while the shots varied significantly in total charge weight. Total charge weights for the blasting cap, 1-lb booster, and three pattern shots were: 1 cap, 1 lb, 136 lb, 408 lb and 408 lb. [Data for the blasting cap was recorded but is not reported within this paper to save space.] Maximum recorded pressures (without correcting to a common distance) in order of total charge weight were: 41 psi, 67 psi, 290 psi, 43 psi, and 90 psi. It is easy to note the largest pressure of 290 psi {2,000 kPa [136 lb (61.7 kg), total charge weight; 17 lb (7.7 kg), charge weight per delay]} was for the poorly confined hole of AP36. The range of total charge weights exceeds a multiple of 1,000, while the maximum pressures clearly do not correlate to total charge weight. Parameters other than total charge weight control the maximum pressure and impulse. Hempen et al. (2005) found similar results for the KVK. KVK Shots 014 and 010 produced comparable peak pressures. Shot 014, had only two shot holes, with a maximum charge weight per delay of 72 lb {33 kg (total charge weight of 98 lb (44 kg)]}, while shot 010 had 25 shot holes, with a maximum charge weight per delay of 73 lb {33 kg [total charge weight over 1,500 lb (680 kg)]}. These results support the suggestion of Munday et al. (1986) that the use of delays effectively reduces each detonation to a series of small explosions. Resulting blast overpressure levels are directly related to the size of the charge in each delay, rather than the summation of charge weights detonated in all holes. The use of delays has been suggested as a potential mitigation measure to reduce pressure exposure to aquatic organisms (Keevin 1998).

There are a number of physical attributes of the pressure waveform from the confined shots measured in this study that suggest that mortality would be lower than indicated by the peak-pressure measurements. The rapid oscillation from a high, brief overpressure and a moderate, but longer, underpressure associated with detonation of high explosives in the water column is most probably responsible for organ damage and mortality in fish. This oscillation in waveform is responsible for the rapid contraction and overextension of the swimbladder resulting in internal damage and mortality (Wiley et al. 1981). It has also been suggested that the negative phase (relative to ambient) of the pressure wave is responsible for organ damage (particularly the swimbladder) and mortality (Anonymous 1948; Hubbs and Rechnitzer 1952 and Wiley et al. 1981). During the current study, the abrupt compressing pressures, usually associated with the detonation of high explosives, were reduced in amplitude and negative pressures were small relative to the background noise.

Hubbs and Rechnitzer (1952) determined that the lethal threshold peak pressure for a variety of marine fish species exposed to dynamite blasts varied from 40 psi (280 kPa) to 70 psi (480 kPa). The more conservative pressure of 40 psi from Hubbs and Rechnitzer (1952) was used to develop Equations 2 and 3, even though their range extends much further than for 70 psi. Keevin (1995) found no mortality or internal organ damage to bluegill exposed to a high explosive at pressures at or below 60 psi (420 kPa). The 40-psi value is also conservative because the waveform of the mortality value was established from an open-water testing program and not from similar confined shots that did not have clear extension (negative pressure) phases for measurable impulse and energy measures. There is some evidence, as previously stated, that confined shots may not have mortal pressures as low as those for open-water shots, but this conclusion requires further testing.

This study clearly demonstrates that explosives shot in open water will produce both higher amplitude and more rapidly oscillating shock waves than rock removal shots. Thus, the use of blasting in rock removal will result in lower aquatic organism mortality than the same explosive weight detonated in open water. This conclusion is important because the majority of aquatic organism mortality models were developed using open water shot data that will overestimate rock removal shot mortality. Safety zones calculated using open water mortality models are used to establish watch plans and optimal observer locations to protect aquatic organisms (Jordan et al. 2007). If the observation area becomes too large, based on the use of open-water shot pressures, then there is also the possibility that the level of intended species protection is diminished. It is much easier to monitor a small area than a very large area. As the dimensions of a watch zone unnecessarily increase, there is undoubtedly a safety radius that would also preclude blasting because of the high cost of monitoring, long blasting delays due to aquatic organisms wandering into the enlarged blast zone, and the reduced efficiency of being able to protect the organisms of concern.

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