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# THEORETICAL COMPARISON OF CUMULATIVE SOUND EXPOSURE ESTIMATES FROM JACKET AND TRIPOD FOUNDATION CONSTRUCTION

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## Abstract:

*Foundation pile driving during offshore construction has led to increasing concerns regarding radiated noise and its effects on the marine fauna (receptors). In the case of many static offshore developments two commonly used foundation techniques are tripod and jacket constructions involving installation of a series of smaller diameter piles surrounding a central structure and mono-piles using a single larger diameter pile. Pile installation itself may involve sequences of percussive piling at different hammer energies, vibro-piling (more rapid, lower level vibrations) and drilling. In some cases all three techniques are used on a single pile installation. The spectral characteristics, as well as duration and level of the total radiated energy from these techniques can vary significantly and may result in different Sound Exposure Levels (SEL) experienced by marine fauna.*

*This paper theoretically explores the potential difference in total SEL for various receptor scenarios for both jacket and tripod construction using available source characteristics data. The effects of the use of mitigation techniques such as Acoustic Deterrent Devices (ADDs) is also explored. The total sound SEL's for each scenario are compared and model sensitivities identified.*

**Keywords:** Underwater noise, marine piling, SEL, Sound Exposure Level, Cumulative

## 1. INTRODUCTION

The work presented here estimates cumulative sound exposure levels (SEL) for various piling events assuming different receptor responses in the vicinity of a marine piling event. Piling scenarios that were tested include tripod and jacket construction, both with and without the use of Acoustic Deterrent Devices (ADDs). For each piling scenario the receptor was assumed to (i) swim away continuously at the beginning of the first piling event, (ii) swim away only during piling and remain at that range and (iii) swim away and then return after individual leg construction.

These examples are based on data derived from work carried out on the Alpha Ventus windfarm construction site [1]. It should be noted, however, that the work presented here is for illustrative purposes only. It should not be seen as a robust assessment of actual SEL exposure events recorded during the construction of this windfarm, but rather as an assessment of potential variations between various piling scenarios and a demonstration of methodology that may be used to assess cumulative exposure from this type of marine piling. The examples for tripod constructions are based loosely on AV7-AV12 piles [1]. These foundations were constructed by individually piling each of the three tripod legs. The total piling period per leg ranged from 1-2 hours with total construction taking between 8-18 hours. Using this, an average period of 12.5 hours was assumed to complete the construction of the foundation.

Jacket installation data used here are broadly based on piling specifications for AV1-AV6 piles [1]. These foundations consist of a frame resting on four legs each piled individually. A complete piling period per leg ranged between 1 and 14 hours with total construction taking between 2 and 12 days. Using this, an average period of 7.5 days was assumed to complete foundation construction. However, it should be noted that this prolonged activity during jacket installation construction is at least in part due to unfavourable weather conditions during the operation and could in principle be much shorter. In each case piles 2.5 m in diameter constitute a single leg foundation. Mitigation methods applied during the construction of this wind farm include 'soft-start' (lower initial hammer energies), use of Acoustic Deterrence Devices (ADDs), and barrier methods such as bubble curtains.

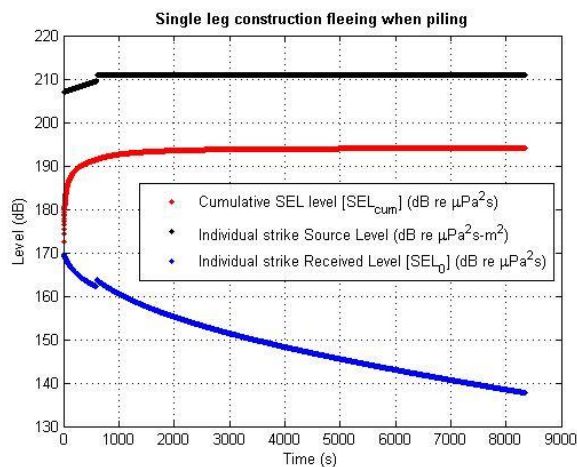
This work adopts use of ADDs 20 minutes before initiation of piling which starts with a 'soft-start' (lower hammer energy). In the following models this soft-start period was taken to be a starting point of 100 kJ linearly increasing to 350 kJ over a 10 minute period (400 hammers strikes, assuming a 1.5 s inter-strike interval). At the end of this sequence the hammer energy was increased to 500 kJ for the remainder of the piling sequence. Using data from Alpha Ventus an average number of total hammer strikes per leg was 5573 strikes for tripod construction and 3202 strikes per leg for jacket construction. These data were used in the models presented below. A generic piling sequence for construction of all legs based on the above average piling profile (number & levels) and average total construction build time was established including mitigation periods. ADD specifications applied in these models were derived from previous literature [4,5] giving SEL source level of 189 dB re  $1\mu\text{Pa}^2\cdot\text{m}^2$  for a 0.2 s long signal. The acoustic emission associated with the ADD system are included in the total SEL exposure estimate. Note that actual sequences showed considerably more variation, however, the 'idealized' version is used

here to illustrate the assessment methodology. However, in future applications actual piling sequences could be substituted to better approximate actual total SEL exposure.

## 2. METHODOLOGY

In order to estimate the potential received level in the sound field as a receptor moves around an estimate of the equivalent far-field (monopole source level) was made again based on the received level estimates taken from the Alpha Ventus foundation constructions. Using measured data from [1] an equivalent maximum SEL source level of 211 dB re  $1\mu\text{Pa}^2\text{s.m}^2$  was assumed. Equating this to a maximum hammer energy of 500 kJ, Source Levels at beginning (207 dB re  $1\mu\text{Pa}^2\text{s.m}^2$  [100 kJ]) and end (209.5 dB re  $1\mu\text{Pa}^2\text{s.m}^2$  [350 kJ]) of the soft-start period were also estimated. This scaling to hammer energy is based on observation for a 2 m diameter pile in UK waters[2].

Taking an assumed swim speed of  $1.5\text{ ms}^{-1}$  (based on mother-calf pair) [3] the total cumulative exposure for a receptor at a fixed start distance can then be calculated assuming that the animal swims directly away from the source. Transmission loss in this case is based on a simple  $15 \times \log_{10}(\text{range in meters})$  geometrical spreading law. However, more complex range dependant (bathymetry, sediment type) propagation can also be used. Figure 1 shows the Source Level (black curve), the instantaneous SEL received level (blue curve) as the animal moves and the cumulative (SEL) total exposure the animal receives (red curve) for an animal that starts 300 m from the source. In this case the total exposure for a single leg construction resulted in an cumulative exposure of around 194 dB re  $1\mu\text{Pa}^2\text{s}$ .



*Fig. 1: Source Level (black line), instantaneous received level (blue line) and cumulative exposure (red line) for a receptor starting at a range of 300m from the adopted tripod installation constructions and assumed to swim away at  $1.5\text{ ms}^{-1}$ .*

10 x water depth) have not been considered to help avoid this problem. The use of more sophisticated propagation loss models, however, should allow more representative assessment of closer to source start ranges.

Using this fixed start type model the total SEL exposure can be compared to various injury criteria. Note: caution should be taken at closer start range estimates. The simple geometric spreading law used for propagation loss, is applicable to far-field, long range estimates and in combination with a simple source level it is a reasonable approximation at longer ranges, however, a near-field is likely to exist at shorter ranges particularly for a distributed source such as a marine piling event. In the current case start ranges  $< 300\text{ m}$  (approximately

### 3. FIXED START RANGE (300 m) RESULTS

Figure 3 shows the fixed start range model for a continuously fleeing animal for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire foundation construction of (tripod) three legs over a 12.5 hours.

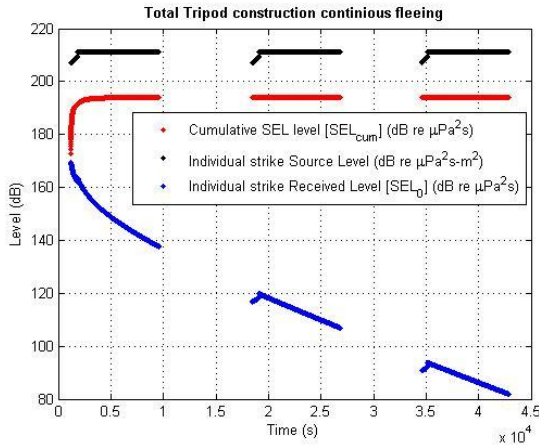


Fig. 3: Exposure level for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire tripod construction period without use of ADD's animal assumed to keep moving

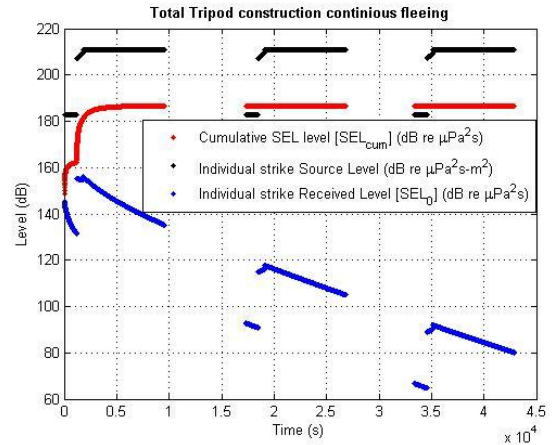


Fig. 4: Exposure level for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire tripod construction period with use of ADD's animal assumed to keep moving

Various 'fleeing' scenarios were then tested. These include a case where the animal is assumed to keep swimming as commencement of the piling soft-start (figure 3) or the beginning of the use of the ADD (figure 4) and is assumed to keep moving. Two other potential scenarios include a case where the animal flees but stops between piling construction on individual legs. Figure 4 shows the same sequences with the use of ADDs 20 minutes prior to the onset of piling, in line with procedures used on the Alpha Ventus site (pers. comms, Boethling, 2011). In each example the animal is assumed to continue swimming away throughout the whole period. Note that the animal is assumed to start swimming away at either the start of the soft-start or at the deployment of the ADD devices if these are considered. Figures 5 and 6 show the case for the entire piling sequences for both tripod and jacket foundation construction respectively where the animal flees then remains static at the end of the acoustic emissions (each leg construction). In both cases the use of an ADD system is included 20 minutes before each construction period (each leg). These data can be compared with the alternate scenario where the animal is assumed to return to a start range in this case of 300 m between sequences. Figures 7 and 8 again show the total construction period exposure for the entire construction sequence for tripod and jacket construction. Again the use of an ADD system 20 minutes prior to construction is assumed on each leg.

Significant variation in the instantaneous received levels (shown in blue) between leg construction in each case is observed due to the receptors relative movements and positions; with significantly higher levels observed for the latter leg constructions in the case where the animal returns in both jacket and tripod foundations. In terms of total

exposure these additional exposures result in higher overall SEL levels over the entire construction period.

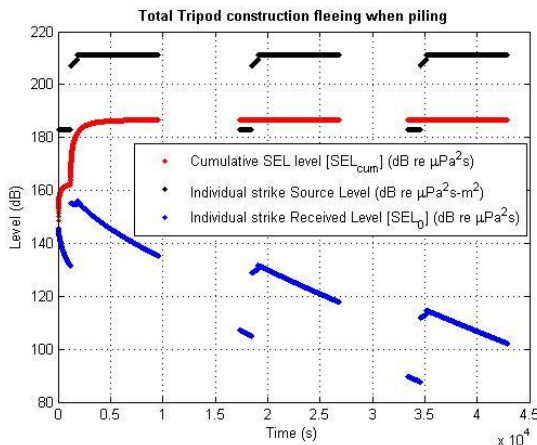


Fig. 5: Exposure level for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire tripod construction period with the use of ADD's animal assumed to stop and remain static between construction periods

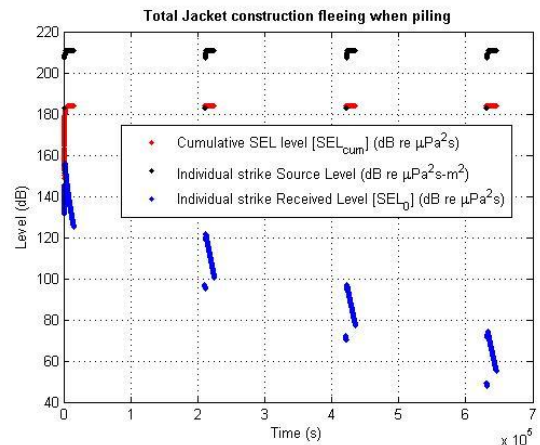


Fig. 6: Exposure level for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire jacket construction period with the use of ADD's animal assumed to stop and remain static between construction periods

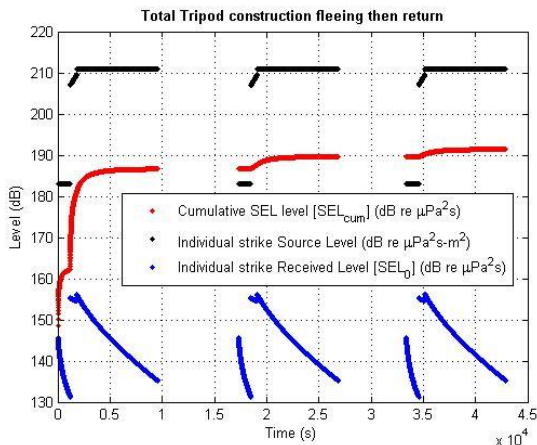


Fig. 7: Exposure level for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire tripod construction period without use of ADD's animal assumed to stop and return to start range of 300m between construction periods

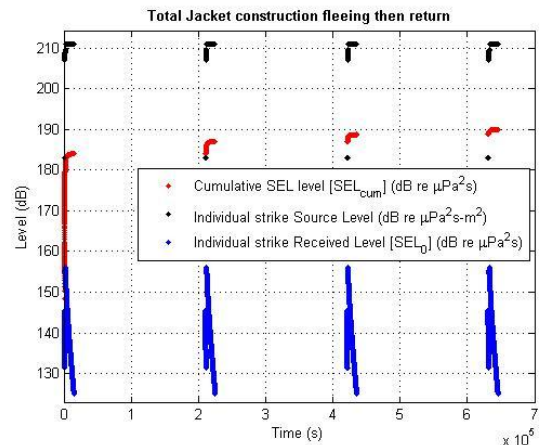


Fig. 8: Exposure level for a start range of 300 m and swim speed of  $1.5 \text{ ms}^{-1}$  for the entire jacket construction period without use of ADD's animal assumed to stop and return to start range of 300m between construction periods

#### 4. TOTAL SEL EXPOSURE VERSUS START RANGE

As with the single tripod leg construction sequence shown in Figure 2 the total exposure level (SEL) for complete construction periods for both tripod and jacket constructions can be made. The models run in section 3 for fixed start ranges are then rerun consecutively for various start ranges and functional hearing group [6]. Figure 9 shows the start range versus total SEL exposure for a fleeing animal where the animal is assumed to keep moving as shown for the fixed start range case shown in Figure 3. In the case of a full

tripod construction using ADD's at the beginning of each piling sequence (each leg pin) the cumulative SEL impact criteria of 198 dB re 1  $\mu\text{Pa}^2\text{s}$  suggested by Southall [7] is not exceeded for start ranges less than 300 m. For pinipeds however total exposure levels of below the lower threshold of 186 dB re 1  $\mu\text{Pa}^2\text{s}$  [7] occur at start range greater than 2.5 km.

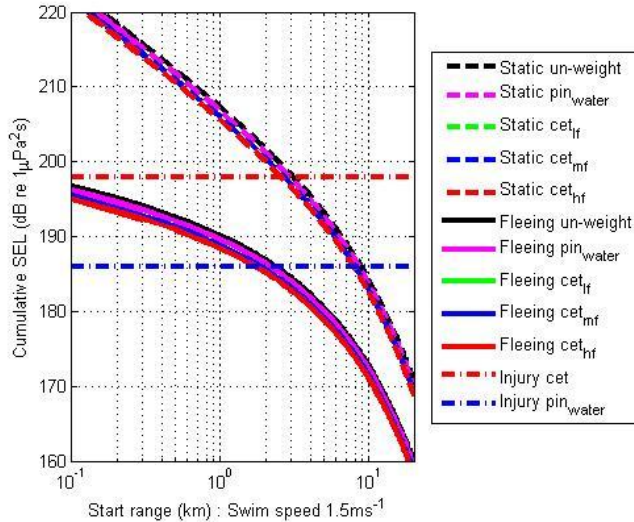


Fig. 9: Start range versus total cumulative exposure for an entire tripod foundation construction for different functional hearing groups assuming the animal continues to swim away from source.

exposures of around 184 dB re 1  $\mu\text{Pa}^2\text{s}$  and 186 dB re 1  $\mu\text{Pa}^2\text{s}$  for jacket and tripod respectively giving approximately 8-9 dB lower total exposures due to the use of an ADD system. Comparison of total exposures for a continuously fleeing animal and an animal that stops shows nearly identical total exposures. This is primarily due to the relatively low received levels experienced by the following leg construction making relatively small contributions to the cumulative exposure experienced at longer ranges, whether the animal continues to swim or remains static.

These data can be directly compared with the flee and return case where exposures levels are in the order of 198-199 dB re 1  $\mu\text{Pa}^2\text{s}$  for both jacket and tripod without the use of ADDs and 190 dB re 1  $\mu\text{Pa}^2\text{s}$  and 191 dB re 1  $\mu\text{Pa}^2\text{s}$  for jacket and tripod respectively using ADDs. In this case total exposures are in the

These scenarios can then be tested for each fleeing case (continues to move, stops and remains static and returns) for each foundation type and with and without use of ADD's prior to individual piling sequences. Figure 10 shows the total SEL exposure for a start range of 300 m for each of the cases discussed above. In this case total exposure for a continuous fleeing animal is 193 dB re 1  $\mu\text{Pa}^2\text{s}$  and slightly higher at 194 dB re 1  $\mu\text{Pa}^2\text{s}$  for jacket and tripod construction respectively without the use of the ADDs prior to piling. For a start range of 300 m the use of the ADDs results in total

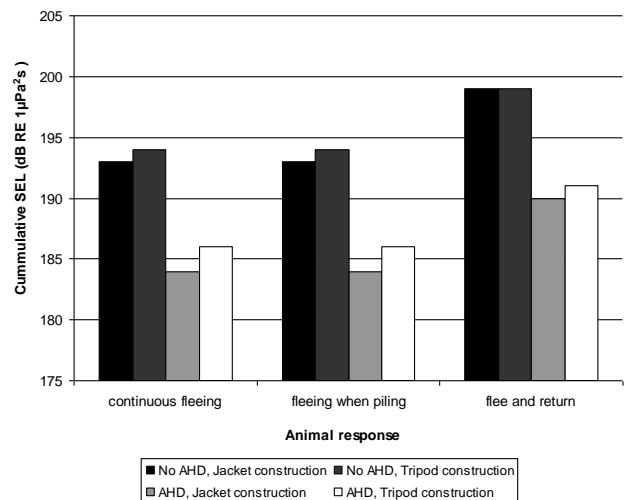


Fig. 10: Total un-weighted SEL exposure for various fleeing animal scenarios for a start range of 300 m and swim speed of 1.5  $\text{ms}^{-1}$

order of 5-6 dB higher if the animal is assumed to return between leg constructions to a start range of 300 m.

## 5. CONCLUSIONS

The above examples provide an illustration of a methodology for estimating total cumulative exposure of marine mammals and other species from a sequential 'noise' event such as marine piling for foundation constructions. Various assumptions with regards to the source level, propagation loss and behavioural response of the species of interest were made. However, these models can be used to 'test' potential scenarios and look at differences between various piling approaches (*e.g.* tripod and jacket construction) and effects of mitigation methodologies (barrier methods, soft-starts, ADDs, *etc*) in terms of cumulative exposure from these events. For example, more realistic, sophisticated behavioural response other than fleeing and static can and have been implemented. These include maximum swim distance, and transiting animals rather than just static and fleeing cases. In addition, integration of range dependant propagation loss models allows near-to-source effects to be more accurately estimated and takes local bathymetry into account and finally integration of actual recorded piling sequence data (levels and timing) allows real piling sequences to be tested. Nonetheless, simple calculations shown here can be used to inspect efficacy of ADD use as well as differences between different piling approaches, in this case tripod and jacket constructions.

The results illustrate that if an individual is assumed to start fleeing when the operation commences, employing mitigation procedures such as soft start, ADDs, results in a lower overall SEL. For a 300 m start range the use of ADDs for example can result in lower total exposure levels in order of 8-9 dB. It should be noted however that higher differences are likely at closer start ranges due to the rapid increases in initial levels at shorter ranges likely near to the pile (much larger variation in propagation losses with distance). The acoustic emission of the ADD itself contributes relatively little to the total exposure allowing the animal to move further away from the source before the higher intensity piling (soft start level) piling begins resulting in lower cumulative exposures overall.

Comparison of the two foundation types show relatively little differences in total exposure with the tripod data often slightly higher (1-2 dB) in these scenarios. Given the diameter of all piles was the same (2.5 m) and identical source levels are assumed; larger cumulative SEL levels could have been expected in the case of the jacket construction, due to additional (fourth) leg. However, in these examples gaps between piling events were much larger and the number of strikes per leg lower in the case of jacket installations, resulting in slightly lower cumulative SEL values compared to tripod construction. The final case of a fleeing and returning animal showed typically higher total exposures (5-6 dB) for a start ranges of 300 m due to the higher received levels experienced during the latter leg construction, as would be expected. This difference is likely to be higher at shorter start ranges due to higher variation in propagation loss at shorter ranges.



## 6. ACKNOWLEDGMENTS

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