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Structure borne sound from tunnelling works for underground infrastructure

Clas Ola Høsøien
Multiconsult Norge AS, Nedre Skøyen vei 2, NO-0276, Norway, coh@multiconsult.no

Underground works in densely populated areas is an increasing necessity as the urbanisation process is accompanied with a demand for increased infrastructure capacity. During the tunnelling works for the Follo Line project in Norway, consisting of two 20 km train tunnels, extensive measurements of structure borne sound from the tunnel boring machines (TBMs) were carried out. The goal of the measurements was partly to assess, and potentially modify, the early phase model and calculations. Analysis of the measurement data is presented together with refinements in the prediction model of sound propagation in hard rock and attenuation effects.

1 Introduction

The Follo Line project in Norway consists for the most part of two parallel train tunnels, partly under densely populated areas with overburden varying from approximately 20 m to 100 m. To assess the structure borne sound level from the tunnel boring machines (TBM), available measurement results from Norway, Sweden and Switzerland was used as a basis for early phase noise studies. The measurement data was combined with a semi-analytical approach for structure borne sound propagation presented by Ungar and Bender [1], and the early phase estimates was used to map potentially affected dwellings.

As the existing measurement results showed a rather large dispersion, probably mainly due to differences in geological conditions, building foundation and in which floor the measurements were carried out, long term measurements at several locations were carried out during the Follo Line excavation.

The distances between immission points and tunnel centreline were in the range of approximately 10-300 m, with a total of 29 different immission points along the tunnel route.

2 Model and early phase estimates

2.1 The Ungar and Bender approach

The early model was based on the Ungar and Bender semi-analytical approach as referred by Eitzenberger [2] combined with existing data from measurements in Sweden [3] and internal reports/memos from other projects in Norway and Switzerland. Because of the large dispersion in reported sound pressure levels in the various projects, it was recommended to prepare a monitoring programme to verify the preliminary predictions, and if the new data were more consistent than the existing data, modify the prediction model.

The basic structure for wave attenuation given by the Ungar and Bender approach is summarized in Equation (1):

$$A_T = A_g + A_d + A_i \tag{1}$$

where A_T is the total attenuation of compression waves (P waves) in rock/soil, A_g is geometrical attenuation, A_d is attenuation due to internal losses (dissipation) in the medium and A_i the effect of layered rock/soil on P waves passing interfaces between two layers with different material properties.

The original Ungar and Bender approach was related to vibrations from underground trains, so the geometrical attenuation in their model is based on line source characteristics. Dissipation depends on distance from the source, frequency, loss factor and velocity for P waves in the medium. See Table 1 for wave propagation properties for typical rock/soils according to Ungar and Bender. Attenuation caused by layer interfaces in rock/soil is not covered this paper.

Table 1: Wave propagation properties for typical soils according to Ungar and Bender.

Soil class	Wave speed, c [m/s]	Loss factor, η [-]	Density, ρ [kg/m^3]
Rock	3500	0.01	2.65
Sand, silt, gravel	600	0.1	1.6
Clay, clayey soil	1500	0.1-0.2	1.7

2.2 Early phase estimates

Some of the existing measurement data used in the early phase are shown in Figure 1 to illustrate the dispersion in results, including the final early phase estimates based on Ungar and Bender for worst- and best-case scenario for TBM.

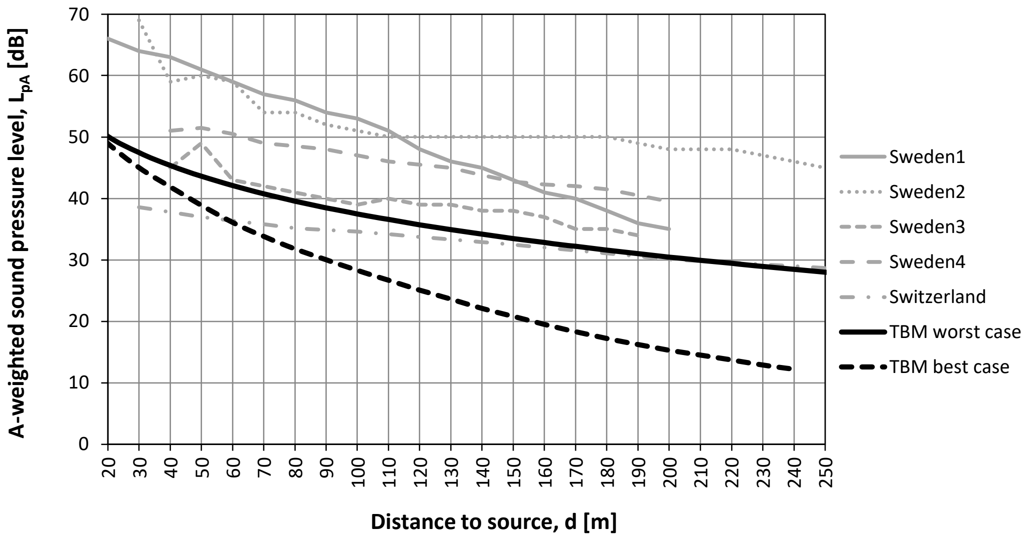

Figure 1: Data from measurements of structure borne sound pressure levels from TBM in Sweden and Switzerland, and final early phase estimates for worst- and best-case sound pressure levels from TBM related to distance to the source.

The TBMs in the Swedish measurements were rather small, with cutter head diameter 3.5 m, compared to the planned cutter head diameter 10.5 m for the Follobanen tunnel. Calculation of maximum cutter head speed for these two diameters results in a ratio of approximately 2.5 (Swedish projects / Follobanen tunnel). According to Ho & Wong [4] a doubling of rotational speed could lead to a 4-5 dB increase in excitation force level, which they related directly to a similar increase in A-weighted level. As the Follobanen TBM maximum cutter head speed is approximately half of the maximum speeds presumed in the Swedish projects, the levels were therefor reduced by 5 dBA for the estimates. The Swedish measurement results were used to establish the "TBM worst case", i.e. resulting sound pressure level in basements in buildings founded directly on rock. Unpublished measurements from Switzerland on ground floor in buildings without basement, founded on fractured rock or more soft ground/soil, were used to establish the "TBM best case" results.

The sound level attenuation varied between 3-5 dB per distance doubling, so the line source characteristic was kept, as dissipation accounted for the additional attenuation.

3 Results from the Follo Line measurements

3.1 Trend lines from measurement data

Measurements in the Follo Line project were carried out in several locations, logging A-weighted sound pressure levels for several weeks in most locations. The sound levels were plotted against distance between measurement point and TBM position reported every day. Typical plots are shown in Figure 2 and Figure 3 below, together with trendlines generated from the datapoints.

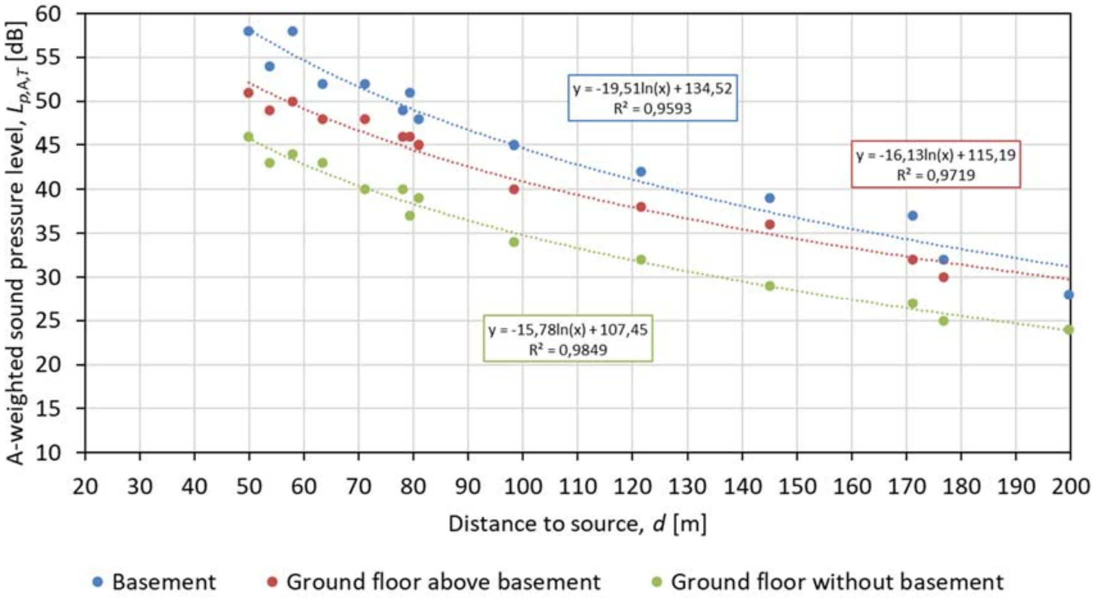

Figure 2: Data from measurements of structure borne sound pressure levels from TBM on one location in different rooms with varying ground coupling. The basement is founded directly on rock.

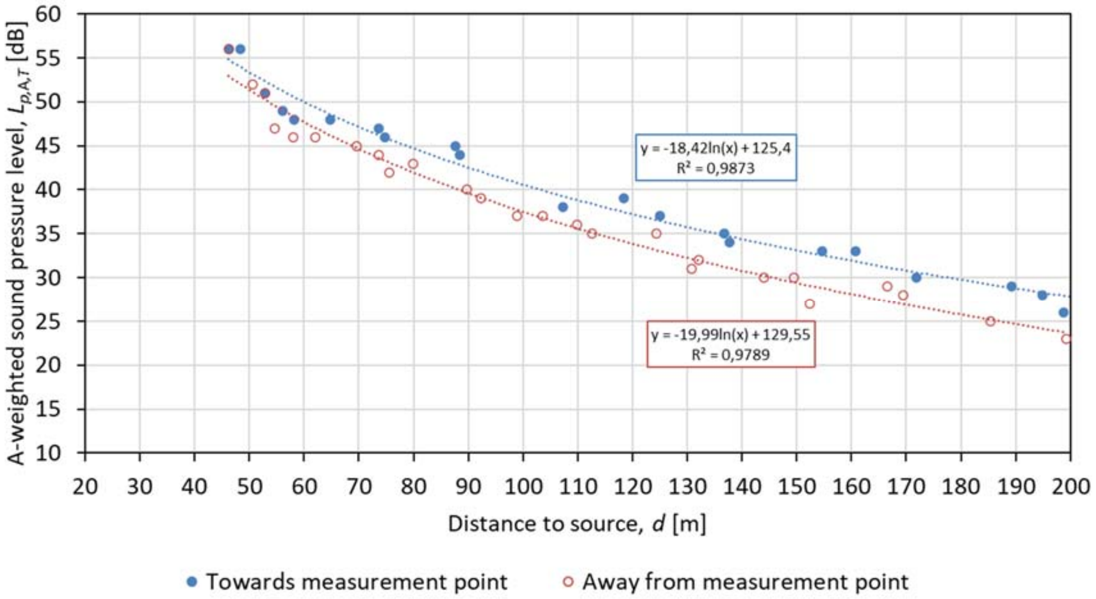

Figure 3: Data from measurements of structure borne sound pressure levels from TBM on one location in a room on the ground floor above basement founded directly on rock.

3.2 Compiled trend lines compared to model estimates

The trendlines generated from plots for different situations were compiled, average values calculated and compared to model estimations to find the best fit adjusting different parameters in the model. Figure 4 - Figure 9 below shows three different situations. In all figures the grey area represents 90 % confidence level (two-sided test) around the calculated average values. The measurement results in Figure 4 - Figure 7 are from concrete structure buildings, while results in Figure 8 -Figure 9 are from lightweight structure buildings.

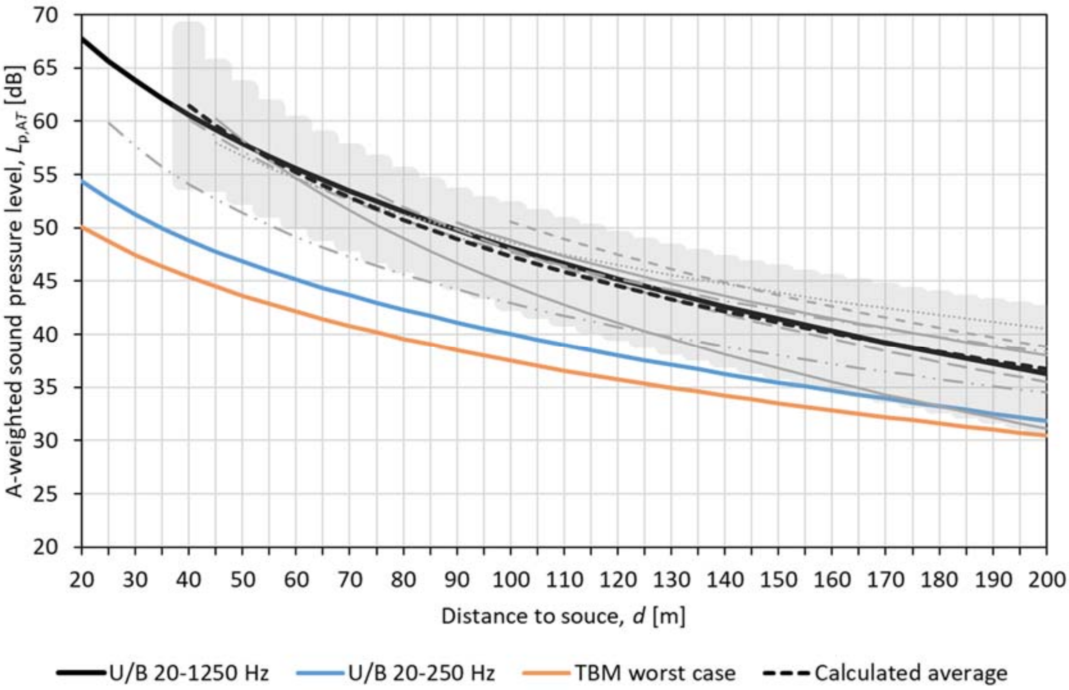

Figure 4: Estimated sound pressure level based on Ungar/Bender (U/B with different cutoff frequencies), calculated average and trendlines from measurements in rooms in basement founded directly on rock (dotted black and grey lines, respectively), and TBM worst case estimate from the early phase.

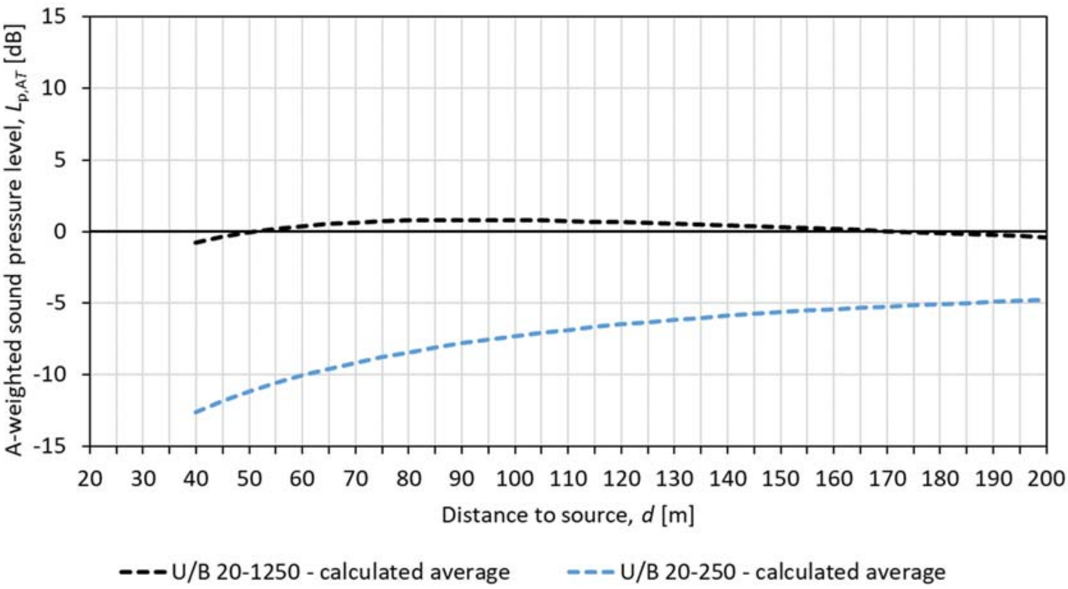

Figure 5: Difference between model estimates and calculated average with data as shown in Figure 4.

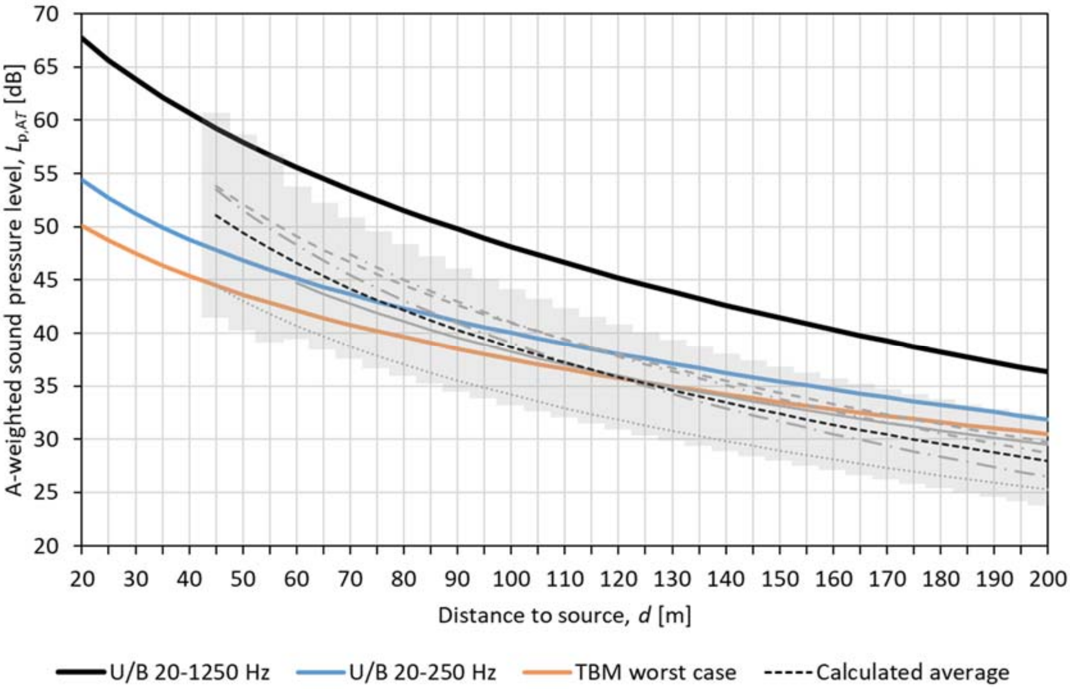

Figure 6: Estimated sound pressure level based on Ungar/Bender (U/B with different cutoff frequencies), calculated average and trendlines from measurements in rooms on ground floor over basement founded directly on rock (dotted black and grey lines, respectively), and TBM worst case estimate from the early phase.

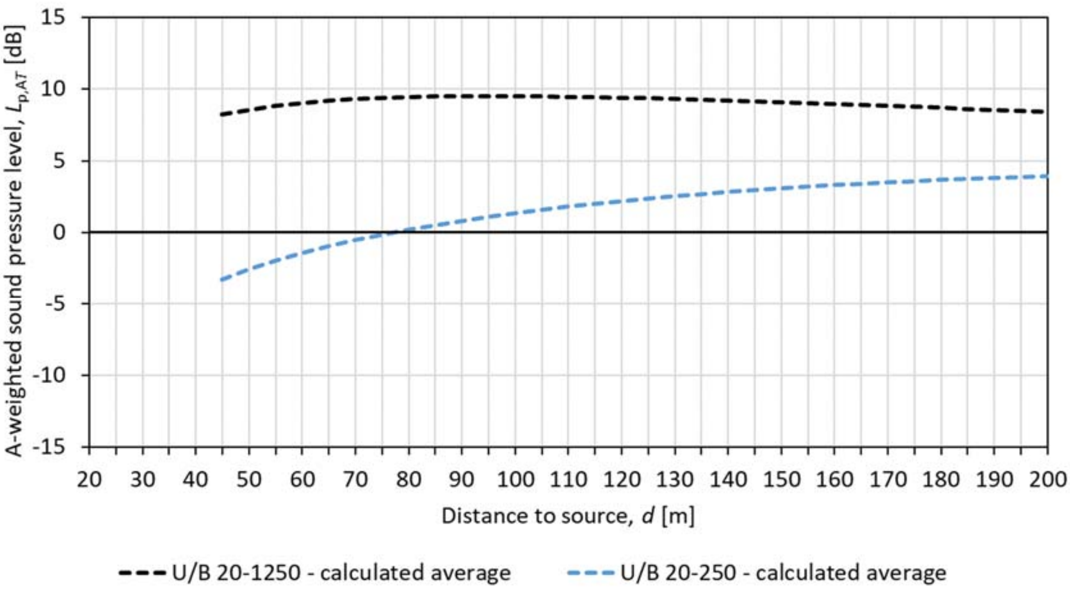

Figure 7: Difference between model estimates and calculated average with data as shown in Figure 6.

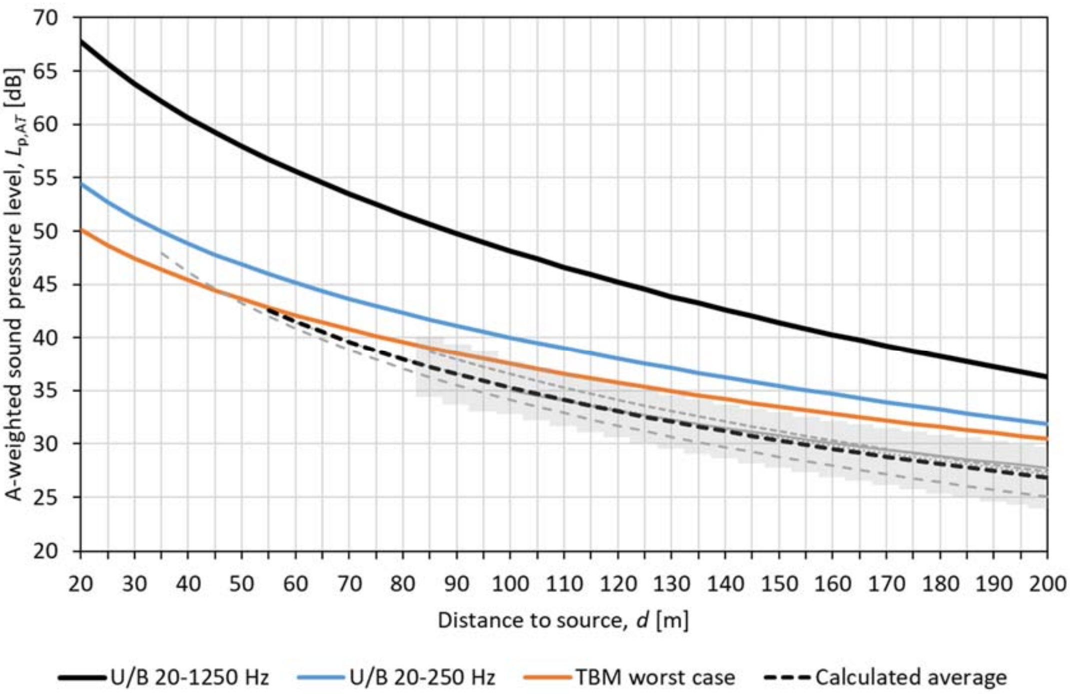

Figure 8: Estimated sound pressure level based on Ungar/Bender (U/B with different cutoff frequencies), calculated average and trendlines from measurements in rooms on ground floor without basement, founded on soil (dotted black and grey lines, respectively), and TBM worst case estimate from the early phase.

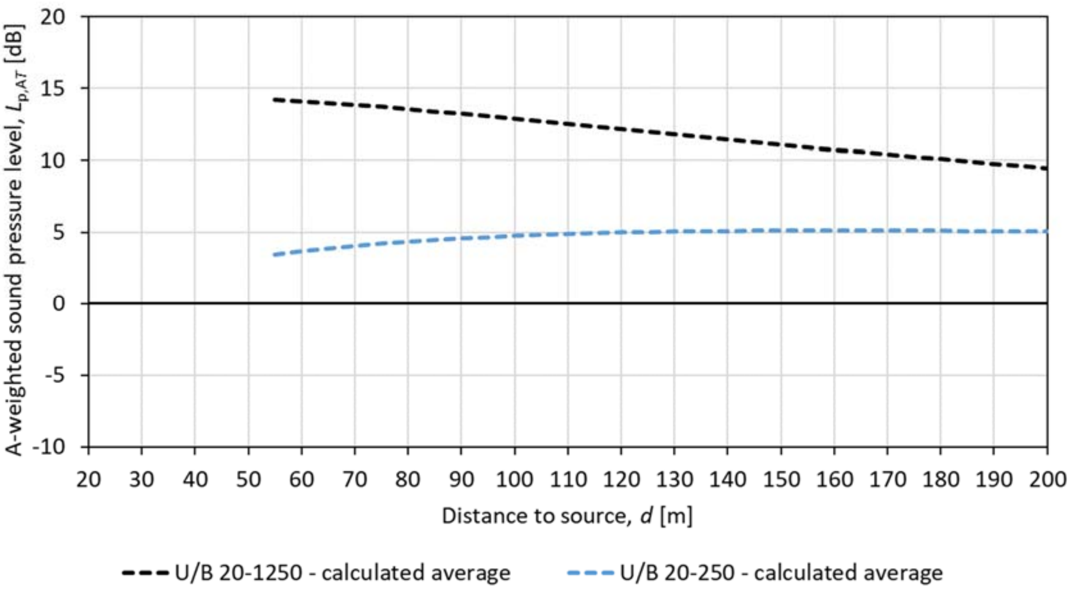

Figure 9: Difference between model estimates and calculated average with data as shown in Figure 8.

4 A few conclusions this far

From the figures in chapter 3 it is obvious that the early phase estimates were too optimistic, especially at short distances between source and receiver. Part of this may be due to non-adequate assumptions about the cutter head speed effects. Another factor is that the measurements from the Follo Line project fitted better with point source propagation combined with a doubled loss factor compared to the value for rock in Table 1. The tunnels were excavated in rock consisting of gneiss with an average P-wave velocity 4500 m/s, i.e. higher than given in Table 1. These new adjustments means that the sound pressure level at short distances is quite higher but descends more rapidly with distance than in the early phase estimates. The adjusted model is also more in line with the Swedish measurements.

Measurements were analysed in 1/3-octave bands from 20 Hz to 1250 Hz, which is a wider range than given in e.g. NS 8177:2010 [5] (20-250 Hz) and ISO 14837:2005 [6] (16-500 Hz). The highest 1/3-octave contributing to overall A-weighted sound pressure level is shown for a number of frequency analysed measurements in Figure 10. For most critical situations, i.e. short distance, buildings with concrete/masonry structure founded directly on rock, 1/3-octave bands up to 1000 Hz should be considered included. For rooms on ground floor in lightweight buildings without basement, founded on soil, a cutoff frequency 250 Hz seems appropriate.

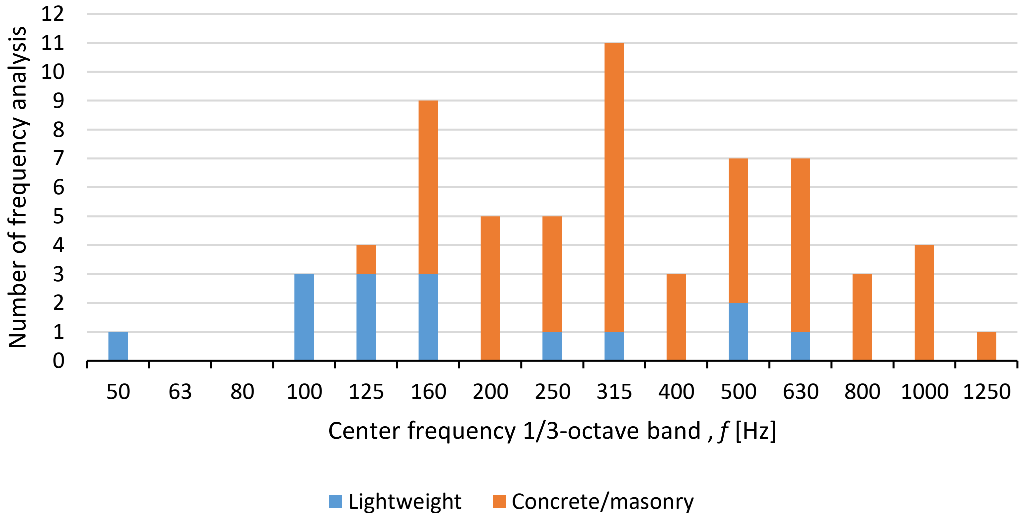

Figure 10: Highest 1/3-octave band contributing to overall A-weighted sound pressure level.

The model estimates are as of now limited to A-weighted levels, and because of issues regarding separation of modules in the source-path-receiver chain and uncertainties related to geological conditions, building foundation and construction, the model is best suited for surveys, not detailed calculations for individual buildings.

References

[1] Ungar and Bender, 'Vibrations produced in building by passage of subway trains; parameter estimation for preliminary design', Sendai, Japan, Aug. 1975, pp. 85–92.

[2] Andreas Eitzenberger, 'Train-induced Vibrations in Tunnels – A Review', Luleå University of Technology, Apr. 2008.

[3] Nitro Consult - Skanska, 'Jämförelse av strukturbundet buller från olika tunnelborrningsmetoder', SBUF projekt 9035, Nov. 1992.

[4] Wilson Ho and Banting Wang, 'Seminar 1: TBM Groundborne Noise Prediction Models'. Jun. 01, 2010.

[5] Standard Norge, 'NS 8177 Akustikk. Måling av lydtrykknivå fra togtrafikk', 2010.

[6] ISO, 'ISO 14837-1 Mechanical vibration. Ground-borne noise and vibration arising from rail systems. Part 1: General guidance.', Jul. 2005.