Hydroacoustic Modeling of Pile Driving for the South-Central Region of San Diego Bay

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Abbreviations, Acronyms and Symbols

*	multiply
3D	three-dimensional
µPa	microPascal
ASCII	American Standard Code for Information Interchange
dB	decibels
Caltrans	California Department of Transportation
ESRI	Environmental Systems Research Institute
f	acoustic frequency
FHG	functional hearing group
ft	feet
ft/s	feet/second
GIS	geographic information system
Hz	hertz
kHz	kilohertz
kg/m^3	kilogram/cubic meter
L_{50}	statistical noise level exceeded "50" percent of the time
m	meters
MMPA	Marine Mammal Protection Act
m/s	meters/second
NAVFAC SW	Naval Facilities Engineering Command Southwest
Navy	U.S. Department of Navy
NBSD	Naval Base San Diego
NEPA	National Environmental Policy Act
NMFS	National Marine Fishereis Service
NOAA	National Oceanic and Atmospheric Administration
Nx2D	two-dimensional approach
PTS	permanent threshold shift
r	range
re 1 µPa	referenced to one microPascal
re 1 μPa^2-s	referenced to one microPascal squared seconds
RMS	root mean square
s	second
SEL	sound exposure level
SEL_{cum}	cumulative sound exposure level over 24 hours
S(f)	spectral weighting function
SPL	sound pressure level
TDI	Tierra Data, Inc.
TL	transmission loss
UW-APL	University of Washington-Applied Physics Laboratory
z	receiver depth
ZOI	zone of influence

1.0 Executive Summary

This report summarizes the modeling of the underwater sound field from pile driving or extraction associated with marine construction activity at Naval Base San Diego (NBSD), San Diego Bay. Three locations were modeled, representing northern, central and southern areas within NBSD (Figure 1-1). The modeling incorporates the complex bathymetry in the vicinity along with effects due to shadowing by landforms and bay geometry. The modeling also incorporates differences in pile type (concrete, steel, plastic), in terms of the pile source frequency spectrum, and the effects of marine mammal functional hearing group (FHG) weighting on this spectrum. FHG weighting is only applied for Otariid pinnipeds since California sea lions (*Zalophus californianus*) are the only marine mammal expected to occur in south-central San Diego Bay (U.S. Navy [Navy] 2019). Modeling results are in the form of acoustic transmission loss (TL) referenced to a source location 10 meters (m; 33 feet [ft]) from the pile, where TL at this range is defined as 0 decibels (dB). Underwater noise levels 10 m (33 ft) from the pile that depend on pile type were input as source values for calculating distances to marine mammal acoustic injury and disturbance thresholds based on modeled TL. Spatial maps of modeled zones of influence (ZOIs) relative to acoustic thresholds are presented for a range of pile sizes and types at the end of this report.

Figure 1-1. South-Central San Diego Bay modeling locations at Naval Base San Diego.

2.0 Modeling Approach

The University of Washington-Applied Physics Laboratory (UW-APL) modeled acoustic TL based on approaches outlined in Dahl et al. (2015), Dahl and Dall'Osto (2017), and Dall'Osto and Dahl (2017). Other approaches (e.g., Lippert et al. 2018) share some similarities but were not used because of the significant bathymetric variation associated with the project area.

For this model, the general method involves representing the wetted length of the pile as a line distribution of sound sources, with the line source length corresponding to water depth at the pile location. This approach differs slightly from Dahl et al. (2015). In particular, here the necessary acoustic normal modes[1] are added together incoherently, or without regard to the phase of each mode function. This allowed for the simplifying assumption of uniform excitation over the length of the line source, rather than computing individual sources separately. The accuracy of this approach was confirmed by matching precisely the pile driving data given in Dahl et al. (2015, e.g., as shown in Figure 4 of that study).

The same approach was taken for each pile type regardless of pile composition (concrete, steel or plastic), with the influence of pile type and noise metric (e.g., Peak or Sound Exposure Level [SEL]) subsequently added to the final result in terms of a calibration factor based on correspondingly measured underwater sound data taken at a range of 10 m (33 ft) from the pile. This means both impact pile driving, and vibratory pile driving were treated in the same manner, apart from differences in their underwater sound data measured at a distance range of 10 m (33 ft). This was because the goal was to model the averaged transmission or propagation loss, and not necessarily to produce detailed waveform simulations. Thus, for example, the detailed, pressure waveform simulations given by Dahl and Dall'Osto (2017) associated with the Mach wave from impact pile driving are necessarily averaged out over range and since a non-averaged result provides little additional information.

As described in Dahl et al. (2015), the complex pressure field, $p(r,z;f)$ at acoustic frequency (f), range (r), and receiver depth (z) is computed using adiabatic mode theory[2] which accommodates gradual changes in depth as a function of range from the pile. It is the magnitude square of this quantity, $|p(r,z;f)|^2$, that is ultimately used and computations are limited to the frequencies corresponding to the one-third octave band center frequencies from one-third octave spectra obtained from reported pile driving noise measurements at various naval and transportation-related marine construction sites (California Department of Transportation [Caltrans] 2015; Illingworth and Rodkin 2017; Naval Facilities Engineering Command Southwest [NAVFAC SW] 2019). These one-third octave spectra differ depending on pile type and are further modified as required to accommodate the frequency dependency associated with marine mammal FHG weightings.

As an example of the modeling effort, the steps taken from preliminary calculations through final broadband TL are provided in Section 2.1 for concrete piles. The same steps were followed for steel and plastic piles, the main difference being the spectral frequency associated with those pile types (Section 2.2). Methods used to map and calculate ZOIs relative to acoustic thresholds are provided in Section 2.3.

[1] The method of normal modes is a standard means to compute the acoustic pressure field in an underwater waveguide bounded by the sea surface and seabed. It is particularly applicable to the case of pile driving where the frequencies are generally low and the water depth is relatively shallow.

[2] Normal mode functions apply to a given frequency, seabed condition and water depth. In the event the latter changes reasonably slowly with range, separate mode functions can be computed and the technique of blending of such functions for different ranges is associated with adiabatic mode theory. Adiabatic mode theory is utilized for pile driving applications in Dahl et al. 2015, and further information is found in the references therein.

2.1 Modeling Example – One Location and Pile Type

2.1.1 Example Behavior of Frequency and Range Dependence in a Preliminary Calculation

The example analysis is based on a typical transect that extends west of the Pier 6 site at NBSD. The Pier 6 location and complex bathymetry around San Diego Bay are shown in Figure 2-1. Figure 2-2 illustrates the behavior of $|p(r,z;f)|^2$ for three representative third-octave band center frequencies (at 100, 500, and 1000 hertz [Hz]) for the transect in the vicinity of Pier 6. While Figure 2-2 illustrates the frequency dependence in our model, the figure is not meant to represent any kind of final result for pile driving, as in peak pressure or SEL, which must necessarily include a band of frequencies. The depth contour in Figure 2-2 is interesting as it highlights the deep shipping channel that borders the east side of the bay; the depth rapidly decreases from about 12 m (39 ft) to 4 m (13 ft) beyond this channel.

The contours of $|p(r,z;f)|^2$ expressed in dB are exactly proportional to a frequency dependent propagation loss that is a function of range and depth. For the computations in Figure 2-3, bathymetry (or depth) affects the computations differently depending on frequency. For example, at 100 Hz there are fewer modes, which are ultimately cut-off (or severely attenuated) by the shallowness of the transect beyond the shipping channel at a distance range of about 800 m (2,625 ft), and this greatly reduces the overall pressure magnitude squared field compared with higher frequencies.

In addition to the bathymetry, a nominal sound speed in the water column of 1,516 m/second (s; 4,974 ft/s) was used. The seabed boundary was represented as a generic sandy seabed with sound speed of 1,650 m/s, density of 1,900 kilogram/cubic meter (kg/m^3; 118 pounds/cubic foot), and compressional wave attenuation of 0.36*(frequency/1000) 1.8 dB/m/kilohertz (kHz) (frequency given in Hz). Note that this modeling analysis differs from the practical spreading model where propagation loss is described by a $15*\log_{10}(\text{Range}/10)$ model (i.e., Range in m), which is not capable of representing frequency dependent changes nor changes in depth.

2.1.2 Incorporation of Pile-Specific Source Spectrum

Our next step was to take a depth-average of $|p\ (r,z;f)|^2$, yielding $<|p\ (r,f)|^2>$, which is a function of only range r and frequency f. To this we then applied a frequency-dependent spectral weighting function *S(f)* (depending on pile type) to produce contours of propagation loss.

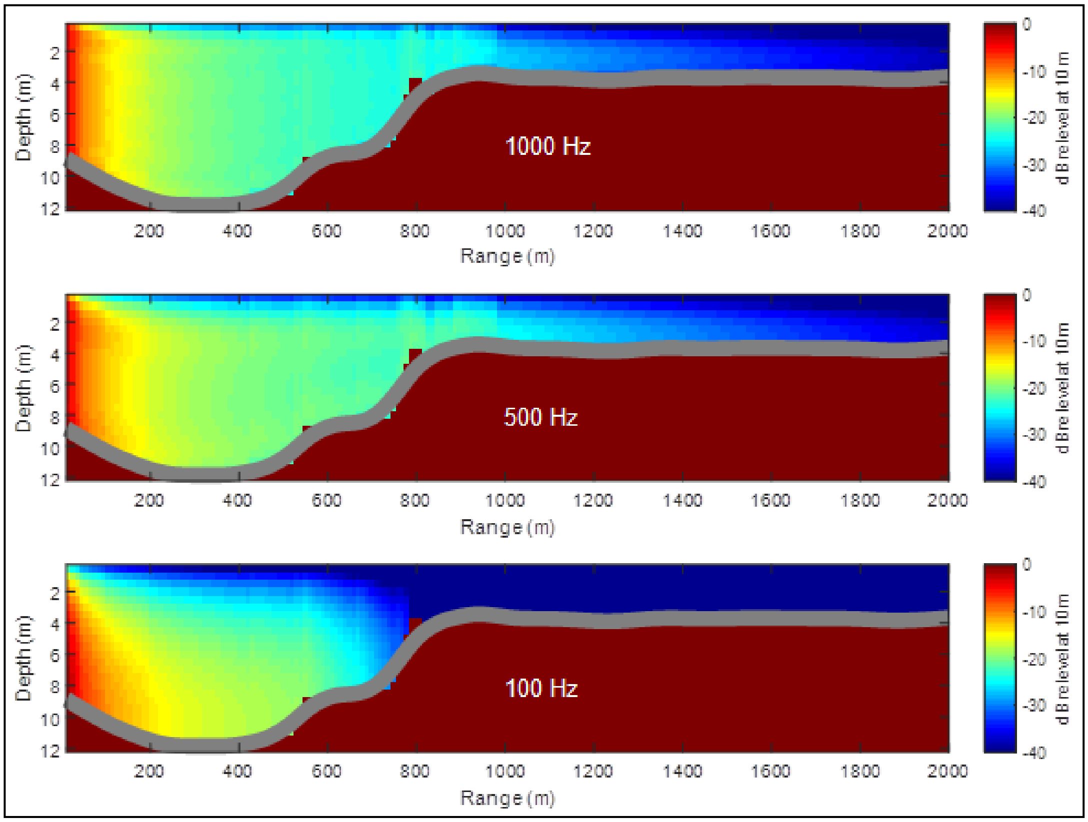
Figure 2-3 shows the pile-type spectral weighting function for 24-inch octagonal concrete pile data (the spectral data was digitally extracted as originally published in Illingworth and Rodkin [2017], Figure B9). Referring now to the unweighted data (light bars in Figure 2-3), the maximum third-octave band spectrum level is 164 dB at 250 Hz[3] and the next highest level is 160 dB at frequencies of 80, 160, and 200 Hz. Thus, at 250 Hz we identify a concrete pile spectral weighting, *S(f)*, equal to 1 upon conversion to normalized linear units (corresponding to 0 dB). Similarly, *S(f)* equals 0.398 at frequencies of 80, 160, and 200 Hz, given the spectral values are 160 dB or 4 dB lower (and -4 dB is decibel equivalent of reduction from 1 to 0.398). This inventory was continued for all third-octave center frequencies. For example, at 1,000 Hz the level is 136 dB or 28 dB lower than the highest level at 164 dB; therefore, *S(f)* equals 0.0016. Thus, it is anticipated that frequencies in the neighborhood of 1,000 Hz contribute little to

[3] Spectral values in Illingworth and Rodkin 2017 (Figure B9) are in fact higher but have a constant decibel offset from the values identified herein in Figure 2-3. The reduced spectral values in Figure 2-3 are used to be consistent with the maximum 10-m SEL value of 168 dB reported for 24-inch octagonal concrete piles in Caltrans 2015.

the overall acoustic field predicted at some range. The spectrum modified by the Otariid FHG weighting function in Figure 2-3 (dark bars) is discussed in Section 2.1.3 below.

Notes: (1) Pier 6 location is the green dot. (2) Darker-to-lighter blue indicates shallowing depth (darkest blue is 18 m [59 ft]).

Figure 2-1. Map showing qualitative view of bathymetry in the vicinity of Pier 6 in San Diego Bay.



Notes: (1) While the figure illustrates the frequency dependence of the model, it is not meant to represent any kind of final result for pile driving or particular pile size or type. (2) Depth contour is shown by the thick, gray line. (3) Occasional staircase like features in the bathymetry are the result of 10-m (33-ft) range resolution used in this illustration; final model result use 1-m (3-ft) resolution.

Figure 2-2. Pressure magnitude squared field (expressed in dB) for three acoustic frequencies as a function of range and depth over a transect that extends westward from Pier 6.

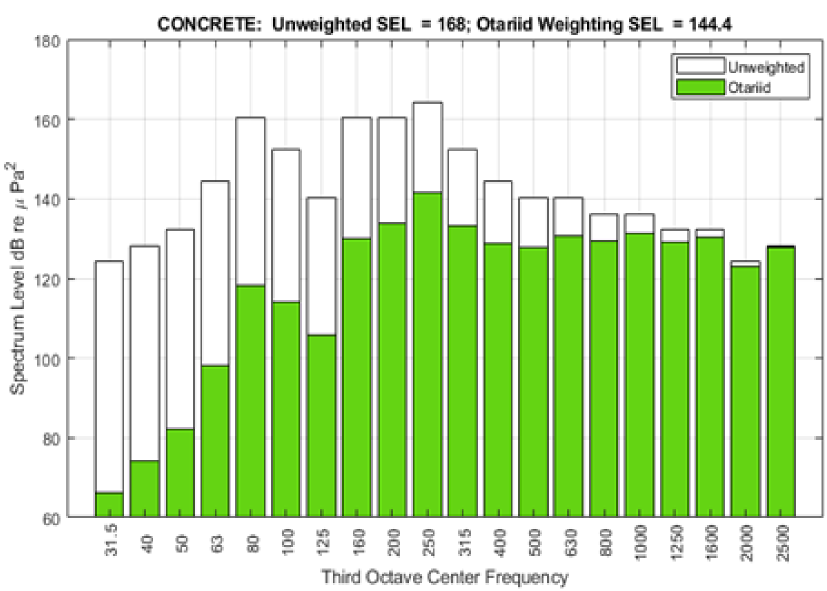


Figure 2-3. Third-octave band spectrum for 24-inch diameter concrete piles, unweighted data (light bars) and the spectrum that has been further modified by the Otariid marine mammal functional hearing group weighting function (dark bars).

The frequency dependent model was then modified to represent the pile spectrum *S(f)*, by multiplying $<|p\ (r,f)|^2>$ by the weights (i.e., 1/3 octave spectral shape) for the 20 third-octave center frequencies as shown in Figure 2-3. For example, the normalized weights for the 24-inch octagonal concrete piles at f = 250 Hz correspond to 1 (the maximum); whereas, at f = 160 Hz, $<|p\ (r,\ f)|^2>$ is multiplied by 0.398. The field was then summed and normalized to unity at a range of 10 m (33 ft), representing 0 dB TL at 10 m (33 ft). This computation was undertaken for every range (or azimuthally) dependent transect that radiates away from the pile source location in increments of 1 degree. However, other more subtle effects such as diffraction or bending around landforms are not accounted for in this purely two-dimensional approach (which is referred to as Nx2D). Therefore, an additional component representing horizontal refraction phenomena was added using the approach outlined in Dall'Osto and Dahl (2017). This additional diffractive (three-dimensional [3D]) modeling component is also frequency dependent.

In terms of 3D effects, the adiabatic results (i.e., results akin to those illustrated in Figure 2-2) remain relatively unchanged along bearings, being affected only by a change in depth until the propagation path is obstructed (or blocked) by a land feature. To model the field beyond an obstruction, a 3D propagation model is used to modify the Nx2D result for blocked regions. The 3D effects that carry sound into blocked regions relate predominately to propagation of the lowest mode (mode-1) and blocked-regions from the Nx2D adiabatic result are superseded by the numerical solution to the horizontal dependence of mode-1.

2.1.3 Broadband Transmission Loss

Figure 2-4 (left side) shows final acoustic TL as a function of Cartesian coordinates centered on the Pier 6 pile location, relative to range 10 m (33 ft) from the pile source, such that TL within a radius of 10 m (33 ft) centered at the pile is 0 dB. This figure now includes all key effects: those due to changing depth and those due to significant obstructions of the acoustic path, both being dependent upon frequency.

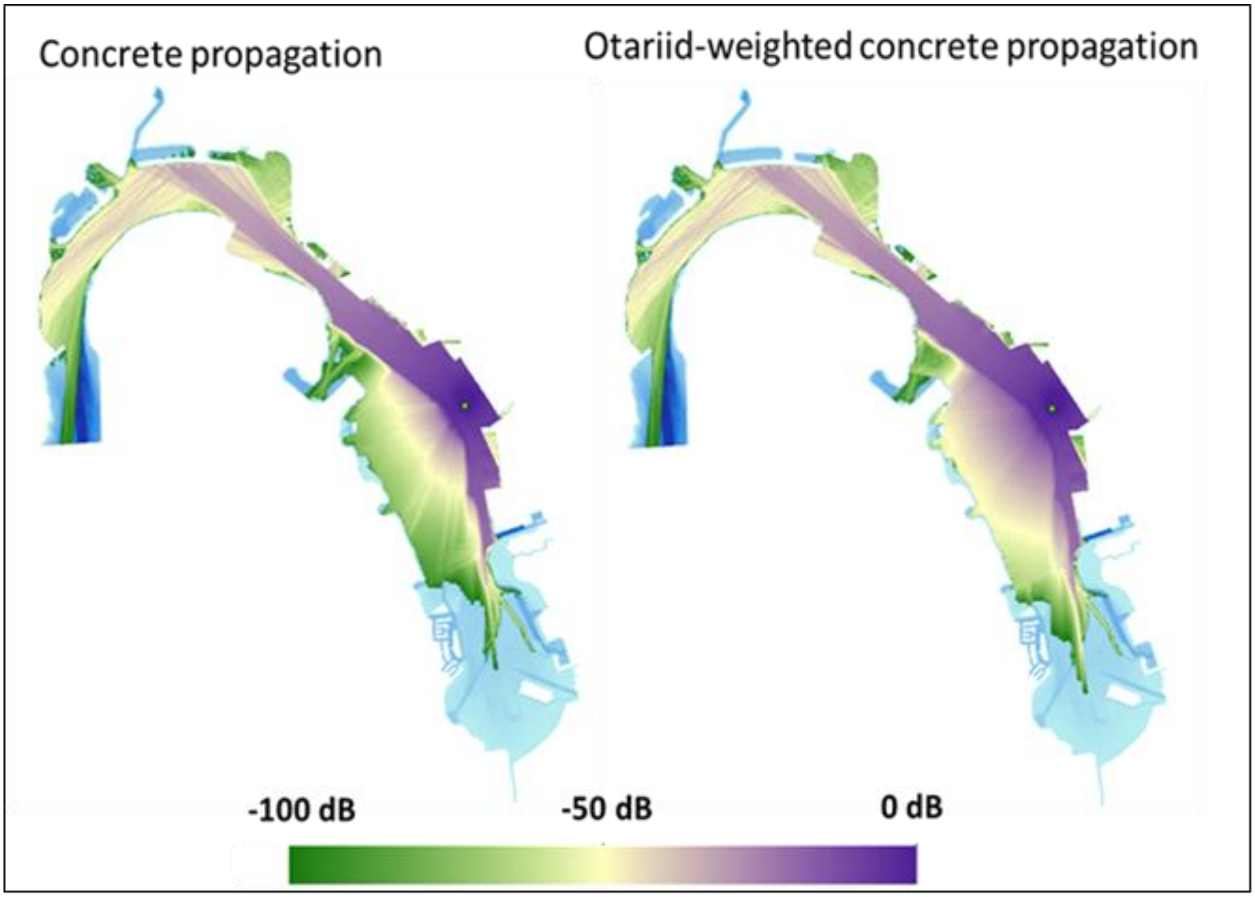
The model commences at 10 m (33 ft) from the pile driving location; therefore, distances closer than 10 m (33 ft) were not modeled. This is because source SPLs considered herein and typically reported are at a distance of 10 m (33 ft) from the pile.

In terms of frequency content, Figure 2-4 (left side) is based on that of 24-inch octagonal concrete piles without frequency weighting (see Figure 2-3, unweighted graph). In contrast, Figure 2-4 (right side) includes the effects of modifying the one-third octave band spectrum for 24-inch octagonal concrete by the Otariid FHG weighting function (Figure 2-3, Otariid graph). Application of Otariid FHG weighting discounts the 10-m (33-ft) datum by 23.6 dB, but also modifies the TL map. Specifically, the Otariid FHG discounts lower frequencies while leaving higher frequencies relatively unchanged, as apparent in the FHG-weighted spectrum for a concrete pile in Figure 2-3 (dark bars). As a consequence, a new pile-type and FHG specific spectral weighting is applied to the propagation model. For example, the maximum third-octave center frequency remains at 250 Hz, however 1000 Hz is given very nearly the same relative level, and thus revised inventory for all third-octave center frequencies is required to identify the FHG weighted *S(f)*. Proceeding then exactly as was done with the original (light bars) spectrum in Figure 2-3, we obtain a revised acoustic TL map (Figure 2-4, right side) that embodies this FHG frequency weighting.

At first look, Figure 2-4 seems paradoxical insofar as the broadband TL as the result for Otariid weighting appears to have less TL. The higher frequencies received more emphasis with this FHG weighting, and this reduced the TL into shallower areas where only the higher frequencies propagate (as shown in Figure 2-2). The paradox is resolved upon adding the surrogate values for pile driving data at range 10 m (33 ft); e.g., SEL value of 168 dB referenced to one microPascal squared seconds (re 1 μPa^2-s) for no FHG weighting applied and 144 dB for the Otariid FHG weighting applied (see Figure 2-3).

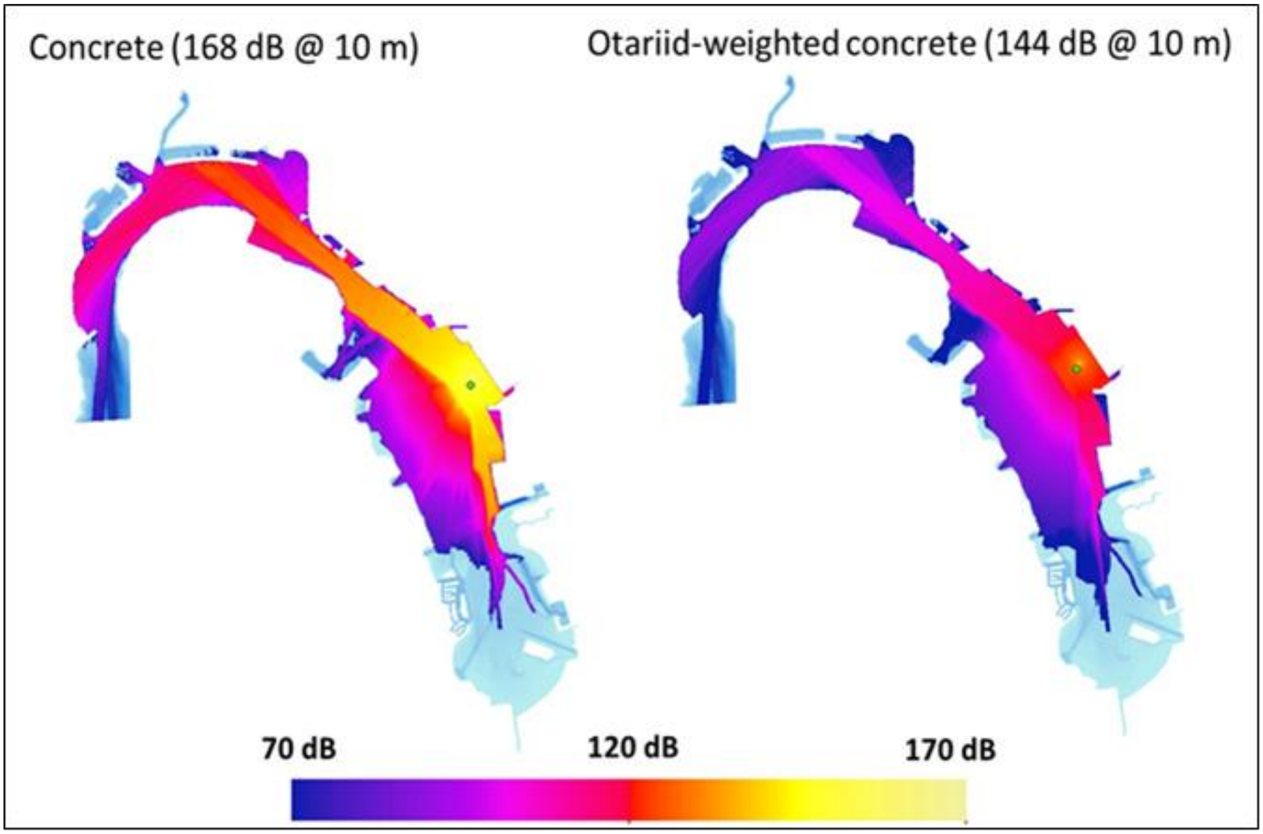
Figure 2-5 shows a SEL map with the paradox resolved; the contours with no FHG weighting are external of the FHG weighted levels.

The concrete model, although based on frequency spectral data for 24-inch octagonal piles, is considered generally applicable to driving concrete piles of different sizes and types (e.g., octagonal, square) apart from their differences in underwater sound data measured at a distance range of 10 m (33 ft) from the pile.



Notes: (1) Pile source is identified by green dot, nominally co-located with Pier 6. (2) TL is referenced from a distance range of 10 m [33 ft] from the pile (where TL = 0 dB).

Figure 2-4. Broadband TL referenced to 10-m (where TL = 0 dB) for 24-inch concrete piles (left side), and the same analysis but based on Otariid marine mammal FHG weighted spectrum (right side).



Note: Pile source is identified by green dot, nominally co-located with Pier 6.

Figure 2-5. Model result for area dependence of depth-averaged SEL in dB re 1 µPa²-s corresponding to a single strike of 24-inch concrete pile (left side), and the same analysis but based on Otariid marine mammal function hearing group weighted spectrum (right side).

2.2 Modeling Other Pile Types

Two additional pile types were modeled using the same methods described above in Section 2.1. Figure 2-6 shows the pile-type spectral weighting function for 30-inch steel piles (taken from Dahl and Dall'Osto 2017). As in Figure 2-3, the unweighted data (light bars) and the effect of Otariid FHG weighting (dark bars) are shown on Figure 2-6. For such steel piles, application of Otariid FHG weighting discounts the 10-m (33-ft) datum by about 14 dB, and as similar to concrete piles, it is the lower frequencies that are primarily influenced by the weighting.

Figure 2-7 shows the spectral weighting function for a generic plastic pile. While the Navy anticipates driving 16-inch fiberglass piles and removal of 12-inch timber-plastic piles at NBSD, no acoustic measurements specific to those types of piles are currently available. In a recent published final rule for a marine mammal letter of authorization (National Marine Fisheries Service [NMFS] 2018a), data for 13-inch plastic piles (from Caltrans 2015) was used as a proxy for 16-inch fiberglass reinforced plastic piles. Following that example, we digitally extracted the frequency spectrum for the 13-inch plastic piles (Caltrans 2015, Figure I.12-2), which had somewhat poor resolution, to create the unweighted spectrum (light bars) in Figure 2-7. The surrogate value at 10 m (33 ft) was based on the reported maximum SEL value of 145 dB (Caltrans 2015). Figure 2-7 also shows the effect of Otariid FHG weighting (dark bars); in this case, application of Otariid FHG weighting discounts the 10-m (33-ft) datum by 16 dB, with main influences again toward lower frequencies.

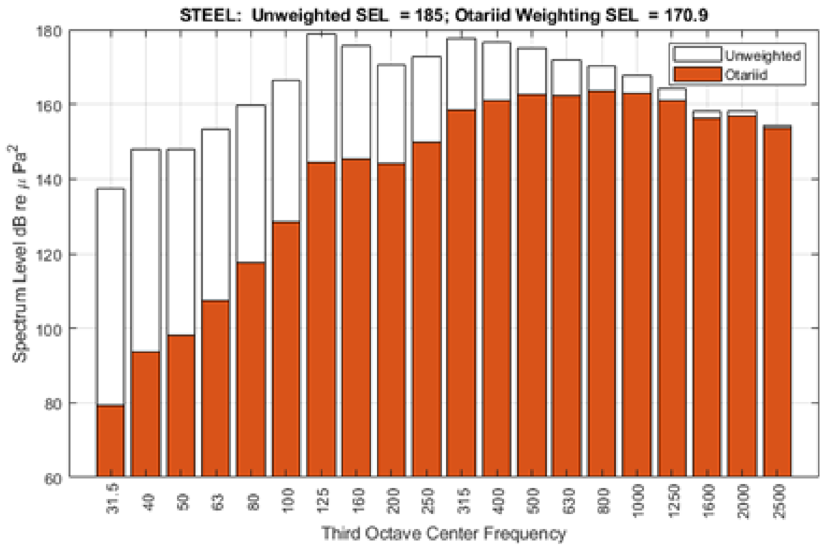


Figure 2-6. Third-octave band spectrum for 30-inch diameter steel piles, unweighted data (light bars) and the spectrum that has been further modified by the Otariid functional hearing group weighting function (dark bars).

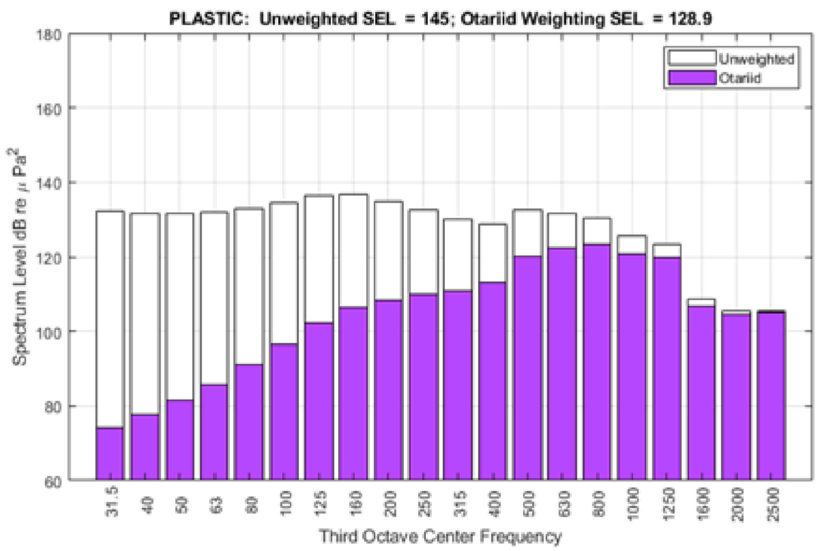


Figure 2-7. Third-octave band spectrum for plastic piles, unweighted data (light bars) and the spectrum that has been further modified by the Otariid functional hearing group weighting function (dark bars).

This generalized plastic pile spectrum is considered a proxy for 16-inch reinforced fiberglass plastic piles herein, although its applicability should be verified when appropriate pile driving measurements for fiberglass piles become available. This spectrum also may be reasonably used as a proxy for timber-plastic piles, recognizing that surrogate noise levels at 10 m (33 ft) would differ as appropriate for pile driving or extraction based on reported values by pile size, as available.

2.3 Summary of Broadband Transmission Loss and Otariid Weighting for All Pile Types and Modeled Locations

Broadband TL for the three pile types at each of the modeled locations, Piers 2, 6, and 13, are summarized in Figure 2-8 through Figure 2-10, respectively. For this comparison of TL, the corresponding unweighted spectra of each pile type is used (see Figure 2-4 for an example of unweighted versus FHG weighting). In each case, sound propagation is concentrated within the deeper navigation channel that runs along the eastern boundary of the bay. This is anticipated based upon inspection of Figure 2-2, which shows how the shallow waters along the western part of the bay produce a significant reduction in sound level depending on frequency. Generally, there is less TL with steel pile types compared to the other pile types owing to the somewhat greater contribution of higher frequencies towards the spectrum of steel piles (see Figure 2-6). Additionally, the modeled TL by pile type is considered representative for a range of pile sizes; however, the underwater source noise datum at 10 m (33 ft) from the pile would vary depending on pile diameter and type of pile driving activity (impact, vibratory).

Table 2-1 lists the decibel reduction of source underwater noise levels (10-m [33-ft] from pile driving) based on the Otariid FHG weighting function for each pile type. The reduction is applied to the unweighted SEL_{cum} to obtain an Otariid FHG adjusted SEL_{cum} source datum at 10 m (33 ft). The Otariid FHG adjusted source datum is the input value (where TL = 0 dB at 10 m [33 ft]) in the Otariid FHG TL maps.

Table 2-1. Reduction to source-datum by pile-type based on Otariid FHG.

Pile Type	Otariid FHG reduction to 10 m (33 ft) Source Datum (31 Hz – 2.5 kHz)
Steel	-14.1 dB
Plastic	-16.1 dB
Concrete	-23.6 dB

2.4 Model Application for Determining Marine Mammal ZOIs for In-Water Construction and Demolition Activities

A total of 18 TL maps, six for each of the three pile locations (Piers 2, 6, and 13), representing three pile types and propagation with or without Otariid FHG weighting, were provided to Tierra Data, Inc. (TDI) by the UW-APL team. The maps represent 0-dB TL at a radius 10 m (33 ft) from the pile center.

TDI used the following methods to prepare ZOI maps relative to Level A and B acoustic thresholds. All eighteen TL maps provided by UW-APL were originally in ASCII format. Using ESRI ArcMap in editing mode, TDI converted each ASCII file into a raster format. Once the raster was generated, the ArcGIS Spatial Analyst Surface tool (named Contour) was used to convert the raster into shapefiles, with isopleth lines and polygons (each representing a falloff of 1dB) radiating from the sound source (10 m [33 ft] from in-water activity).

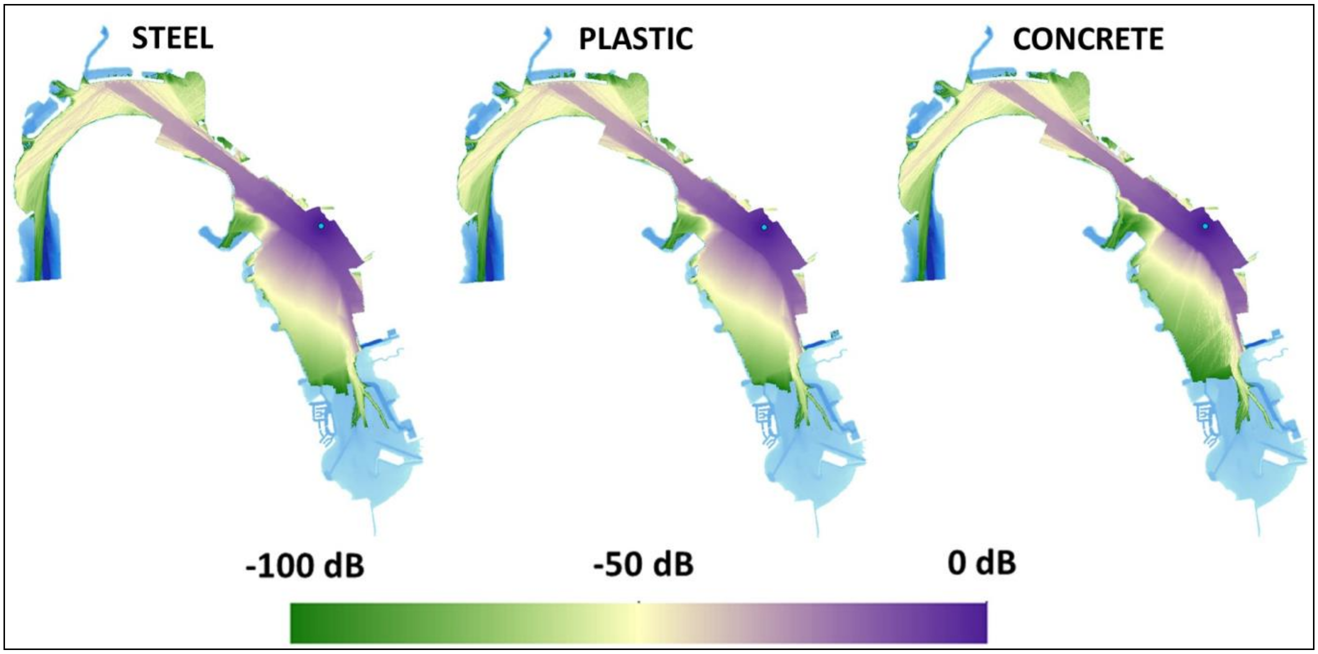


Figure 2-8. Summary of broadband TL referenced to 10-m (33 ft; where TL = 0 dB) for steel, plastic and concrete piles at the northern Pier 2 location.

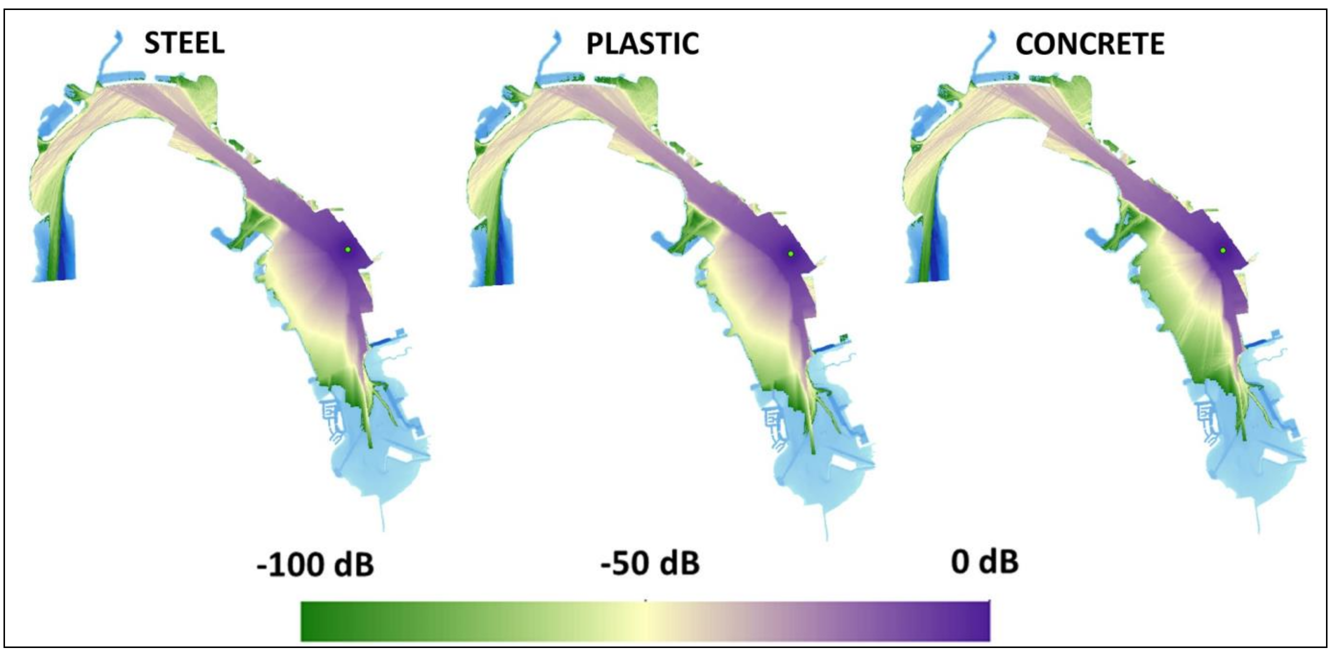


Figure 2-9. Summary of broadband TL referenced to 10-m (33 ft; where TL = 0 dB) for steel, plastic and concrete piles at the central Pier 6 location.

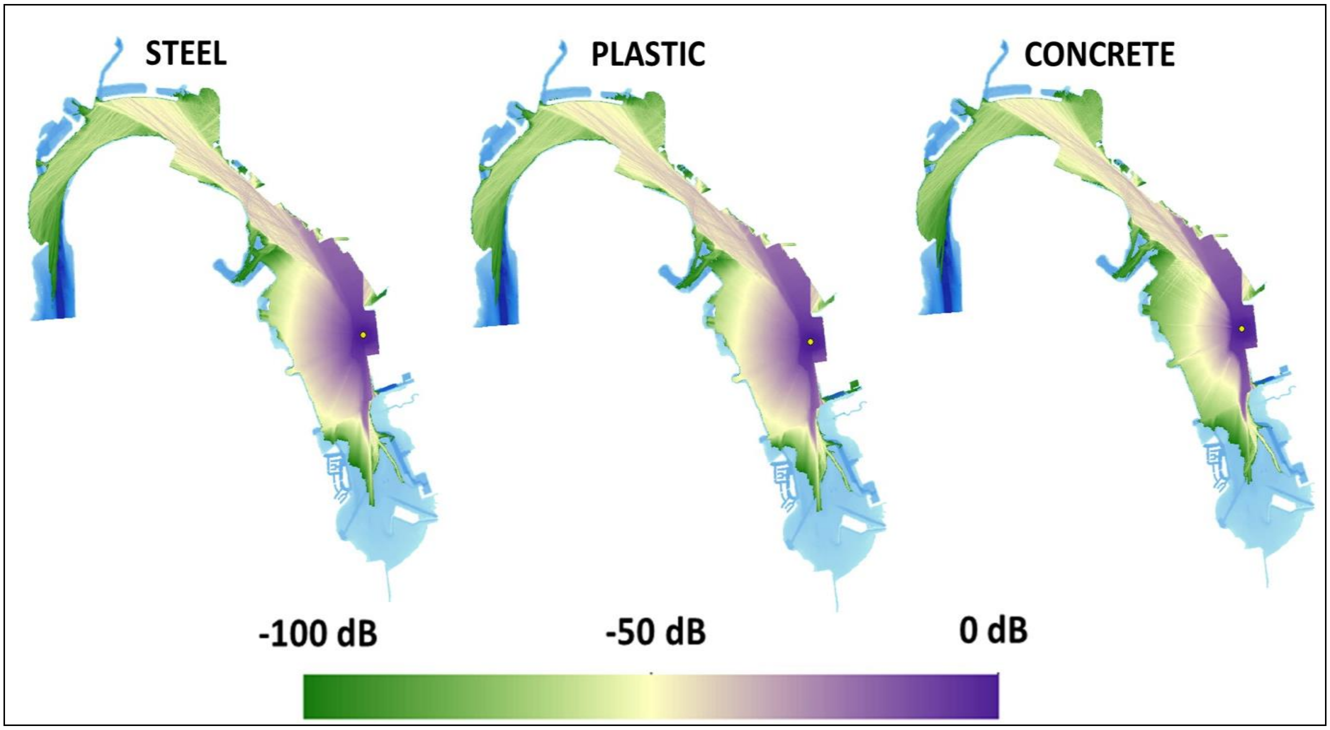


Figure 2-10. Summary of broadband TL referenced to 10-m (33 ft; where TL = 0 dB) for steel, plastic and concrete piles at the southern Pier 13 location.

Once in this shapefile format, a surrogate noise source level 10 m (33 ft) from a notional pile location was used as the starting underwater noise level (i.e., 0 TL). The surrogate noise levels for a range of pile sizes/types of interest to the Navy (McConchie, 2019 pers. com.) were obtained from relevant literature sources (Caltrans 2015; NAVFAC SW 2019). SEL_{cum} was computed for impact driving using the following formula: SEL single strike+10*$\log_{10}$(number of strikes), and then adjusted by the model-specific Otariid weightings according to pile type (see Table 2-1). For vibratory driving or extraction, the above formula included the root mean square (RMS) source value (instead of SEL single strike) and duration of sound production over 24 hours (instead of number of strikes).

From the starting noise level, the decrease in noise level was counted down one contour (i.e., one dB) at a time using the appropriate modeled TL shapefile to reach the appropriate regulatory acoustic threshold (see Section 3.1). TDI then determined the width, length, and area of the ZOIs using simple ArcMap tools such as the “Ruler” and “Calculate area” functions.

ZOIs for impact and vibratory driving or extraction based on the acoustic model indicate that sound propagation is substantially influenced by local bathymetry, with the steep slope of the navigation channel limiting sound transmission across the bay. Closer to land, adjacent piers are expected to influence sound transmission, but the rate of reduction is uncertain. In addition to the total ZOI area, separate calculations were made for those portions of the ZOI associated with open water versus areas influenced by piers.

3.0 Representative Marine Mammal ZOIs

Under the Marine Mammal Protection Act (MMPA), the NMFS has defined levels of harassment for marine mammals. Level A harassment is defined as "any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild." Level B harassment is defined as "any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including but not limited to migration, breathing, nursing, breeding, feeding, or sheltering."

Table 3-1 provides acoustic threshold criteria (NMFS 2018b) for Level A injury and Level B disturbance for the Otariid FHG. The NMFS equates the onset of permanent threshold shift (PTS), which is a form of auditory injury, with Level A harassment under the MMPA. The Level A criteria use a dual metric threshold, cumulative sound exposure level (dB SEL_{cum}) and peak pressure (dB PEAK), whichever is greater. Level B harassment occurs when marine mammals are exposed to impulsive underwater sounds above 160 dB root mean square (RMS) re 1 µPa, such as from impact pile driving, and to non-impulsive underwater sounds above 120 dB RMS re 1 µPa, such as from vibratory pile driving (Table 3-1). The onset of temporary threshold shift is a form of Level B acoustic harassment under the MMPA. Because the ambient underwater noise levels at NBSD exceed the 120 dB RMS threshold, ZOIs were calculated to the average ambient underwater noise value of 126 dB re 1 µPa, which was based on the average of the reported ambient median L_{50} values (where L_{50} = statistical noise level exceeded "50" percent of the time) within the project area (Dahl and Dall'Osto 2019).

Table 3-1. Injury and disturbance threshold criteria for underwater noise.

Marine Mammals	Underwater Vibratory Pile-Driving or Extraction Noise (non-impulsive sounds) (re 1 µPa)		Underwater Impact Pile-Driving Noise (impulsive sounds) (re 1 µPa)	
	PTS Onset (Level A) Threshold	Disturbance (Level B) Threshold[1]	PTS Onset (Level A) Threshold[2]	Disturbance (Level B) Threshold
Otariidae (sea lions)	219 dB SEL_{cum}	120 dB RMS	232 dB Peak 203 dB SEL_{cum}[3]	160 dB RMS

Key:
µPa = micropascal; dB = decibel, PTS = permanent threshold shift, RMS = root mean square,
SEL = sound exposure level single strike, SEL_{cum} = cumulative sound exposure level over 24 hours.

Notes:
[1] 120 dB is less than the average ambient underwater sound level of 126 dB RMS at NBSD (Dahl and Dall'Osto 2019).
[2] Dual metric acoustic thresholds for impulsive sounds. Whichever results in the largest isopleth for calculating PTS onset is used in the analysis.
[3] Flat weighted or unweighted peak sound pressure within the generalized hearing range.

Table 3-2 presents the surrogate noise levels 10 m (33 ft) from the notional pile locations that were used to calculate the ZOIs. The Level B ZOI calculations used the RMS values as the starting noise level in the model TL maps. Table 3-2 provides the calculated Otariid weighted SEL_{cum} values that were compared to the Level A acoustic thresholds.

Table 3-2. Underwater noise source values used in the unweighted TL model.

Activity Description	Underwater Noise Level (dB re 1 µPa) 10 m (33 ft) from Notional Pile Location	Source
Impact Pile Driving		
36-inch steel piles	215 Peak, 199.5 RMS, 185 SEL	NAVFAC SW 2019
24-inch steel piles	207 Peak, 194 RMS, 178 SEL	Caltrans 2015
16-inch steel piles	200 Peak, 184 RMS, 174 SEL	Caltrans 2015 (14-inch steel, as proxy)
24-inch octagonal concrete piles	188 Peak, 176 RMS, 166 SEL	Caltrans 2015
16-inch fiberglass piles	163 Peak, 153 RMS, 144 SEL	Caltrans 2015 (13-inch plastic, as proxy)
Vibratory Driving or Extraction		
36-inch steel piles	170 RMS	Caltrans 2015
24 or 16-inch steel piles	160 RMS	Caltrans 2015 (24-inch steel, as proxy for 16-inch)
24-inch octagonal concrete piles	160 RMS	Caltrans 2015 (24-inch steel, as proxy)
12-inch timber-plastic piles	140 RMS	Caltrans 2015 (timber, as proxy)

Notes: (1) SEL values are for single strike. (2) Vibratory pile driving is more likely with steel piles; whereas, vibratory extraction may occur with any pile type. (3) The source reference sound levels for vibratory pile driving are considered herein as proxy values for vibratory extraction.

Table 3-3. SEL_{cum} calculation assumptions and weighting for the Otariid FHG.

Pile Type/Size	Source (10-m) SEL	Piles/ Day	Number Strikes/Pile	Total Strikes	10log10 (Total Strikes)	SEL_{cum}	Weighted SEL_{cum}
Impact Pile Driving							
Steel							
36-inch	185	7	600	4200	36.2	221.2	207.1
24-inch	178	7	600	4200	36.2	214.2	200.1
16-inch	174	7	600	4200	36.2	210.2	196.1
Concrete							
24-inch	166	7	600	4200	36.2	202.2	178.6
Plastic							
13-inch	144	7	600	4200	36.2	180.2	164.1
Vibratory Driving or Extraction							
Pile Type/Size	**Source (10-m) RMS**	**Piles/ Day**	**Duration/ Pile**	**Total Duration**	**10log10 (Total Duration)**	**SEL_{cum}**	**Weighted SEL_{cum}**
Steel							
36-inch	170	8	10	80	19	189	174.9
24- and 16-inch	160	8	10	80	19	179	164.9
Concrete							
24-inch	160	8	10	80	19	179	155.4
Plastic							
13-inch	140	8	10	80	19	159	142.9

Notes: (1) The Otariid Weighted SEL_{cum} values were calculated by reducing the SEL_{cum} values by the Otariid weighting function for each pile type as given in Table 2-1 (i.e., steel = -14.1, plastic = -16.1, concrete = -23.6). (2) All vibratory "Duration" values are given in minutes.

Marine mammal ZOIs for pile driving or removal relative to the above-noted acoustic thresholds were calculated and mapped for a range of pile types and sizes using modeled TL at NBSD. The modeled ZOIs are summarized in tables and figures, which are organized below according to the representative northern (Pier 2, Section 3.1), central (Pier 6, Section 3.2), and southern (Pier 13, Section 3.3) areas of

NBSD. Separate figures are provided for Level A and Level B ZOIs. Establishing a "shutdown zone" within which in-water equipment operation is halted is a routine mitigation measure to avoid the potential for injury of marine mammals during marine construction projects. In cases where sound levels meet or exceed Level A thresholds, the shutdown zone would be determined on a project-specific basis but would be no smaller than the Level A ZOI to avoid the potential for acoustic injury. In cases where sound levels would be lower than the Level A acoustic thresholds, a minimum 10-m shutdown zone is routinely employed as a precautionary measure to avoid the potential for physical interaction of protected marine species with in-water equipment operation. A 10-m Physical Interaction Shutdown ZOI is shown on the Level B ZOI figures for reference only. Shutdown zones may vary specific to the project/pile size, as warranted.

3.1 Representative Pier 2 ZOI Maps for a Range of Pile Sizes and Types

Table 3-4 provides the maximum distances and areas associated with marine mammal ZOIs mapped based on modeled TL for Pier 2, which is considered representative for marine construction projects located in the northern waters of NBSD. The ZOIs for a representative range of pile sizes and types are shown in Figure 3-1 through Figure 3-4.

Table 3-4. Pier 2 calculated distances to underwater acoustic thresholds and ZOI areas within the thresholds for a range of pile sizes and types using the South-Central San Diego Bay TL Model.

Activity Description	Minor Injury (PTS Onset) Level A[1,2]		Behavioral Disturbance Level B[1,3,4]			
	ZOI Distance (m) Diameter (Maximum Radial)	ZOI Area (km^2)	ZOI Distance (m) Diameter (Maximum Radial) or Length x Width	ZOI Area (km^2)		
				Open Water	Around Piers	Total
Impact Driving						
36-inch steel piles	56 (31)	0.0024	9,710 x 1,943	7.58	1.30	8.88
24-inch steel piles	0	N/A	7,163 x 1,570	5.09	1.20	6.29
16-inch steel piles	0	N/A	1,813 x 1,110	1.50	0.38	1.88
24-inch octagonal concrete piles	0	N/A	403 (229)	0.13	N/A	0.13
16-inch fiberglass piles	0	N/A	0	N/A	N/A	N/A
Vibratory Driving or Extraction[5]						
36-inch steel piles	0	N/A	12,669 x 2,159	10.05	1.33	11.38
24 or 16-inch steel piles	0	N/A	7,163 x 1,570	5.09	1.20	6.29
24-inch octagonal concrete piles	0	N/A	6,799 x 1,198	4.31	1.19	5.51
12-inch timber-plastic piles	0	N/A	264 (135)	0.06	N/A	0.06

Notes:

1 See Table 3-2 for underwater noise source values used to calculate the acoustic ZOIs.

2 Distances to Level A acoustic thresholds were calculated based on Otariid weighted SEL_{cum} values (see Table 3-3).

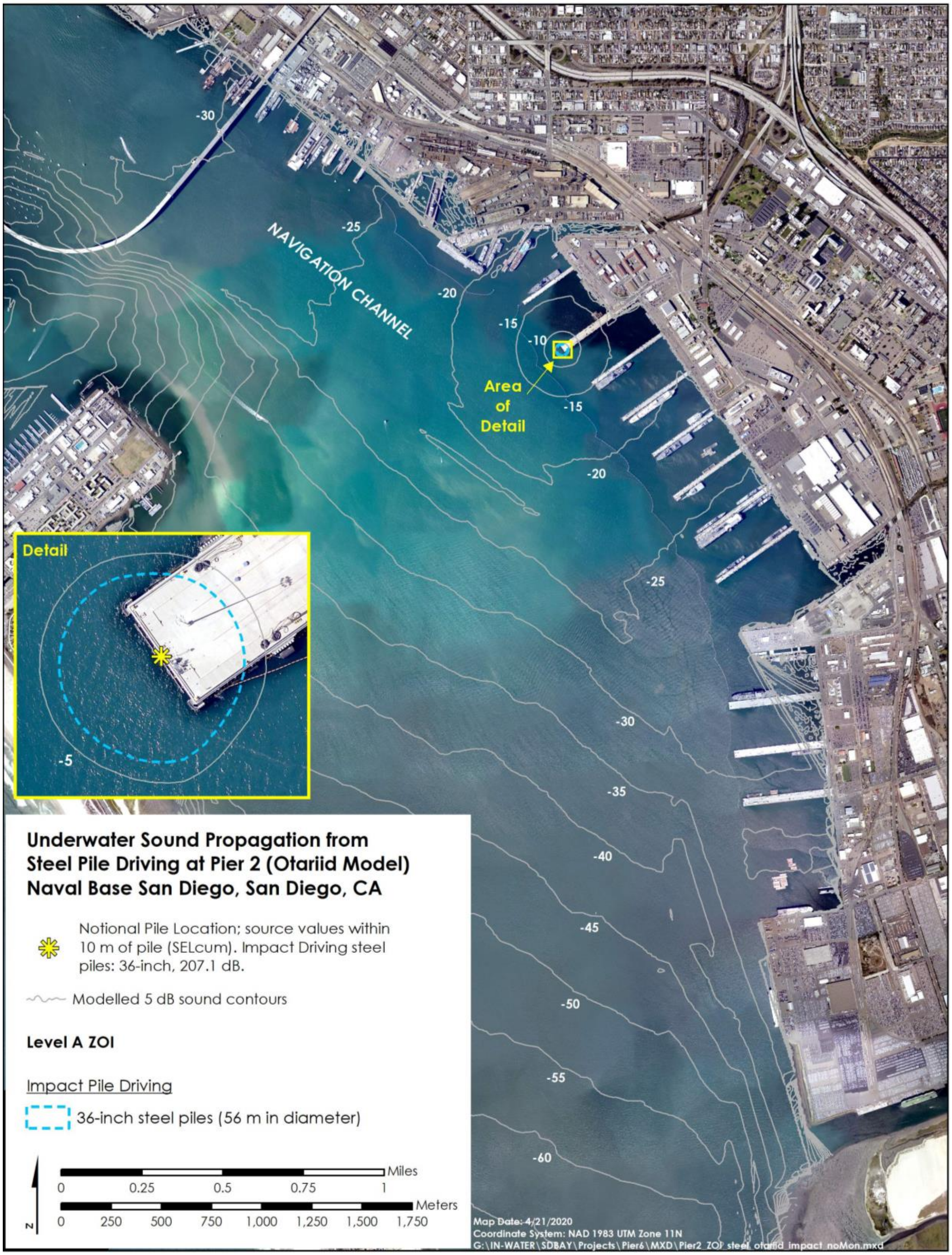
3 The Level B ZOIs for non-impulsive noise sources were calculated to the average ambient underwater noise value of 126 dB re 1 µPa, which was based on the average of the reported ambient median L_{50} values (where L_{50} = statistical noise level exceeded "50" percent of the time) within the project area (Dahl and Dall'Osto 2019).

4 The entire Level B ZOI is shown in the total column, which represents the sum of areas calculated separately for open water versus around piers where the structure's influence on sound propagation is uncertain. The reported total may differ slightly from that obtained by adding the values for open water and around piers due to rounding.

5 Vibratory pile driving is more likely with steel piles; whereas, extraction may occur with any pile type.

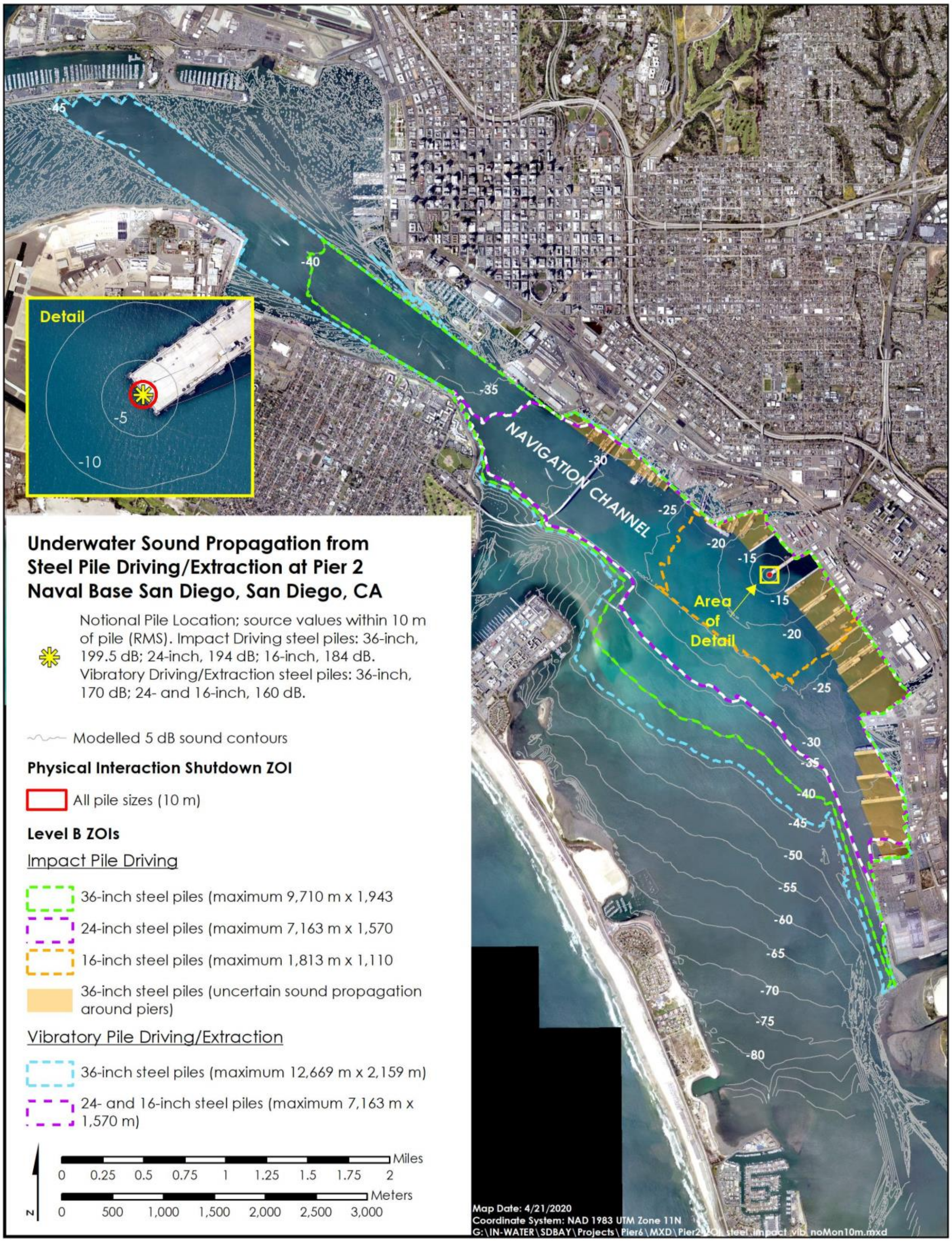
Abbreviations:

dB re 1 µPa = decibels referenced to a pressure of 1 microPascal, km^2 = square kilometers, m = meters, N/A = not applicable because the noise source value is below the acoustic threshold, PTS = permanent threshold shift, RMS = root mean square, SEL = sound exposure level, SEL_{cum} = cumulative sound exposure level over 24 hours, ZOI = zone of influence (area encompassed within acoustic threshold boundary).



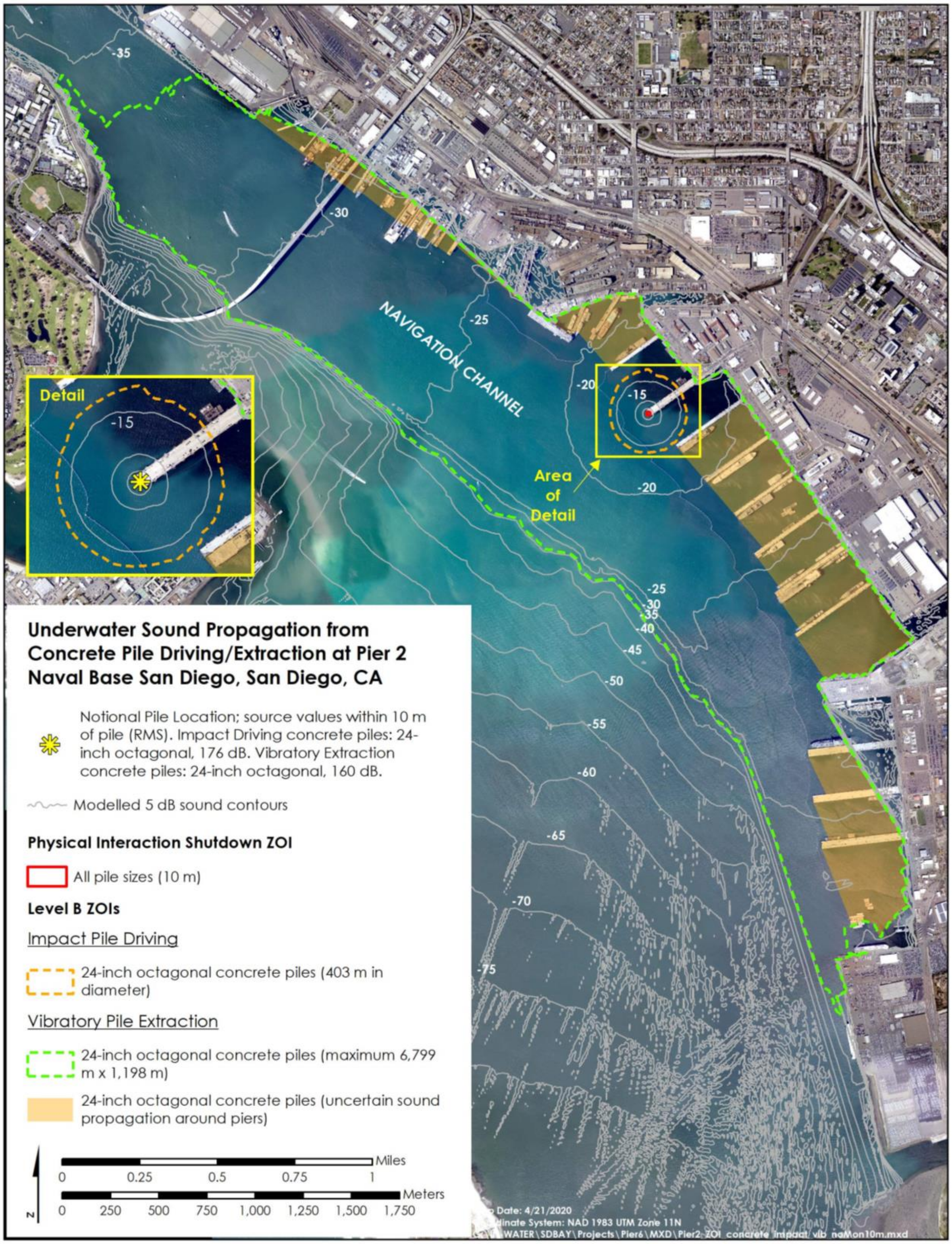
Note: Refer to Table 3-3 for calculation of the SEL_{cum} source value.

Figure 3-1. Otariid FHG Level A ZOI for impact driving of 36-inch steel piles based on modeled TL for a representative northern area location at NBSD (Pier 2).



Notes: (1) A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted. (2) The black shape at the bottom of the figure is from the San Diego Bay bathymetry base map, which lacks data offshore.

Figure 3-2. Level B ZOIs for impact driving and vibratory driving/extraction of steel piles based on modeled TL for a representative northern area location at NBSD (Pier 2).



Note: A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted.

Figure 3-3. Level B ZOIs for impact driving and vibratory extraction of 24-inch octagonal concrete piles based on modeled TL for a representative northern area location at NBSD (Pier 2).

Notes: (1) A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted. (2) The surrogate source datum for impact driving of fiberglass plastic piles is below the Level B acoustic threshold of 160 dB RMS; therefore, no Level B ZOI is mapped for that pile type and activity.

Figure 3-4. Level B ZOI for impact driving of fiberglass plastic piles or vibratory extraction of timber-plastic piles based on modeled TL for a representative northern area location at NBSD (Pier 2).

3.2 Representative Pier 6 ZOI Maps for a Range of Pile Sizes and Types

Table 3-5 provides the maximum distances and areas associated with marine mammal ZOIs mapped based on modeled TL for Pier 6, which is considered representative for marine construction projects located in the central waters of NBSD. The ZOIs for a representative range of pile sizes and types are shown in Figure 3-5 through Figure 3-8.

Table 3-5. Pier 6 calculated distances to underwater acoustic thresholds and ZOI areas within the thresholds for a range of pile sizes and types using the South-Central San Diego Bay TL Model.

Activity Description	Minor Injury (PTS Onset) Level A[1,2]		Behavioral Disturbance Level B[1, 3,4]			
	ZOI Distance (m) Diameter (Maximum Radial)	ZOI Area (km^2)	ZOI Distance (m) Diameter (Maximum Radial) or Length x Width	ZOI Area (km^2)		
				Open Water	Around Piers	Total
Impact Driving						
36-inch steel piles	53 (29)	0.0021	10,147 x 1,940	8.02	1.40	9.42
24-inch steel piles	0	N/A	7,140 x 1,595	5.15	1.28	6.43
16-inch steel piles	0	N/A	1,721 x 1,079	1.33	0.55	1.87
24-inch octagonal concrete piles	0	N/A	366 (192)	0.10	N/A	0.10
16-inch fiberglass piles	0	N/A	0	N/A	N/A	N/A
Vibratory Driving or Extraction[5]						
36-inch steel piles	0	N/A	13,920 x 2,212	10.74	1.40	12.15
24 or 16-inch steel piles	0	N/A	7,140 x 1,595	5.15	1.28	6.43
24-inch octagonal concrete piles	0	N/A	6,990 x 1,173	4.06	1.29	5.35
12-inch timber-plastic piles	0	N/A	254 (129)	0.05	N/A	0.05

Notes:

[1] See Table 3-2 for underwater noise source values used to calculate the acoustic ZOIs.

[2] Distances to Level A acoustic thresholds were calculated based on Otariid weighted SEL_{cum} values (see Table 3-3).

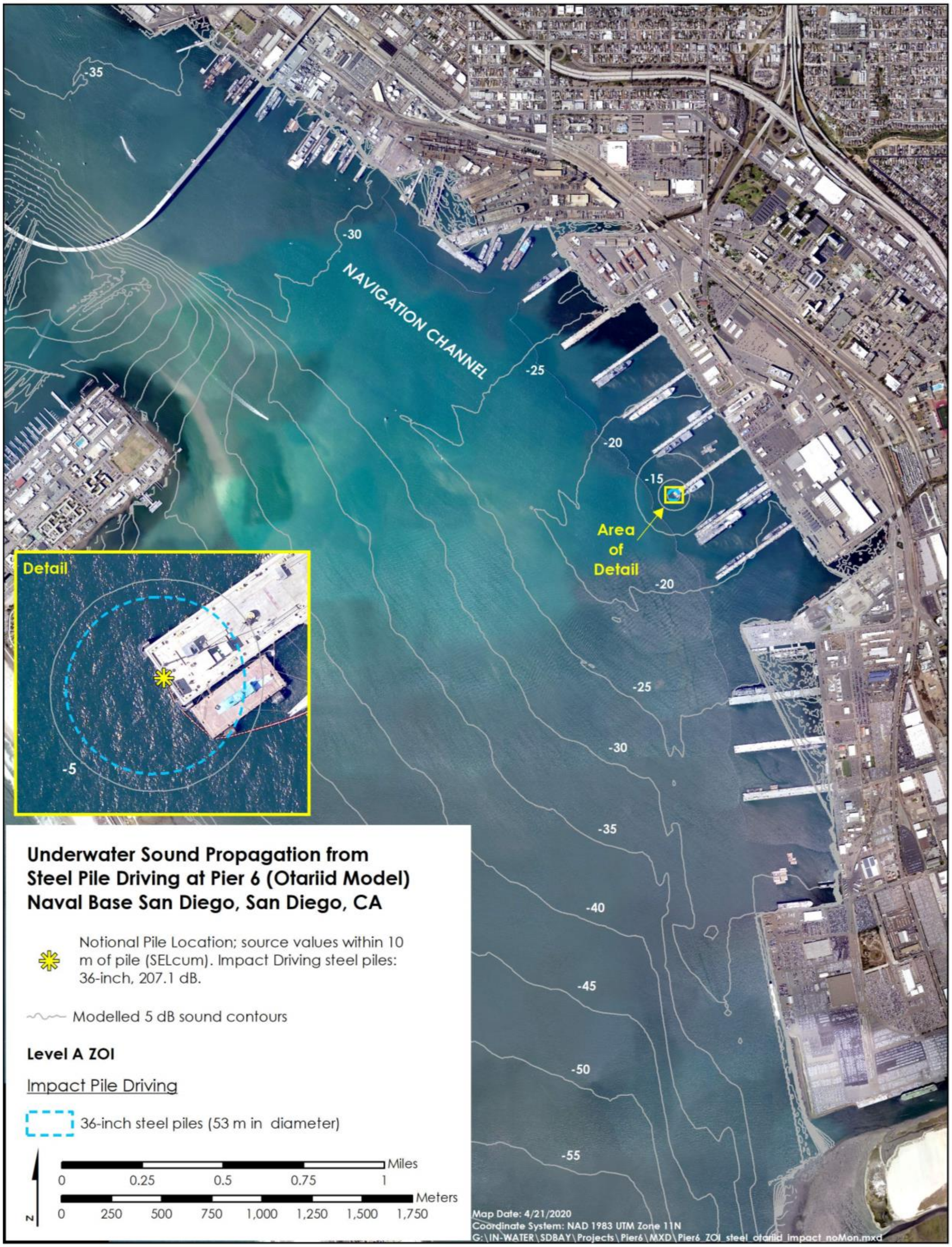
[3] The Level B ZOIs for non-impulsive noise sources were calculated to the average ambient underwater noise value of 126 dB re 1 µPa, which was based on the average of the reported ambient median L_{50} values (where L_{50} = statistical noise level exceeded "50" percent of the time) within the project area (Dahl and Dall'Osto 2019).

[4] The entire Level B ZOI is shown in the total column, which represents the sum of areas calculated separately for open water versus around piers where the structure's influence on sound propagation is uncertain. The reported total may differ slightly from that obtained by adding the values for open water and around piers due to rounding.

[5] Vibratory pile driving is more likely with steel piles; whereas, extraction may occur with any pile type.

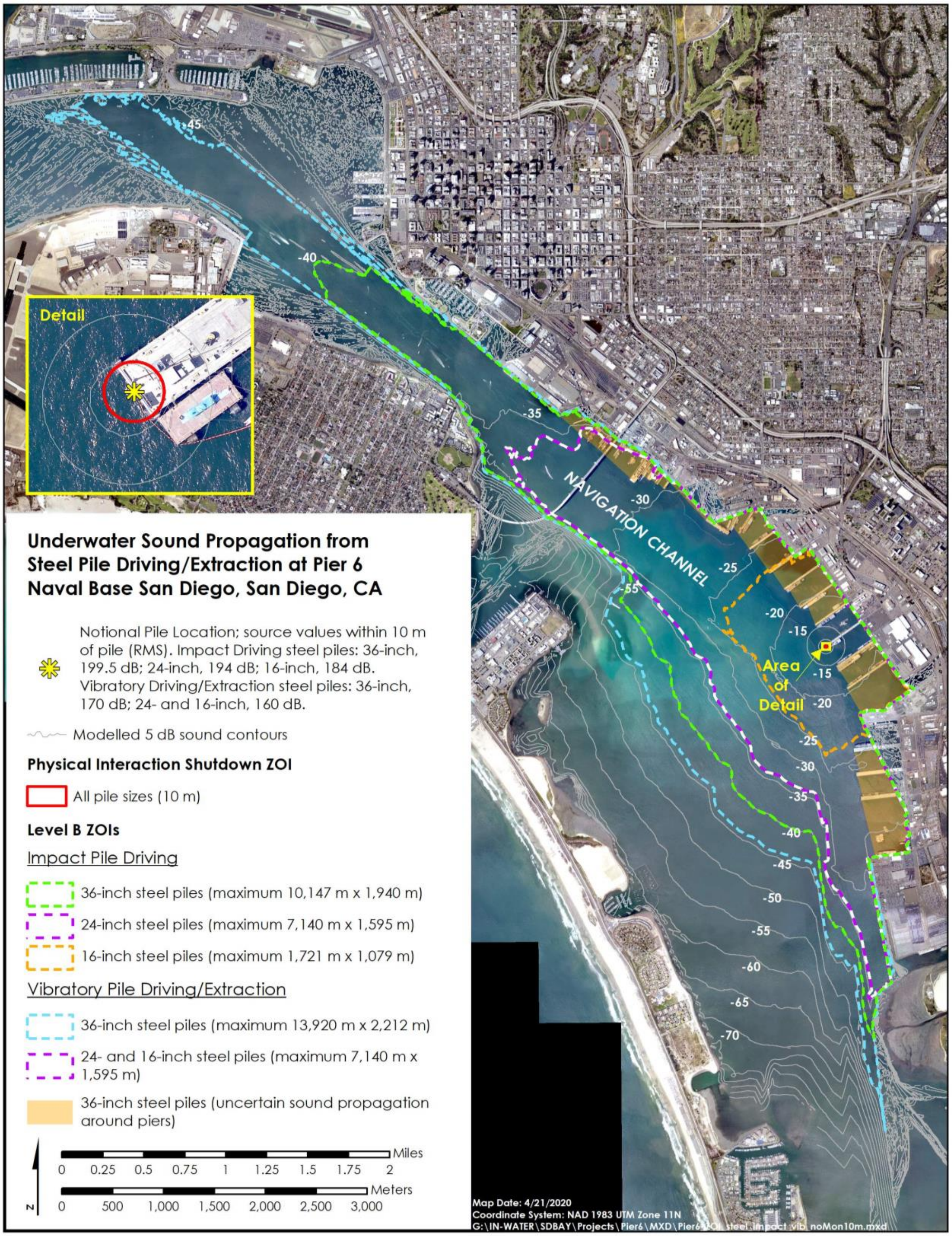
Abbreviations:

dB re 1 µPa = decibels referenced to a pressure of 1 microPascal, km^2 = square kilometers, m = meters,
N/A = not applicable because the source noise level at 10 m (33 ft) is below the acoustic threshold,
PTS = permanent threshold shift, RMS = root mean square,
SEL = sound exposure level, SEL_{cum} = cumulative sound exposure level over 24 hours,
ZOI = zone of influence (area encompassed within acoustic threshold boundary).



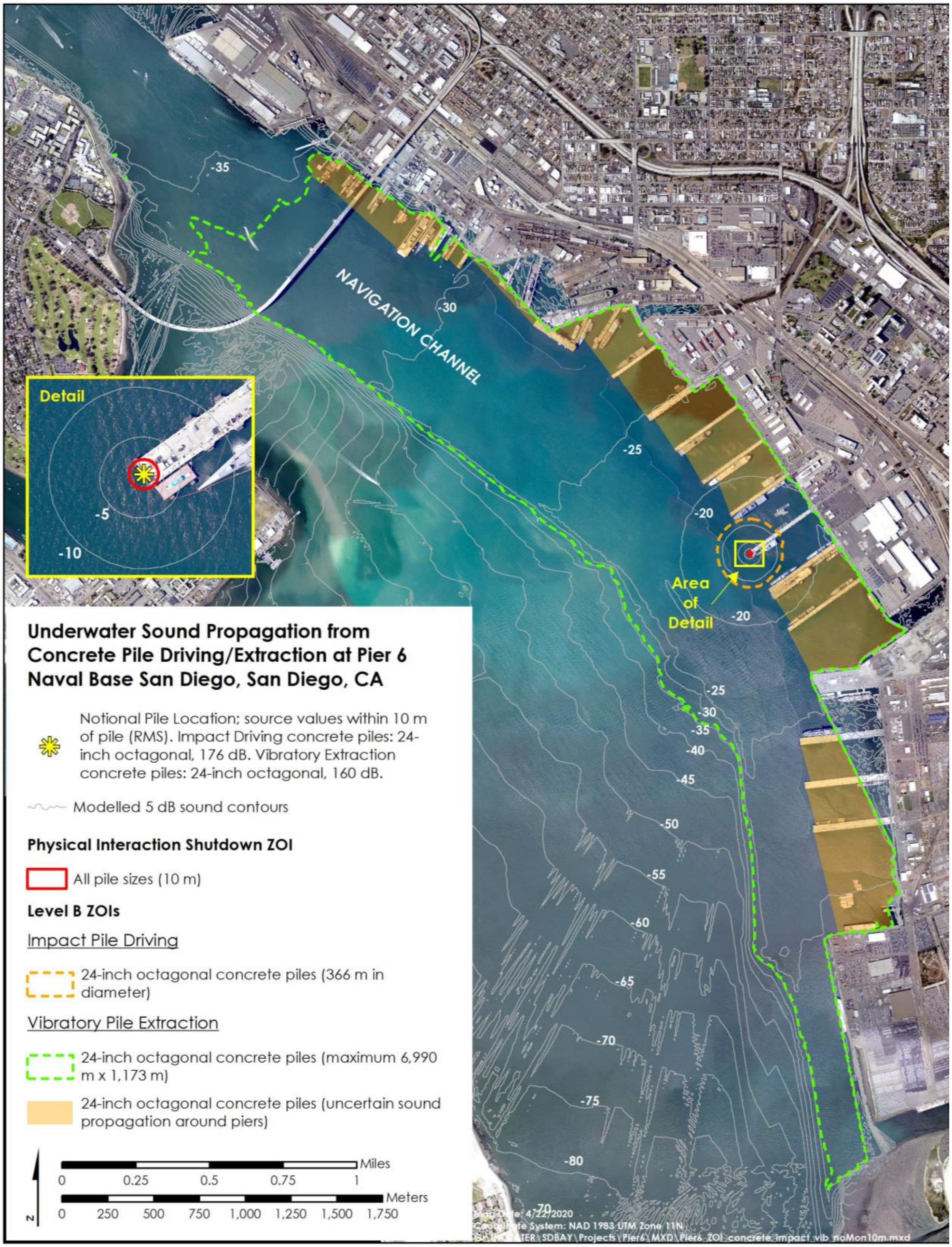
Note: Refer to Table 3-3 for calculation of the SEL_{cum} source value.

Figure 3-5. Otariid FHG Level A ZOI for impact driving of 36-inch steel piles based on modeled TL for a representative central area location at NBSD (Pier 6).



Notes: (1) A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted. (2) The black shape at the bottom of the figure is from the San Diego Bay bathymetry base map, which lacks data offshore.

Figure 3-6. Level B ZOIs for impact driving and vibratory driving/extraction of steel piles based on modeled TL for a representative central area location at NBSD (Pier 6).



Note: A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted.

Figure 3-7. Level B ZOIs for impact driving and vibratory extraction of 24-inch octagonal concrete piles based on modeled TL for a representative central area location at NBSD (Pier 6).

Notes: (1) A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted. (2) The surrogate source datum for impact driving of fiberglass plastic piles is below the Level B acoustic threshold of 160 dB RMS; therefore, no Level B ZOI is mapped for that pile type and activity.

Figure 3-8. Level B ZOI for impact driving of fiberglass plastic piles or vibratory extraction of timber-plastic piles based on modeled TL for a representative central area location at NBSD (Pier 6).

3.3 Representative Pier 13 ZOI Maps for a Range of Pile Sizes and Types

Table 3-6 provides the maximum distances and areas associated with marine mammal ZOIs mapped based on modeled TL for Pier 13, which is considered representative for marine construction projects located in the southern waters of NBSD. The ZOIs for a representative range of pile sizes and types are shown in Figure 3-9 through Figure 3-12.

Table 3-6. Pier 13 calculated distances to underwater acoustic thresholds and ZOI Areas within the thresholds for a range of pile sizes and types using the South-Central San Diego Bay TL Model.

Activity Description	Minor Injury (PTS Onset) Level A[1,2]		Behavioral Disturbance Level B[1, 3,4]			
	ZOI Distance (m) Diameter (Maximum Radial)	ZOI Area (km^2)	ZOI Distance (m) Diameter (Maximum Radial) or Length x Width	ZOI Area (km^2)		
				Open Water	Around Piers	Total
Impact Driving						
36-inch steel piles	54 (30)	0.0023	6,664 x 1,839	5.25	0.99	6.23
24-inch steel piles	0	N/A	5,752 x 1,477	3.65	0.94	4.58
16-inch steel piles	0	N/A	1,908 x 975	1.02	0.25	1.28
24-inch octagonal concrete piles	0	N/A	396 (236)	0.14	N/A	0.14
16-inch fiberglass piles	0	N/A	0	N/A	N/A	N/A
Vibratory Driving or Extraction[5]						
36-inch steel piles	0	N/A	7,457 x 2,071	6.37	1.11	7.48
24 or 16-inch steel piles	0	N/A	5,752 x 1,477	3.65	0.94	4.58
24-inch octagonal concrete piles	0	N/A	5,831 x 1,012	2.72	0.93	3.65
12-inch timber-plastic piles	0	N/A	262 (146)	0.06	N/A	0.06

Notes:

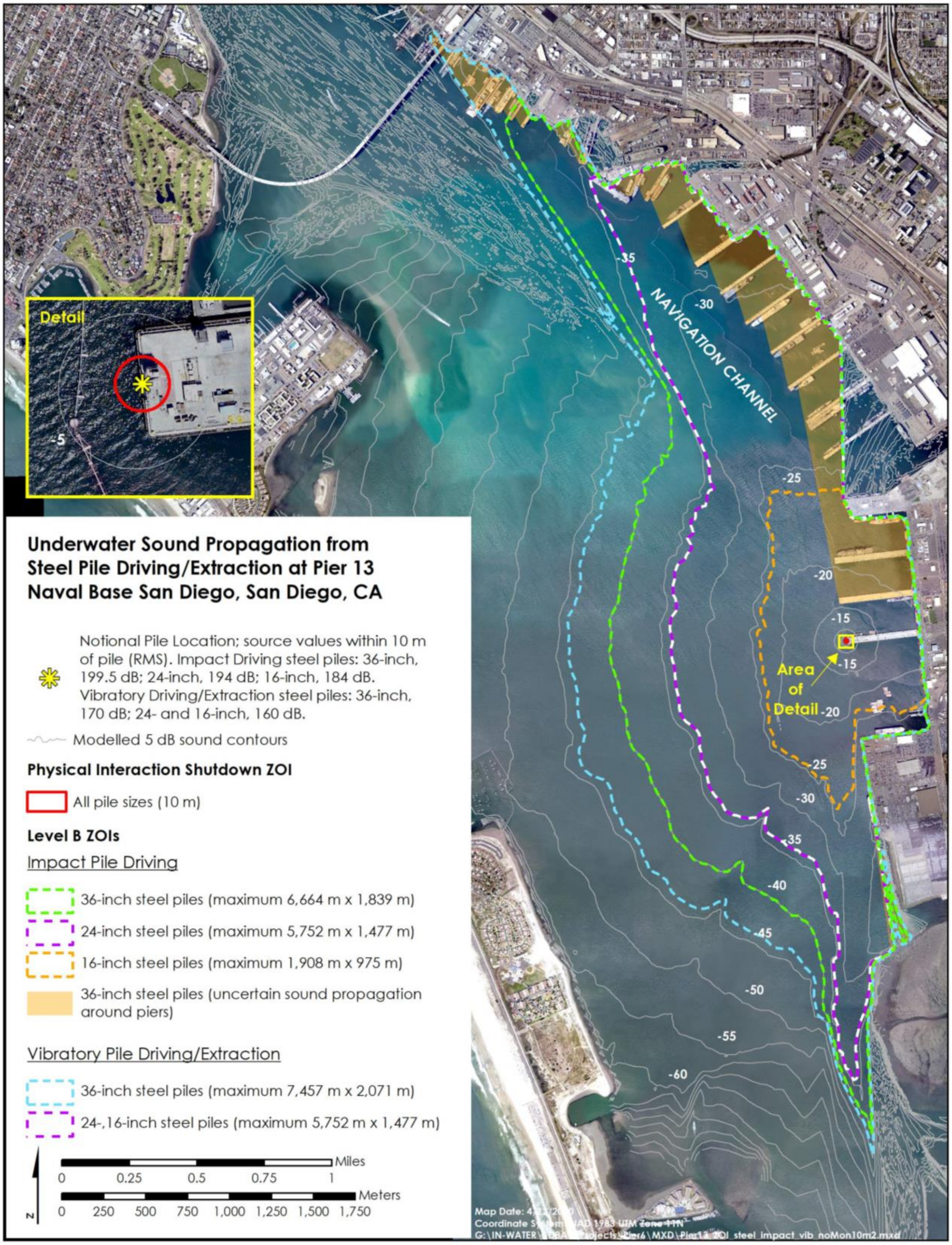
1. See Table 3-2 for underwater noise source values used to calculate the acoustic ZOIs.
2. Distances to Level A acoustic thresholds were calculated based on Otariid weighted SEL_{cum} values (see Table 3-3).
3. The Level B ZOIs for non-impulsive noise sources were calculated to the average ambient underwater noise value of 126 dB re 1 µPa, which was based on the average of the reported ambient median L_{50} values (where L_{50} = statistical noise level exceeded “50” percent of the time) within the project area (Dahl and Dall’Osto 2019).
4. The entire Level B ZOI is shown in the total column, which represents the sum of areas calculated separately for open water versus around piers where the structure’s influence on sound propagation is uncertain. The reported total may differ slightly from that obtained by adding the values for open water and around piers due to rounding.
5. Vibratory pile driving is more likely with steel piles; whereas, extraction may occur with any pile type.

Abbreviations:

dB re 1 µPa = decibels referenced to a pressure of 1 microPascal, km^2 = square kilometers, m = meters,
N/A = not applicable because the source noise level at 10 m (33 ft) is below the acoustic threshold,
PTS = permanent threshold shift, RMS = root mean square,
SEL = sound exposure level, SEL_{cum} = cumulative sound exposure level over 24 hours,
ZOI = zone of influence (area encompassed within acoustic threshold boundary).

Note: Refer to Table 3-3 for calculation of the SEL_{cum} source value.

Figure 3-9. Otariid FHG Level A ZOI for impact driving of 36-inch steel piles based on modeled TL for a representative southern area location at NBSD (Pier 13).

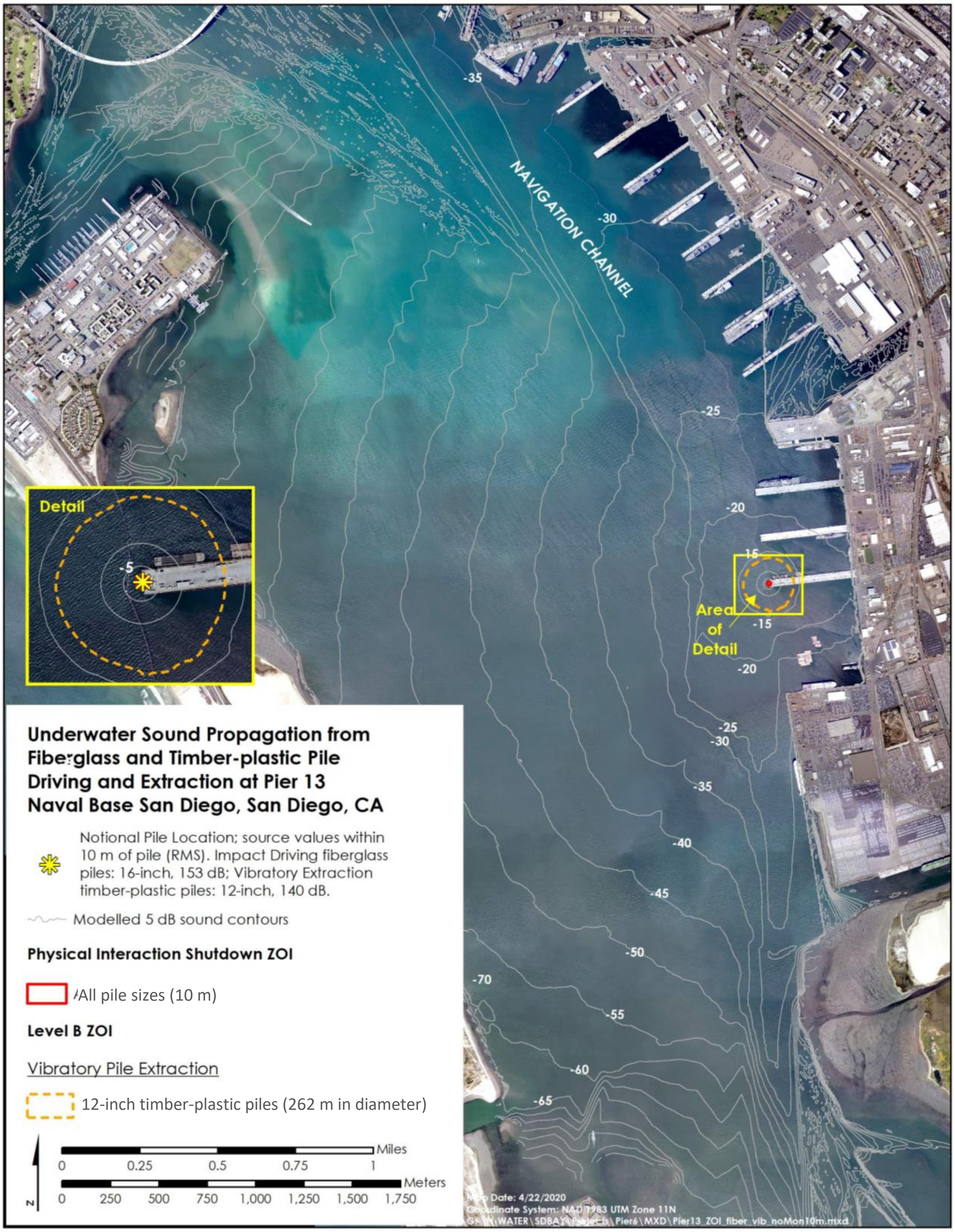


Note: A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted.

Figure 3-10. Level B ZOIs for impact driving and vibratory driving/extraction of steel piles based on modeled TL for a representative southern area location at NBSD (Pier 13).

Note: A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted.

Figure 3-11. Level B ZOIs for impact driving and vibratory extraction of 24-inch octagonal concrete piles based on modeled TL for a representative southern area location at NBSD (Pier 13).



Notes: (1) A 10-m (33 ft) Physical Interaction Shutdown ZOI is shown on the figure for reference only; shutdown zones may vary specific to the project/pile size, as warranted. (2) The surrogate source datum for impact driving of fiberglass plastic piles is below the Level B acoustic threshold of 160 dB RMS; therefore, no Level B ZOI is mapped for that pile type and activity.

Figure 3-12. Level B ZOI for impact driving of fiberglass plastic piles or vibratory extraction of timber-plastic piles based on modeled TL for a representative southern area location at NBSD (Pier 13).

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