Predicted and measured underwater noise levels from the implosion of a re-enforced concrete bridge pier

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ABSTRACT
After the completion of the new east span of the San Francisco-Oakland Bay Bridge in California, large concrete piers of the old span needed to be demolished. In order for this to be considered using controlled blasting, hydroacoustic levels were predicted and monitored with regard to specified fish and marine mammal criteria. The metrics included peak pressure and sound exposure levels (SEL) at distances from 25 to over 4,000 feet from the pier. For peak pressure, the measured levels were slightly higher than estimated while for SEL, the measured levels were somewhat lower than estimated due to the effect of surface reflection. A blast attenuation system (BAS) consisting of a wide bubble stream was used to minimize the hydroacoustic levels in the water surrounding the pier. The implosion event consisted of 588 individual charge detonations ranging from 15.9 to 9.5 kg/delay spaced 9 m-sec apart. Although there were 135 individual detonations of the larger 15.9 kg charges, the highest peak pressures varied in level by 10 to 15 decibels during the course of the implosion. In this paper, the methods for predicting the levels, the measured results, analysis of the data, and the performance of the BAS are reviewed.

Keywords: Underwater, Demolition, Blasting

1. INTRODUCTION
In July 1933, construction of the San Francisco-Oakland Bridge (SFOBB) began and by November 12, 1936 it was opened to vehicular traffic. At a length of 7.24km, it was the world’s longest steel structure at that time. The bridge consists of two segments, the first from Oakland to Yerba Buena Island (YBI) in the middle of the San Francisco Bay and second from YBI to San Francisco. On October 17, 1989, the Loma Prieta earthquake struck the San Francisco Bay Area, measuring 7.1 on the Richter scale. The east span of the SFOBB, connecting the two cities, suffered a collapse of its upper deck span closing the Interstate I-80 for one month. In the wake of this disaster, the California Department of Transportation (Caltrans) took steps to seismically retrofit the flexible west span of the bridge and replace the rigid east span structure. The new self-anchored, single tower, asymmetrical span opened in September 2013. Afterwards, the next concern was removing the old east span, particularly removal of the large concrete piers that support the structure. Several methods for removing the pier were considered, including mechanical removing and explosive methods. After some study, it was determined that removal by a controlled implosion would potentially have less environmental impact on fishes and marine mammals than prolonged mechanical removal. It was decided that the largest pier, Pier E3, would be imploded as a demonstration project to assess whether this method could be used on the remaining 14 piers. Prior to the approval of the Pier E3 implosion, the underwater sound levels had to be predicted in order to obtain permits from the various regulatory agencies. On November 11, 2015, Pier E3 was imploded and the underwater sound levels monitored. This paper summarizes the prediction methods used, the monitoring plan, and its results compared to predictions.

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2. IMPLOSION PLANNING

2.1 Description of the Blast Plan

Pier E3 is a large reinforced concrete structure constructed with interior chambers running the length of the pier, as can be seen in the construction photograph shown in Figure 1. The dimensions and cross sections are shown in Figure 2. The inner and outer walls of the pier are 1.2m thick. The blast plan called for drilling 70 to 76mm diameter holes down through the middle of these partitions in the structure and placing charges at five depths along the holes. The implosion event consisted of a total of 588 individual explosions of 8 different charge weights, varying from the largest of 15.9kg/delay to the smallest of 9.5kg/delay. The blasting sequence was rather complex and is shown schematically in Figure 3. Blasts would start in several interior webs of the southern portion of the structure followed by the outer walls of the south side. The blasts in the inner walls would occur just prior to the adjacent outer walls. The interior first, exterior second blast sequence continued across the structure, moving from south to north. The time for the 588 detonations was 5.3 seconds, with an average delay time of 9 milliseconds (ms) between individual detonations. As the blasting progressed, locations to the east, north, and west of the pier were shielded from the blasting on the interior of the structure from the still standing exterior walls of the Pier. However, towards the conclusion of the blast, each direction experienced blasts from the outer walls that were not shielded. The plan also called for a Blast Attenuation System (BAS) which consisted of an air bubble curtain wall completely surrounding the pier as shown in Figure 4.

2.2 Biological Criteria and Metrics

In order to gain permission from the various agencies, estimations of the distances to injury thresholds for fish and marine mammals needed to be calculated. For fish, the thresholds are dual and expressed in Sound Exposure Level (SEL) and peak pressure. In the absence of specific blast criteria, those used for underwater Impact pile driving applied. As established by the National Marine Fisheries Service for the onset of injury, the SEL criteria of 187 dB re 1 \( \mu \text{Pa}^2\)-s for fish more than 2 grams and 183 dB re
The peak pressure level threshold for injury to fish is stated to be 206 dB re 1μPa. For marine mammals (MM), the primary consideration was for the distance to the hearing Permanent Threshold Shift (PTS), expressed in SEL and peak pressure criteria. These criteria vary with species and have different weighting filters defined for five MM categories. Prior to implosion, the zone inside these thresholds were monitored for the presence of these MM, including sea lions, seals, and porpoises. If MM were present, the implosion would be delayed until they exited the area. The values of these SEL thresholds were 215 dB re 1μPa²-s for sea lions, 192 dB for seals, and 161 dB for porpoises. The peak pressure level criteria were considered also; however, the SEL criteria would be exceeded before the peak pressure level criteria.

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Figure 4 - Schematic drawing of Pier E3 with the installation of the Blast Attenuation System

3. Prediction Methods

3.1 Calculation Assumptions

As far as could be determined, the structure and blast plan were unique, and there was no previous experience to aid in estimating what the underwater sound levels would be. The prediction methods for open water, unconfined single blasts are well defined in the literature. As a result, this type of blast was used as the starting point. To apply these methods, several assumptions were made. First, it was assumed that there was only one blast distance, and it would occur at the closest point on Pier E3 from the receiver point. Given the size of the structure, this was a conservative assumption as the actual distance to all except the very closest charge on the outer pier wall would be greater, creating additional attenuation. Second, it was also assumed that there would be no self-shielding by the pier as the explosions progressed. Given the blast plan shown in Figure 3, this is also a conservative assumption for the SEL calculation, at least for some directions. Additionally, since the charges will be placed in holes drilled into the center of the walls and interior partitions, individual blasts should not be exposed to open water, and some confinement of the blasts was expected. For confined blasts, the calculated pressures can be reduced by 65% to 95%, (1,2,3,4) corresponding to multiplication factors from 0.35 to 0.05, respectively. Based on a review of the available literature and recent data from concrete explosive projects, a conservative confinement factor 0.3475 was assumed. Finally, only the direct wave from any individual blast was considered. Although this assumption has no effect on the peak pressure estimation, it can affect the SEL. In general, the signal at the receiver point could consist of the direct wave, surface-relief wave generated at the water/air interface, a reflected wave from the bottom, and a wave transmitted through the bottom material (5). Given the muddy nature of the San Francisco Bay bottom in the area of Pier E3, bottom reflections and transmission were expected to be minimal. The surface-relief wave is negative, so that when it arrives at the receiver location, it will reduce the positive pressure of the direct wave depending on its arrival time. Close to the pier where the direct and surface-relief waves are separated in time, it could actually increase the SEL since SEL is a pressure squared quantity. However, this increase would be on the order of 3 dB or less for the overall level.
3.2 Peak Pressure

Peak pressures were calculated by following the modified version of the Cole Equation for calculation of blasts in open, deep water (6). The peak pressure is determined by:

\[ P_{pk} = K(\lambda)^{-1.17} \]  \hspace{1cm} (1)

where \( P_{pk} \) is peak pressure in psi (1 psi = 6894.8 Pa), and \( \lambda \) is the scaled range given by \( R/W^{\frac{1}{5}} \), in which \( R \) is the distance in feet (1 ft = 0.3048 m), \( W \) is the weight of the explosive charge in pounds (1 lb = 0.454 kg), and \( K \) is the charge confinement factor. A modified version of the Cole Equation has been documented in U.S. Army Corps of Engineers (USACE) Technical Letter No. 1110-8-11(FR) and is applicable to shallow water cases, such as that of the Pier E3 demolition. In the USACE equation the only difference is that \( K \) taken as is 21,600 for an open-water blast instead of the 22,550 from the original Cole Expression. The confinement factor discussed under the assumptions corresponds to a \( K \) factor of 7,500. A BAS was specified in the blast plan. Based on the literature and recent results from similar projects, reductions in the pressure peak of 85% to 90% or more could be expected for a planned wall of air bubbles. For determining \( P_{pk} \) in this analysis, a conservative reduction of 80% was used. The calculated peak sound pressure levels for an open water blast and a confined blast with and without the BAS are shown in Figure 5, as a function of distance from the pier along with the \( L_{pk} \) criterion for fish.

![Figure 5 - Calculated peak pressure levels for Pier E3 implosion for scenarios of confinement and BAS performance](image)

3.3 Sound Exposure Level

To calculate SEL values as a function of distance from the blast, pressure versus time histories for all of the 8 charge weights were calculated for varying distances. The open-water equation used for these calculations was that modified by the USACE (5), and based on methods developed by Cole (6). Pressure as a function of time is given by:

\[ p(t) = P_{pk} e^{-\left(\frac{t - t_a}{\theta}\right)} \]  \hspace{1cm} (2)

where \( t_a \) is given as \( R/5000 \) and \( \theta \) is:

\[ \theta = 6.0 \times 10^{-5} W^{\frac{1}{5}} (\lambda)^{0.15} \]  \hspace{1cm} (3)

Some of the time histories produced by these equations are shown in Figure 6 for varying distances from the blast. To calculate SEL, time histories were determined for distances from 6 to 4,888 m for...
each charge weight used in the implosion plan. These time histories were then summed numerically to determine SEL using the expression:

\[ SEL = 10 \log_{10} \left( \sum_{i=0}^{t} \frac{p_i^2}{p_{ref}^2} \Delta t_i \right) \]  

(4)

Figure 6 - Calculated blast pressure time histories for different distances from the blast

To determine the SEL for all 588 blasts, the single blast SEL values, as a function of distance, were calculated for each of the charge weights. For each weight, the SEL was determined by adding 10Log(N), where N is the number of the blasts for each weight. These SEL values for each charge weight were then summed (on an energy basis) to get the total implosion event SEL for the unconfined blast sequence. To account for the confinement factor of 0.3472 (K=7,500), 20Log(0.3472) or -9.2 dB was added to the unconfined values.

The BAS would have an effect on the wave once a blast passes through it. Bubble curtains of the type to be used for Pier E3 have been found to reduce the peak pressure and elongate the pressure time history (5). It has also been found for an energy metric, such as SEL, that the reduction produced by the BAS was equal to or greater than the reduction of the peak pressure (1,5,6). To estimate the reduction for SEL values due to the BAS proposed blast design, SEL was reduced by 80%. Effectively, this was done by reducing the SEL by 20Log(0.20), or 14 dB. The unconfined, confined and SEL values with the BAS were then compared to the fish criteria of 183 dB and 187 dB, as shown in Figure 7, as a function of distance. Because the calculation of SEL is based on the peak pressure, these calculated values for the direct wave component were expected to be conservative for the same reasons as described in the discussion for the peak pressures.

For the mammals of concern in the vicinity of Pier E3, seals (Phocidae), sea lions (Otariidae), and porpoises (High Frequency Cetaceans), specific filters needed to be applied. To apply these weightings, the Fast Fourier Transform (FFT) was calculated for the pressure time histories at each analysis distance. Each FFT was then filtered using the frequency weighting specified for each group/species. Filter factors were then determined for each distance by subtracting the filtered result from the unfiltered FFT data and determining the overall noise reduction in decibels due to the filters. These filter factors were then applied to the SEL determined for the entire blast event for a series of distances from Pier E3.

4. Underwater Sound Monitoring

4.1 Monitoring Locations and Methods
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Underwater sound was measured at 13 locations during the implosion event. These were divided into near field and far field locations. The near field locations ranged from inside the BAS, about 7.6m from the pier, to 46.6m away. The far field measurements ranged from 152 to 1219m. With very rapid rise times expected for individual blasts nearer the pier, PCB 138A05 or 138A01 pressure transducers were used to capture signals in this area. These transducers were capable of measuring levels of 271 dB re 1μPa and 257 dB re 1μPa, respectively, with a frequency response up to 1,000 kHz. The outputs of these transducers were recorded by MREL Data Trap II high speed recorders sampling at 1,000,000 samples/second. In the far field, a mixture of pressure transducers and hydrophones and recorders were used. At 152m, it was intended to compare a high speed system to a moderate speed system typically used for measuring underwater sounds from impact pile driving. Both the PCB 138A01 and the Reson TC4013 hydrophone were recorded with Dash 8HF high speed recorders at a sample rate of over 1,000,000 samples/second. The hydrophone had an upper frequency range of 170 kHz. The hydrophone signal was also recorded using Roland solid state recorders sampling at 96,000 samples/second. For locations beyond 152m, hydrophones and solid state recorders were used at all locations. The locations of the near and far field monitoring systems are shown in relation to the pier in Figure 8. The water depths at both the near and far field locations were 12.2 to 15.2m, and transducers and hydrophones were suspended to a depth of 6.1m.

For the hydrophones, the recordings were calibrated with a pistonphone calibrator and hydrophone coupler. For the pressure transducers, the recorded voltages were transformed into pressure versus time using the calibration sensitivity for each sensor. The analysis was simply performed using the digital pressure time histories to identify the peak pressure level and the squared and summed pressure to produce the energy of SEL over the time of the entire implosion event. The appropriate references were applied to report the peak pressure level in dB re 1μPa and SEL dB re 1μPa²-sec. The signals from the solid state recorders were also processed using a Larson-Davis 3000 Real Time analyzer to obtain SEL values in one-third octave band for the duration of the implosion.

4.2 Monitoring Results

The peak pressure levels and SEL values for all of the monitoring locations are shown in Figure 9, along with the corresponding fish criteria. The measured peak pressure levels typically fall on or above the calculated curve. The logarithmic trend line determined by the peak levels is almost parallel to the...
predicted level and is offset by about +3 dB. For SEL data, the measured levels fall on or below the calculated curve, except at one near field measurement location. The trend line of these data decreased at a higher fall-off rate with distance than the calculated level, with a difference reaching about 15 dB at 1,219m. Also indicated in Figure 10 are data points that were acquired by the pressure transducers
and high speed recorders and those that were acquired by hydrophones. At the 152.4m monitoring location, data from both types of transducers were obtained in parallel on a high speed recorder. At this location, the two transducers give almost identical results, with the hydrophone being about ½ to 1 dB lower. The waveforms captured at this location are virtually identical, as shown in Figure 10.

The rise time for the peak pressure appears to be equally well captured by both transducers. The pressure transducer signal does indicate more inherent noise than the hydrophone. This is likely a result of its much lower sensitivity, 1mV/psi versus 194mV/psi for the hydrophone. The same hydrophone signal recorded with a solid state recorder at the lower sample rate was found to produce a peak pressure that was about half of that obtained by the high speed recorder. A comparison of these two recorded signals is shown in Figure 11. The recording from the solid state recorder at 96,000 samples per second does not rise as quickly as that from the high speed recorder at 2,000,000 samples per second, and the recording from the solid state recorder produces a lower positive and negative signal.

To assess the impact on fish, the distances at which the predicted and measured data trend lines intersect the criteria are most important. For the peak level criterion, the distance to the threshold was greater than predicted; 355m actual vs. 250m predicted. For the SEL criteria, the measured distances were substantially less than predicted; 271m vs. 777m for larger fish and 375m vs. 1,219m for smaller fish.

The time histories of sound pressure level for the four far field distances measured along the south line are shown in Figure 12. In this direction, the highest peaks occur in the first two seconds of the implosion event. From the highest peak occurring about 0.5 seconds into the event, the peaks tend to decrease in amplitude with time. For the blast plan, as shown in Figure 3, this is expected as the blasting moves south to north, and the distance from the blasts to the monitoring locations increases.

For the south direction, it is particularly apparent that the “peaky-ness” of the sound pressure levels generally decreases with increased distance from the blasts. This can be seen by considering the peak that occurs at a time of approximately about 1,500 milliseconds shown in Figure 12. At the distances of 152.4 and 250m, the peak is much higher in level than the surrounding levels by about 20 dB. At 475 and 1,219m, this same peak is only about 10 dB greater than the surrounding levels. An interesting exception to this is the peak that occurs at the 1,000-millisecond grid line. In this case, the peak at 1,219m remains quite “sharp” and is about 20 dB higher than the surrounding data.

For measurements on the east side of the pier, as the blasting progresses, the levels are expected to be rather uniform as the distance to the monitoring locations are similar for the entire sequence of the implosion. The pressure time histories for monitoring location along the east measurement line are shown in Figure 13. For most of the event, the peaks are more uniform than the south monitoring
results of Figure 12. However, at about 800msec, two peaks occur that are about 12 to 15 dB higher than any of the others. Based on the range of charge weights, the calculated peak sound pressure levels for the 588 individual charge weights only cover a range of about 2 dB, relative to each other, when distance to the blast and self-shielding by the structure were neglected. Aside from the two large peaks, the variation in peak level over the duration of event, as shown in Figure 13, may be consistent with these two assumptions. For the two large peaks, other circumstances may have contributed to the high levels. Two possible explanations are less confinement than the other charges or a local weakness in the BAS. The data point in Figure 9 that exceeds the measured peak level trend at 152.4m corresponds to the highest peak in Figure 13. This introduces a statistical nature to the prediction of the peak pressure levels which was not considered in the calculation of expected levels.
This is clear from Figure 13 as individual blasts that should all be about equal within 3.4 dB, with 2 dB.

For marine mammals, the criteria of most concern are those for PTS that are based on SEL with proper weighting for the particular species. The monitoring results for the relevant marine mammals are shown in Figure 14. Of the three species considered, porpoises reach their threshold at a further distance than the other two. Based on Figure 8, the zone that had to be monitored for marine mammals and particularly for porpoises, extended out to 1,768m. Based on measured trend lines, this distance needed to extend out to only 542m. This is important for implosion of the remaining piers, as considerable effort was required to visually monitor for marine mammals out to the predicted distance.

### 5.0 Enhanced Prediction of SEL

From Figure 9, it was apparent that the prediction method for SEL needed to be modified to produce...
lower calculated levels to better match the measurements. To understand the limitations of the method used, SEL values were analyzed, as a function of frequency and distance. These data displayed behaviors that indicated interference effects created by the surface reflection wave were possibly occurring.

To examine the possibility of interference effects further, several cases of surface reflection were considered using pressure waveforms, such as those shown in Figure 6. This was done by combining the direct positive waveform with the corresponding negative waveform delayed by the difference in arrival time between the two waveforms. An example of this is shown in Figure 15 for the distance of 213m from blasts at 1.5, 6.1, and 12.2m depths and a receiver depth of 6.1m. At a depth of 1.5m, the total SEL is reduced by 6.6 dB, compared to the direct waveform SEL. At a depth of 6.1m, the cancelation effect is more moderate, with only a 1.4 dB reduction in SEL for the total value. At a depth of 12.2m, the reflected waveform is delayed sufficiently so the total SEL is greater than the direct SEL. These calculations were repeated for distances ranging from 30.5 to 1981m. The results of these calculations, as function of distance, are shown in Figure 16 for the three depths. For blasts near the surface, the resultant SEL curve almost matches the trend line of the measured data. This analysis indicates that it is important to consider the surface reflected waveform in the SEL predictions.

6.0 Conclusions
The methodology developed for prediction, based on classical theory, performed reasonably well, particularly given the uncertainties of this rather unique implosion event. The surface reflected waveform in the analysis should be included or accounted for in the predictions of SEL. The assumptions of a factor of 0.3475 for confinement and 80% efficiency of the BAS seemed to work in this particular case. Since the measured peak levels were higher than estimated, some small modifications to the assumed confinement and/or BAS factors may be appropriate, although it is not clear which
Figure 16 - Calculated SELs for direct and combine direct and reflected pressures and measured results from Pier E3 compared to criteria fish criteria should be altered based on the results. Possibly more important in accurate prediction is the inclusion of some uncertainty factors given the variability in measured peak pressure level over the duration of the 588 individual blasts. For monitoring, at least at distances of 152.4m and beyond, the hydrophone with a maximum frequency range of 170,000 Hz captured the blast waveforms as well as the pressure transducer and possibly better when the inherent noise of the pressure transducer is considered. As distances up to at least 152.4m, the signals need to be captured with a high sampling rate, of at least 1,000,000 samples per second. Additional comparisons are needed to determine where lower rates could be tolerated.

7.0 Acknowledgements

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8.0 References