Fehmarnbelt Marine Mammal Studies

Measurement of underwater noise and vibrations induced by traffic in the Drogden tunnel

Submitted to	Femern AS
Date	2012/02/13
Document No.	ATR ENV0500024
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Version History	Draft

ISBN Number: 978-87-93074-10-1

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1. Executive summary

As part of the EIA for the Fehmarnbelt Fixed Link Femern A/S has commissioned the FEMM consortium to conduct measurements of tunnel induced noise and vibrations of the sea bottom leading to an increase in underwater sound level. The measurements were carried out in the Øresund, directly above and 400 m away from the tunnel connecting Amager with Peberholm.

In order to separate tunnel induced from ambient noise, like shipping noise etc., a geophone and a hydrophone were placed directly above the tunnel alignment to record vibrations of the sea bottom and the resulting underwater noise.

Directly above the tunnel, there are measurable vibration immissions during train passages, causing an increase in underwater sound pressure, i.e. noise immissions.

However, at a distance of about 400 m away from the tunnel, underwater noise level, caused by trains passing the tunnel, was hardly measureable and do not contribute to the overall broadband level caused by shipping.

2. Measurement procedure

The measurements were made on July 19, 2011. Two autonomous recording systems with hydrophones were deployed on the sea bottom. System 1 was placed above the tunnel at 55°37.14'n 12°42.42'e, system 2 was positioned north of the tunnel route, approx. 400 m from position 1 at 55°37.37'n 12°42.58'e (Figure 1). The recording systems are shown in Figure 2 and 4. The hydrophones were kept about 2 m above the sea floor by means of floaters. In addition to the hydrophone, system 1 above the tunnel was fitted with a vibration sensor (geophone, Figure 3). During the measurement, the work vessel JHC Miljø was anchored 500 m north of position 2. The water depth in the measurement area is between 7 m and 9 m.

Since shipping was expected as a major noise source during the measurements, the ship traffic was recorded on board the JHC Miljø by means of an AIS receiver. Because of the vicinity of Københavns Lufthavn (Copenhagen Airport), provisions were also made to measure aircraft noise, as a possible source of underwater noise (Figure 5). However, although starts and landings at the airport could be observed visually from the measurement location, there was no noticeable aircraft noise, as there were no flights at low altitude in the measurement area.

The recording bandwidth was 10 Hz to 20 kHz. The upper limiting frequency range of the geophone, however, was about 1 kHz. The recordings were evaluated later with the aid of software written in MATLAB by itap. Sound and vibration levels versus time and 1/3-octave frequency spectra were computed.

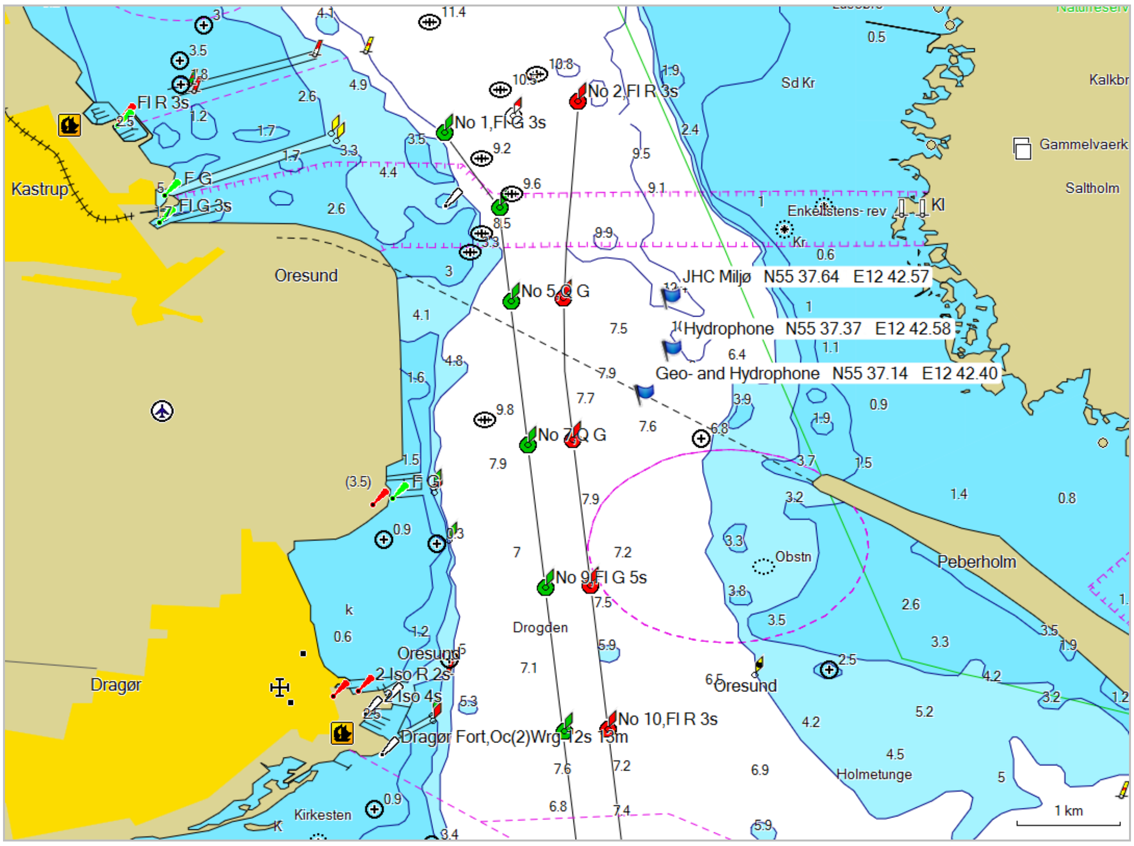

Figure 1 Measurement location. Recording system 1 was placed directly above the tunnel, while recording system 2 was positioned 400 m beside the tunnel route. Map screenshot taken from Garmin(R) BlueChart(R) Northern Europe

Table 1 Equipment used for the measurements

Device	Type	Manufacturer	Remarks
2 x Autonomous underwater sound recording system		(itap)	
2 x Hydrophone	8106	Brüel & Kjær	connected to recording system
Hydrophone calibrator	4229	Brüel & Kjær	
Geophone	SM-6	Sensor Nederland	installed in recording system
Recorder	PMD 620	Marantz	for recording of possible aircraft noise
Microphone	4189	Brüel & Kjær	
Microphone calibrator	4231	Brüel & Kjær	
AIS receiver	MXA-5000	Icom	
GPS device	GPSmap 76cx	Garmin	

Figure 2 Deployment of the recording system above the tunnel. The tubular housing was weighted with steel rods (painted green) with 40 x 40 mm² cross section and 1 m length to ensure a good contact of the geophone to the sea bottom. Background: Tower and other buildings of Copenhagen Airport and a passenger train on a siding (Klaus Betke).

Figure 4 Preparation of the second recorder for deployment 400 m north of the tunnel line (Klaus Betke).

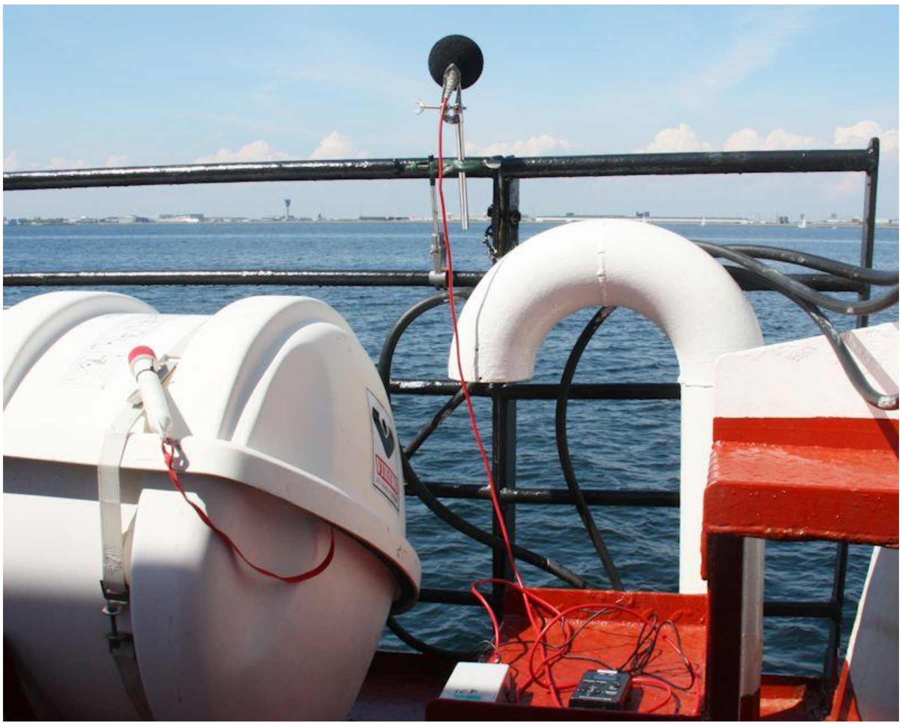

Figure 5 Microphone for recording of aircraft noise (Klaus Betke).

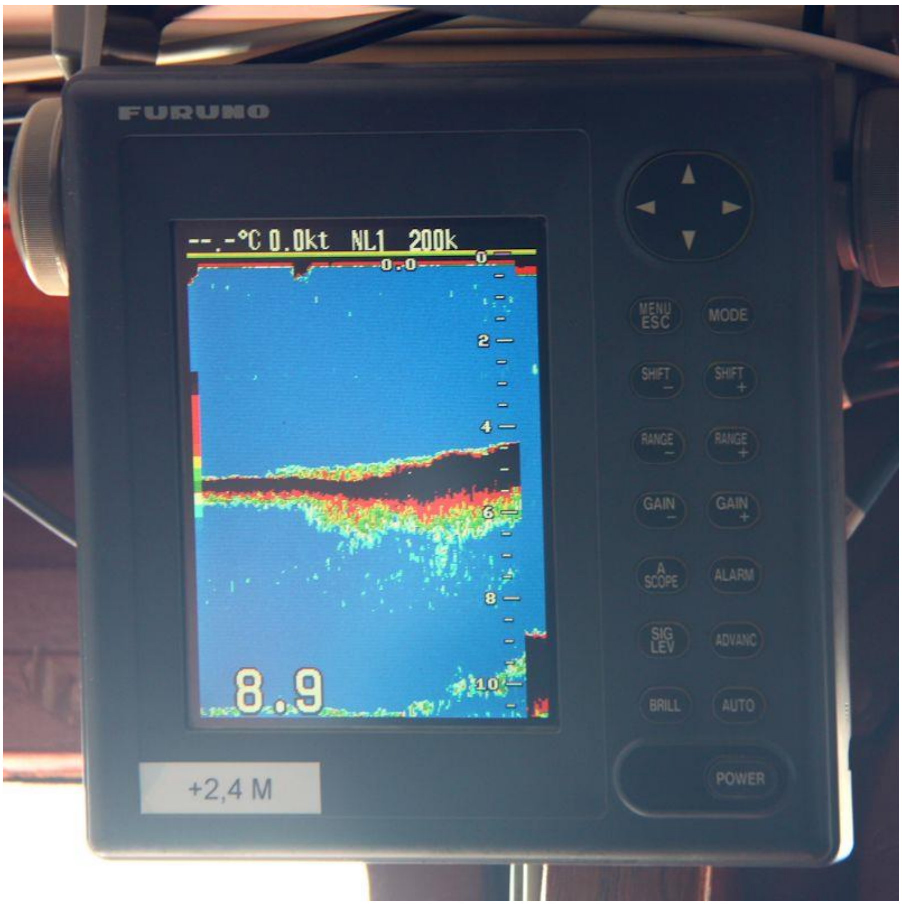

Figure 6 Depth sounder display while approaching the tunnel (note: the depth scale on the right side on the display only belongs to the very right part, which differs from the rest due to automatic range switching) (Klaus Betke).

3. Results

In Figure 7, the broadband noise level measured at position 1 above the tunnel is shown for a period of 105 minutes. The lowest level (background level) observed is approx. 105 dB re 1 µPa. Besides some broad maxima caused by shipping noise, there are distinct peaks that exceed 130 dB re 1 µPa and in some cases 140 dB re 1 µPa. By listening to the recordings, these peaks could be associated with train passages. In the time tables for 2011 available from Öresundståg (oresundstag.se), 20 passenger trains were scheduled to pass the tunnel between 07:30 and 09:15 local time. The number of peaks in Figure 7 is 23. At least one train was found that was most likely a cargo train (at 08:27), which of course does not appear in regular time tables. As can be seen from Figure 8, the increase of noise caused by a train lasts for approx. 10 s, while the cargo train passage at 08:27 lasts approx. 20 s. Vibration levels measured with the geophone on the sea floor show the same temporal characteristics.

When comparing broadband levels of train noise to ship noise the distance to the ships has to be accounted for. Using a conservative approximation for transmission loss, i.e. level decrease with increasing distance, of 15 lg(distance_1/distance_2), yields 15 dB higher levels when the distance to the ship is diminished by a factor of ten. In 50 m distance to the passing ships, the levels shown in figure 7 would be raised to 162 dB at 07:33 and 149 dB at 08:26. These levels exceed the train induced noise levels roughly by 10 – 20 dB.

None of the underwater noise recordings contained audible signals that unambiguously were caused by car-traffic in the tunnel. The same holds for the vibration measurements.

The trains cause a level increase in a broad frequency range, with a broad maximum from 30 Hz to 1 kHz, and an absolute maximum near 50 Hz for most trains (Figure 9). For comparison, spectra of two ship passages at distances of 470 m and 650 m from the measurement position are shown in Figure 10.

The train-induced peaks can also be found in the vibration signal from the geophone (Figure 11). Here the spectral maximum is between 200 Hz and 500 Hz (Figure 12). There is a strong increase in the vibration level below 100 Hz that can not be found in the noise level. The reason for this increase, which is not related to trains or ships, is not clear. It is probably caused by wave-induced movements of the mooring (rope and surface marker buoy). It clearly does not originate from car-traffic in the tunnel because then the noise levels for background noise would have to show higher levels at those frequencies. Vibrations of the sediment cause noise in the water as well as underwater noise produces movement of the sediment. At least down to the cut-off frequency of about 50 Hz, where the shallow water depth prevents sound propagation, there should be noise components if the vibrations were caused by car-traffic.

In order to analyze the correlation between sea bottom vibration and the sound pressure above the tunnel, the coherence between these two signals was computed (Figure 13). The coherence gives the linear correlation as a function of frequency and was averaged over a 6 second interval with and without train passage, respectively with a frequency resolution of 4 Hz. There is an obvious correlation between the sound pressure and the vibration in the frequency range between ca. 100 Hz and 500 Hz. For frequencies below about 100 Hz the coherence drops of sharply, this implies, that the low-frequency parts of the frequency spectra of the sound pressure as well as the vibration are not caused by train noise from the tunnel. With the same reasoning, car-traffic can be excluded as the source of the vibration components below 100 Hz. Neither with nor without train passage a significant coherence below 100 Hz could be detected.

In the sound signal recorded 400 m off the tunnel line, only a few of the peaks associated with railway traffic from Figure 7 can be found, at levels of approx. 120 dB re 1 µPa or lower (Figure 14). The background level at this position was about 113 dB re 1 µPa, and the train passages cause only a slight increase in the frequency spectrum (Figure 15). The ship spectra (Figure 16) are very similar to those measured above the tunnel with respect to level and shape.

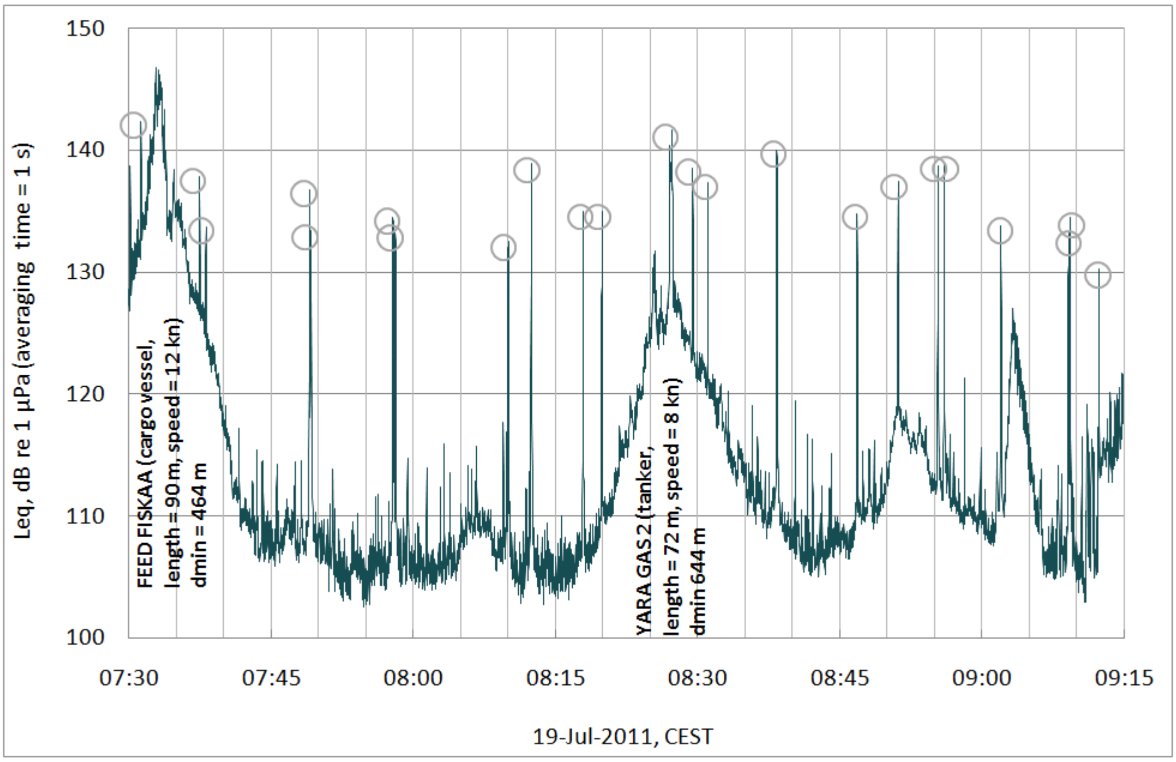

Figure 7 Broadband sound level recorded above the tunnel. The peaks marked by circles were identified as train passages.

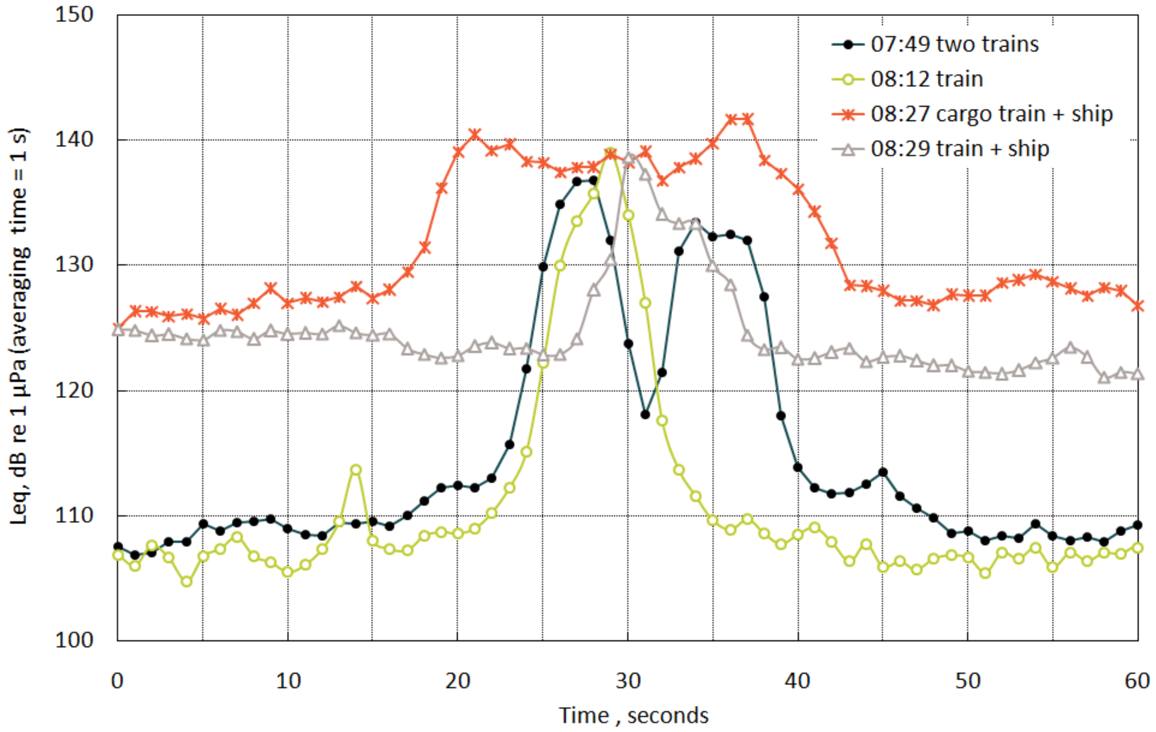

Figure 8 Broadband sound level of some of the train passages in Figure 7 on a shorter time scale

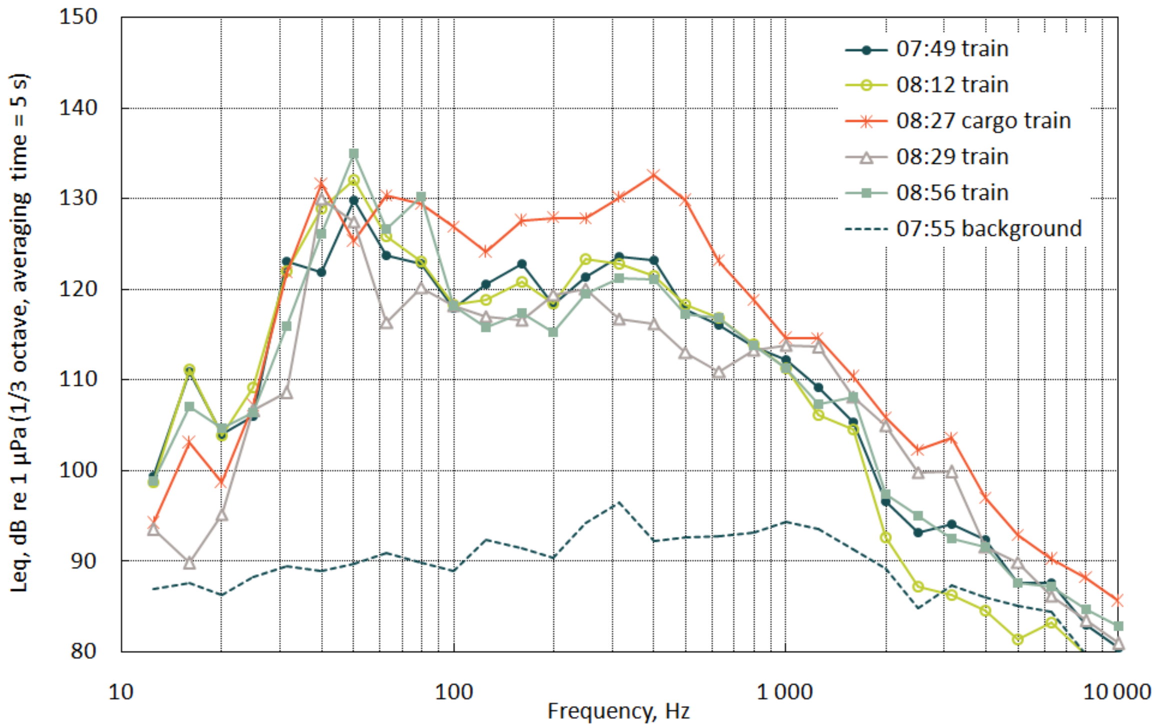

Figure 9 Sound spectra of some train passages recorded above the tunnel

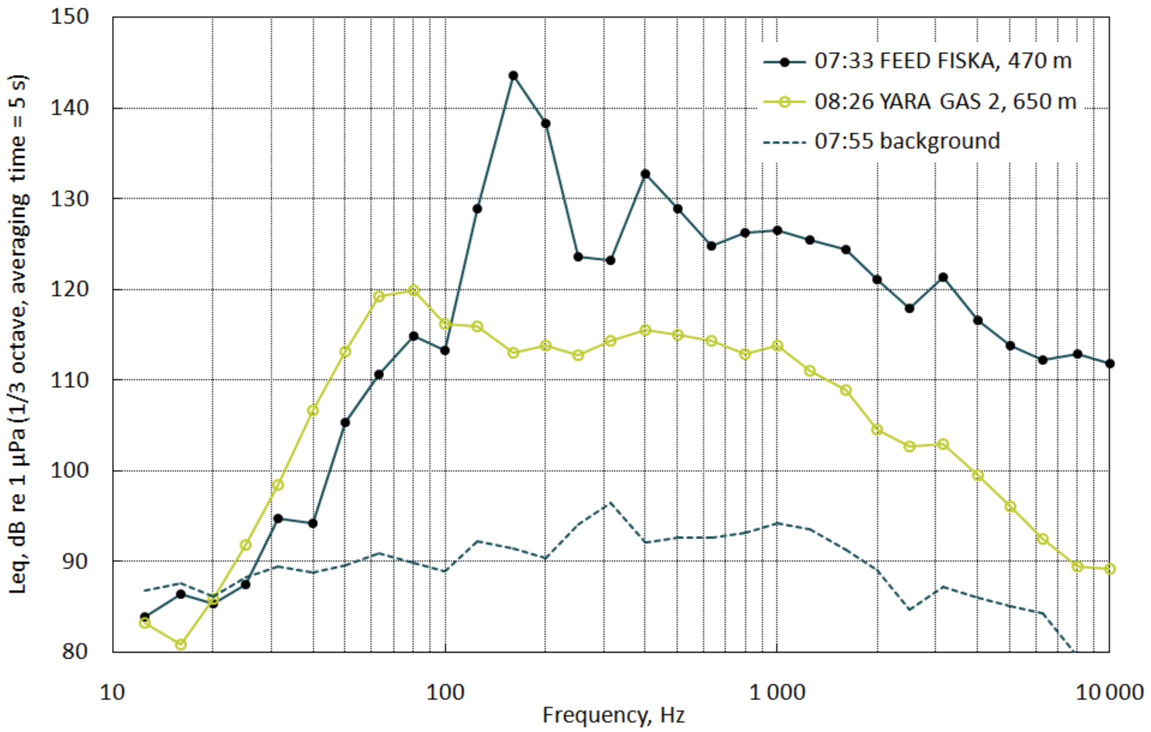

Figure 10 Sound spectra of ships recorded above the tunnel

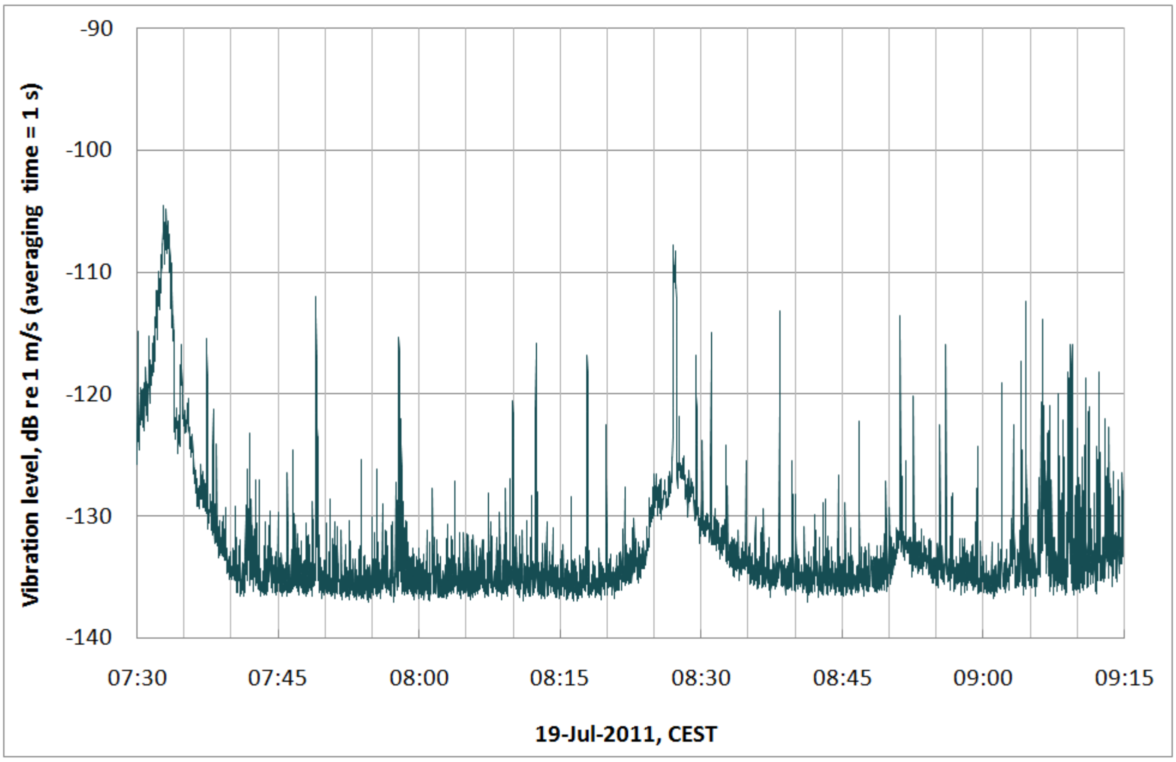

Figure 11 Broadband vibration level (100 Hz high-pass filtered) recorded on the sea bottom above the tunnel

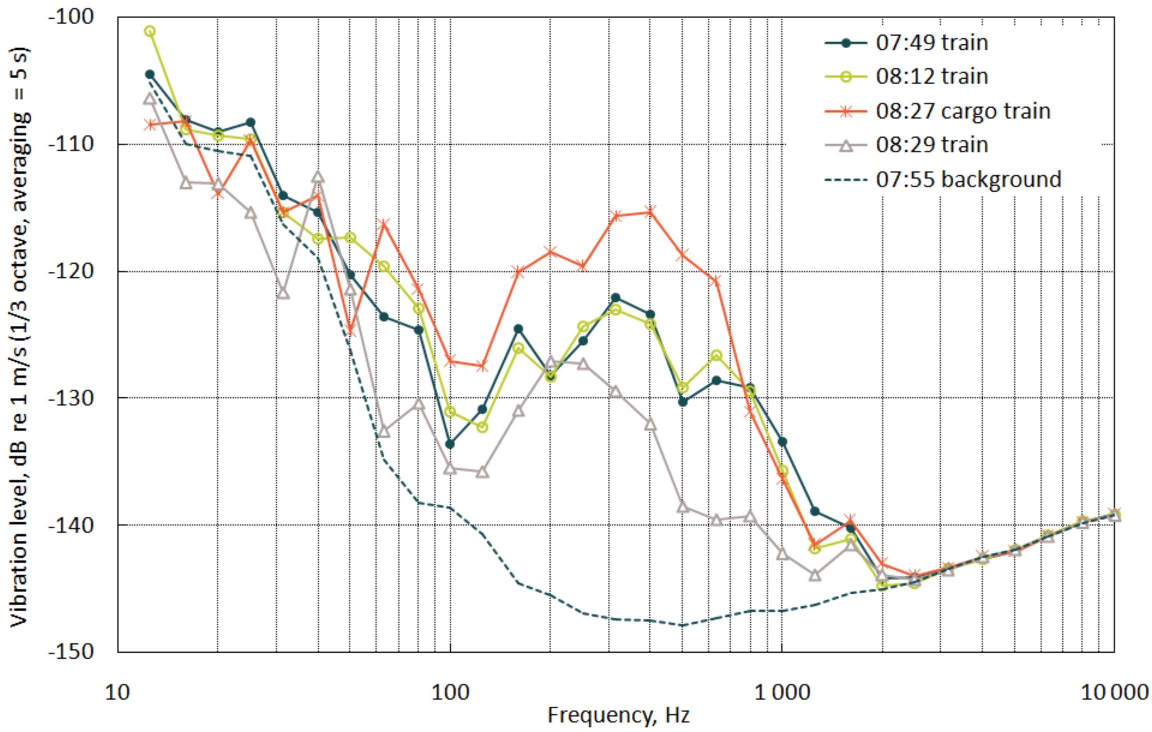

Figure 12 Vibration spectra of the sea bottom above the tunnel

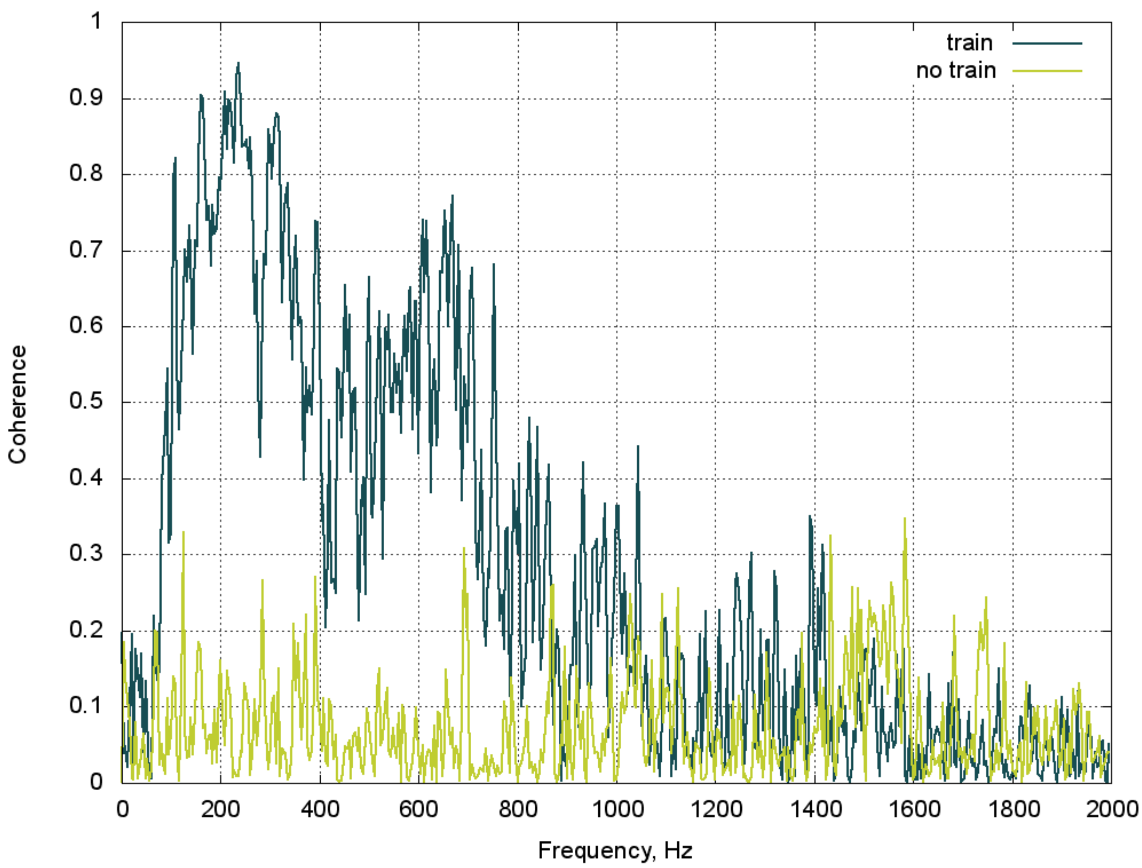

Figure 12 Coherence between the sound pressure and the vibration of the sea bottom above the tunnel

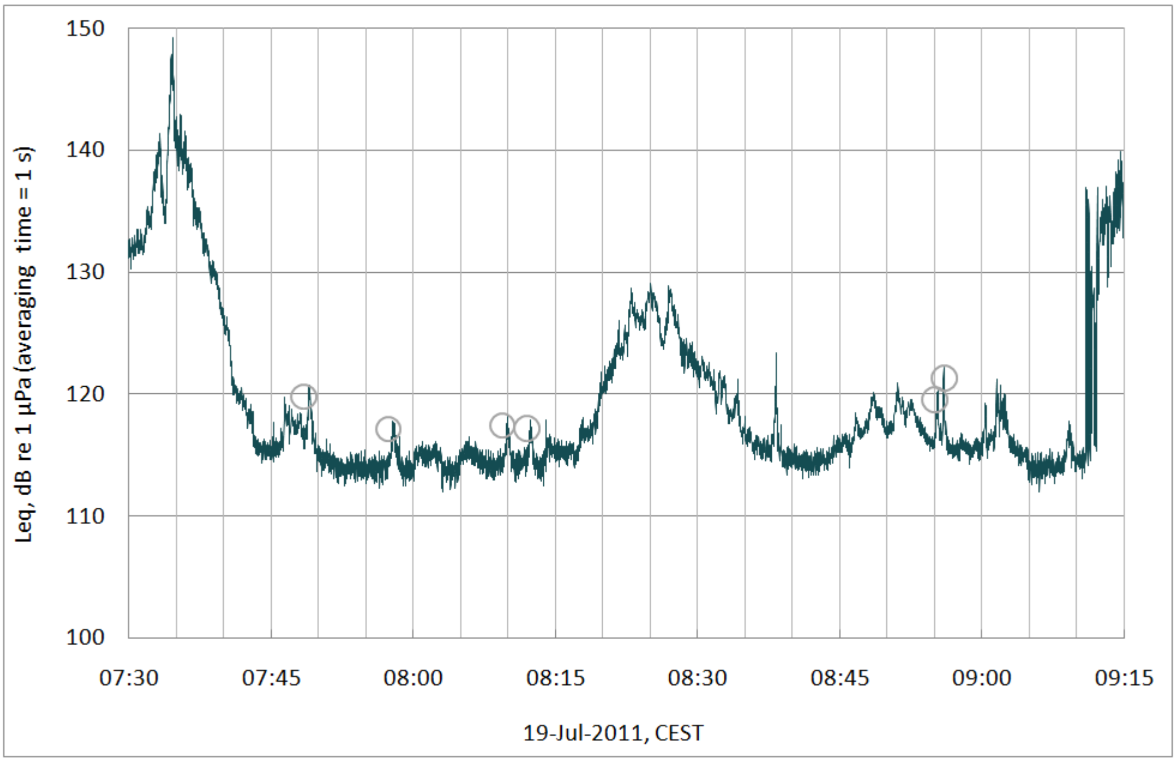

Figure 13 Broadband sound level recorded 400 m north of the tunnel line. Only a few of the peaks associated with railway traffic from Figure 7 can be found in this signal.

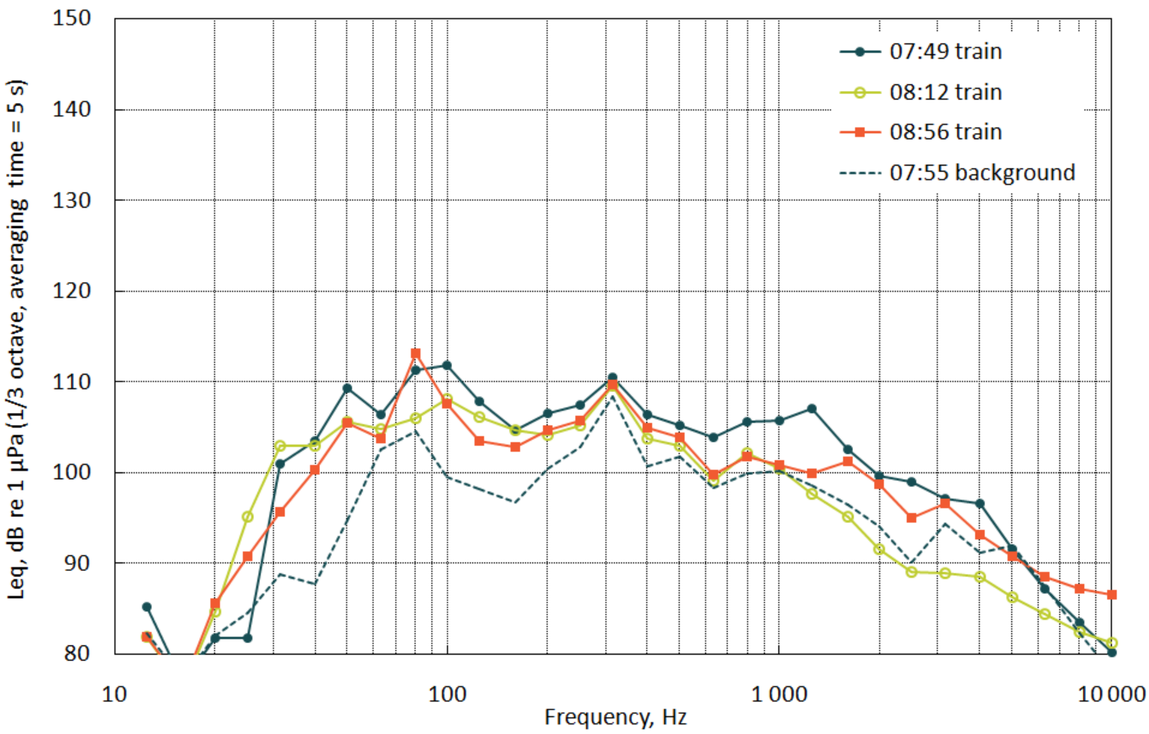

Figure 14 Sound spectra of trains in the tunnel recorded 400 m north of the tunnel

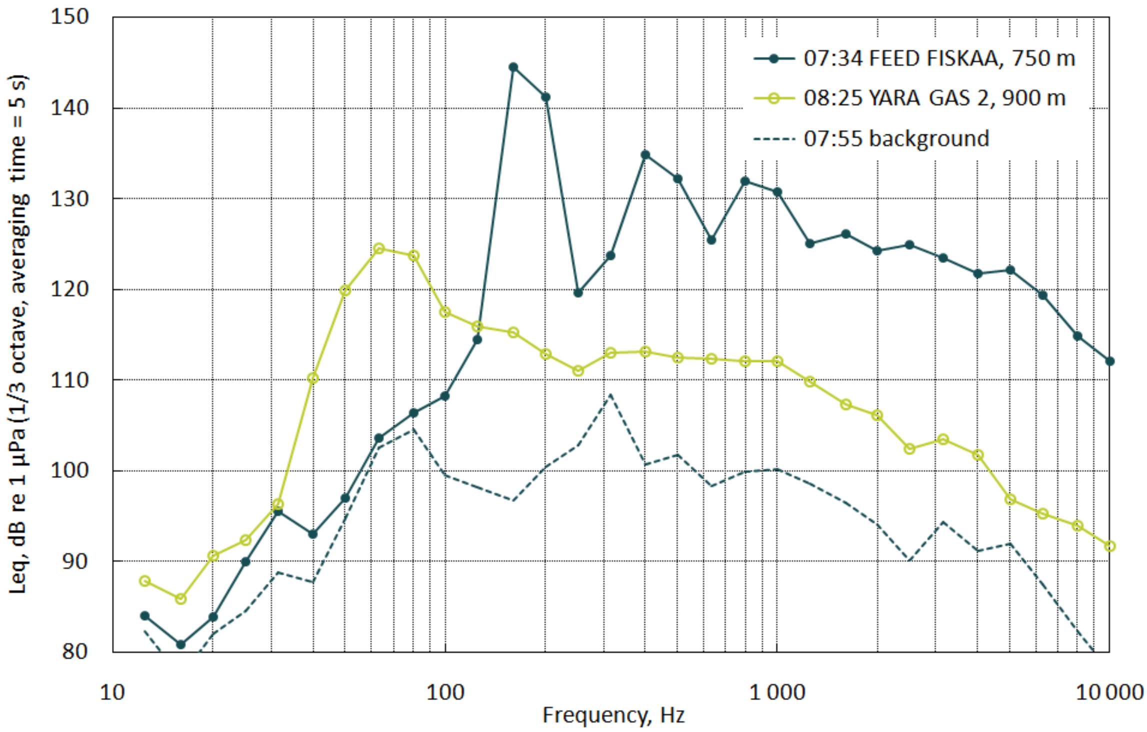

Figure 15 Sound spectra of ships recorded 400 m north of the tunnel

4. Discussion

Simultaneous measurements of underwater sound pressure and sea bottom vibrations directly above the Drogden tunnel alignment were conducted in order to evaluate the impact on the noise and vibration level caused by train passage and car-traffic induced vibrations.

A typical train passage lasts ca. 10 seconds and causes an increase in sound level to about 140 dB directly above the tunnel. Cargo trains lead to comparable level increases for about 20 seconds. This has to be compared to shipping noise that, for each passing ship, lasts several minutes and can reach noise levels above 140 dB at more than 400 m distance.

In a distance of 50 m to a passing ship the shipping noise can exceed the train induced noise by more than 20 dB.

The highest vibration levels of -106 dB re 1 m/s were measured directly above the tunnel during a ship passage in a distance of approx. 470 m. Shipping noise can therefore induce sea floor vibration levels that directly underneath the ship exceed the train induced vibrations by more than 20 dB.

Sound level measurements at a distance of 400 m to the tunnel showed a level of about 120 dB during train passages. Due to shipping noise, only a fraction of train passages could be clearly identified at this distance to the tunnel.

Car-traffic as a source of vibrations and noise could not be detected even directly above the tunnel.