Revised requirements for stiffness of ballast mats in new Norwegian railway lines

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ABSTRACT: In the Oslo region new railway lines which include many and long tunnels below dwelling areas, now are constructed and planned. All the tunnel tracks are ballasted track. Ballast mats are the preferred remedial actions for reduction of ground borne noise. In the paper the work which lead to revised requirements for ballast mats are presented. Ballast mats having a stiffness of $C_{dyn,3\ Hz} = 0.01\ N/mm^3$ have been installed in the most critical sections of the new tunnels. The required thickness of ballast for this track is 550 mm between sleeper underside and ballast mat surface. In the paper the definition and measurement method for maximum structure borne noise levels are given. The paper also shortly presents the results of a social survey on annoyance from this kind of noise, the calculation methods for structure borne noise transmission, and a method for measuring the vibration transmission from the tunnels before the track is installed.

KEY WORDS: Ballast mat, structure borne noise, tunnel, rock, annoyance.

1 INTRODUCTION

In the Oslo area many rock tunnels for railway and subway lines are situated below dwelling areas. In some cases the highest structure borne noise levels in the dwellings are in the order of $L_{p,max} = 50$ dBA, time constant "fast". In the building regulations for new dwellings in Norway, the limit for structure borne noise from tunnels is $L_{p,max} = 32$ dBA in dwellings. This noise limit is valid for new railway- and suburban lines as well.

A new railway line is now under construction from Oslo to the suburban cities on the southwest side of the town, fig 1. The line passes in tunnels below dwelling areas, and a great number of dwellings would have structure borne noise levels high above the limit if no remedial action is made. In this paper are presented results of studies concerning structure borne noise from railway traffic which have been initiated from the project. The main part of the paper is concerning the studies which have been made on ballast mats in order to reach as high noise reduction as possible. Part 1 of the project from Asker to Sandvika is finished and train traffic will start in the tunnel this summer. The planning of part 2 from Sandvika to Lysaker started this spring. An extensive measurement program have been set up for part 1, and the experiences will be important input for the planning of part 2.

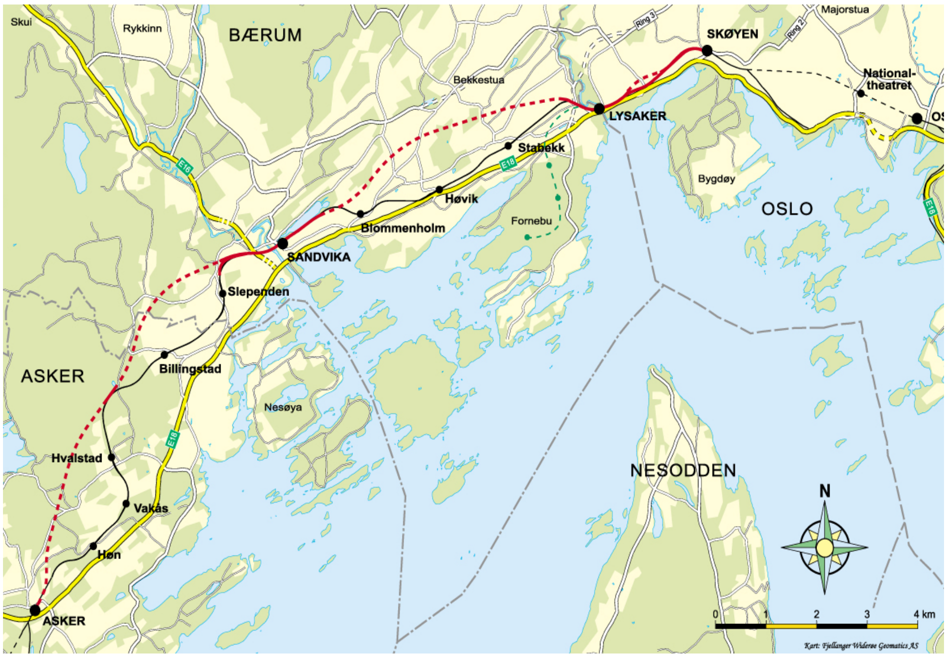


Figure 2: New line Skøyen - Asker. Rocktunnels are dotted red line. Part 1 of the project, from Asker to Sandvika is finished and planning of part 2 to Lysaker is started.

2 DEFINITION OF MAXIMUM STRUCTURE BORNE NOISE LEVEL

The noise limit is stated as the maximum level from the train passages. It was necessary to define this maximum level. In a new Norwegian standard for measurements of vibration in buildings from land based transportation, the maximum level is defined as a statistical maximum value, being the 95 % confidence value. This implies that there is 5 % probability for a randomly selected passing to give a value that is higher than the statistical maximum value. (NS 8176, 1999). In the project this definition also is applied to the maximum structure borne noise level. The statistical maximum structure borne noise level is calculated from :

$$L_{A,str,95} = L_{A,str,mean} + 1.65\ s$$

The maximum values from each train passage is assumed to be normal distributed. $L_{A,str,mean}$ is the mean value of the measured maximum structure borne noise levels, and s is the standard deviation. At least 15 single passings must be measured. For railway traffic at least 20 % of the passages shall be of the train type that gives the highest levels. In most cases, this will be freight trains.

The spectrum of the structure borne noise from train traffic often have a high degree of low frequency content. The sound pressure level then varies very much across the rooms, and a number of microphone positions should be used. In the new ISO 16032 necessary a microphone position in a corner is included, and the "strongest" corner should be found. (ISO 16032, 2004) The inclusion of this corner position will reduce the measurement uncertainty, and improve the correlation to the true room average. If the corner position is not included, there will be a negative bias in the measured mean value for the room.

3 STUDY ON ANNOYANCE FROM STRUCTURE BORNE NOISE IN DWELLINGS ABOVE RAILWAY TUNNELS

In order to see if the noise limit in the regulation is reasonable The Norwegian National Rail Administration (JBV) financed a survey on annoyance. The project was a joint project between Brekke & Strand akustikk as and the Norwegian institute of public health. (Engdahl, 2003).

Buildings exposed to structure borne noise from railway tunnels were identified through a survey by The Norwegian National Rail Administration (JBV) covering the complete railway net of Norway. From this survey, 278 buildings containing 521 dwellings that did not have a direct view to the open track, were selected for a socio-acoustical survey. A questionnaire was sent to one randomly selected person above 18 years of age from each dwelling. The subjects were not informed that the noise levels should been evaluated. The questionnaire consisted of 32 questions including questions on personal information, living and general conditions, general sleep quality, health, and different questions on annoyance to environmental disturbances including noise. In the questions on annoyance there were 5 levels: extremely annoyed, very annoyed, moderately annoyed, a slightly annoyed, not annoyed. 313 persons filled in the sheets. This is 60 %, which is reasonable for a survey of this kind.. The main results are :

- There is a clear relation between the level of structure borne noise and annoyance.
- 25 % of the persons are a little or more than a little annoyed. Only two persons are extremely annoyed.
- At a maximum level of 32 dBA, 20 % were a slightly or more than a slightly annoyed, and 4 % were moderately or more than moderately annoyed. See fig.3. This conclusion support the 32 dBA limit in the regulations.
- Other factors that increase the annoyance are a large number of freight trains pr day and if the sound insulation of the building facades were good.

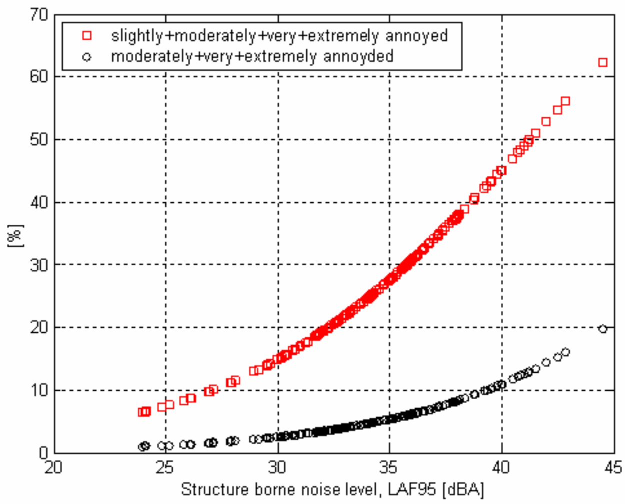


Figure 3: Cumulative distribution of persons annoyed from different levels of structure borne noise in dwellings above railway tunnels.

4 MEASUREMENTS AND CALCULATIONS OF STRUCTURE BORNE NOISE LEVEL FROM ROCK TUNNELS

If the vibration level at the foundation positions of the house is known it is fairly simple to calculate the structure borne noise levels in the building, using well known formulas for sound radiation and if necessary thumb rules or theoretical methods for noise reduction pr floor. The calculations of the vibration transmission in the rock from the rail to the foundation is more complicated to validate. The finite element - or boundary element method may be used. However, idealized material models for the rock may be very wrong. The rock is often cracked and non - homogenous, and the results therefore are uncertain.

We have measured structure borne noise from heavy railway and subway trains in a great number of dwellings above rock tunnels in the Oslo area. The maximum structure borne noise level, $L_{A,str,95}$, have been measured in rooms in which the floor is founded directly on the rock. Fig. 4 shows measured structure borne noise levels.

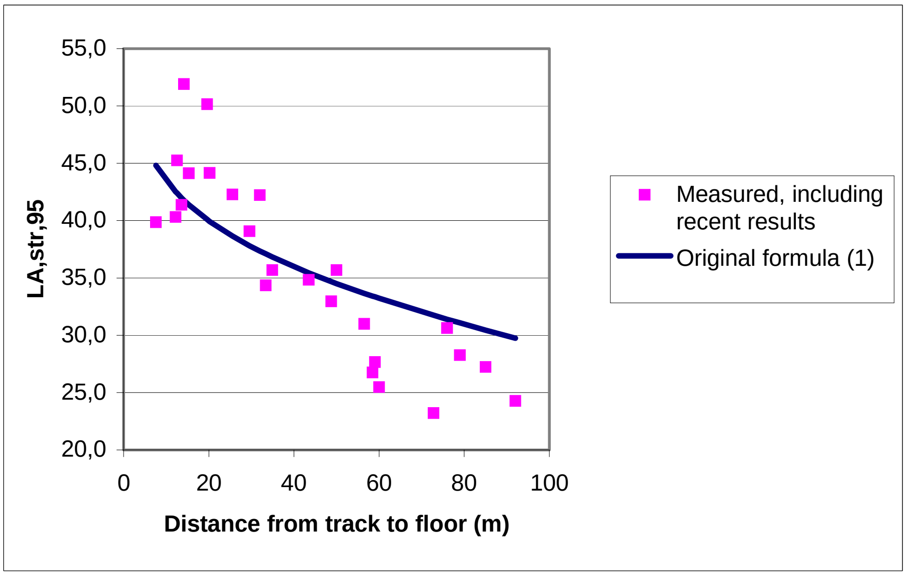


Figure 4: Measured structure borne noise levels in dwellings above rock tunnels.

The vibration attenuation in the rock is partly geometrical spreading, which is proportional to - N log d, and partly material dissipation, proportional to - αd. In our first studies we found that the geometrical term was a line source, -10 log d. An empirical formula was found to be :

$$L_{A,str,95} = 56 - 10 \log d - 0,05\,d \qquad (1)$$

At small distances from the track, wheel flats on freight wagon wheels often gives the highest structure borne noise levels. However a single wheel flat is a point source, having a - 20 log d slope. At greater distances this noise therefore is less dominating. At short distances the formula (1) may underestimate the structure borne noise levels if very pronounced wheel flats occurs.

During the project work considerable more measurements have been made, and it is found that formula (1) underestimates the levels at short distances and overestimates at long distances. A new empirical model now is developed in which the calculations is made in octave bands.

5 MEASUREMENT OF THE VIBRATION TRANSMISSION FROM THE TUNNELS BEFORE THE TRACK IS INSTALLED

The vibration transmission from the tunnels to the surface is the most uncertain factor in the calculation of the structure borne noise level. This mainly because of cracked zones and inhomogeneties in the rock. In order to obtain the best possible precision in the calculated structure borne noise level measurements of vibration transmission from the tunnels to the surface above have been made.

Vibration is generated in the rock in the tunnel and vibration measurements are made on the tunnel walls. On the surface vibration and noise are measured in buildings above. This procedure have been followed in an existing tunnel, and calibration factors have been calculated based on corresponding measurements from train passages in the tunnel.

Different excitation methods were examined. Methods which have been used in projects in Sweden and Denmark have been a big vibrator and a heavy weight which falls from a given height. These methods were time consuming, and we were anxious if acceptable signal to noise ratio could be reached in the dwelling very high above the tunnel. We found that a simpler and more suitable method was to use small explosions in the tunnel wall. (Rothschild, 2002). The maximum permitted amount of explosive was 50 gram. Tests showed that this was sufficient for measurements up to 90 meters above the tunnel. 2 meter deep holes for the explosives were bored in 3 groups of 6 holes in each. The distance between the holes were 1 meter, and the distance between each group were approximately 20-50 meters. The explosives were fired with a couple of minutes between each. In figure 5 is a picture which shows some of the bored holes in the new tunnel.

Figure 5: Position of three bore holes in the new tunnel.

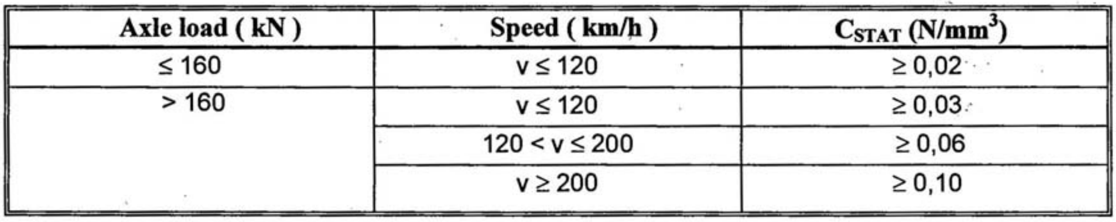
Measurements of vibration transmission have been made in 8 dwelling areas in part 1 of the project. The input to the calculations have been of great value

6 REQUIREMENTS FOR STIFFNESS OF BALLAST MATS

There are three values for stiffness which should be considered for ballast mats :

C_{stat} = Static stiffness. Gives deflection from stopped train.
C_{dyn} = Dynamic stiffness, around 2-5 Hz . Gives deflection from moving train.
C_{acou} =Acoustic stiffness. Is dynamic stiffness around 30-250 Hz. Gives noise reduction.

In the standard specifications from The Norwegian National Rail Administration (JBV)the requirements is given to static stiffness, table I:



Axle load (kN)	Speed (km/h)	C_{STAT} (N/mm^3)
≤ 160	v ≤ 120	≥ 0,02
> 160	v ≤ 120	≥ 0,03
	120 < v ≤ 200	≥ 0,06
	v ≥ 200	≥ 0,10

Table I: Requirements for stiffness of ballast mats in standard spec from JBV

The requirements are identical to the values from Deutche Bahn , DB-TL 918 071, 1979. The tunnels are built for a speed of 200 km/h. The required stiffness for ballast mats therefore are $C_{stat} = 0.06\ N/mm^3$.

7 CALCUATION OF NOISE REDUCTION FROM BALLAST MAT

The noise reduction (called insertion loss) from the ballast mats may be calculated from impedance theory from the formula (Wettschureck, 1997):

$$I = 20\log\left|1 + \frac{\frac{j2\pi f}{s_M}}{\frac{1}{Z_i} + \frac{1}{Z_a}}\right|$$

Z_i = Input impedance from the top side of the ballast mat towards the source.
Z_a = Terminating impedance from the bottom of the mat.

$$\frac{1}{Z_i} = \frac{j2\pi f}{s_s}\left(1 - \left(\frac{f_o}{f}\right)^2\right)$$

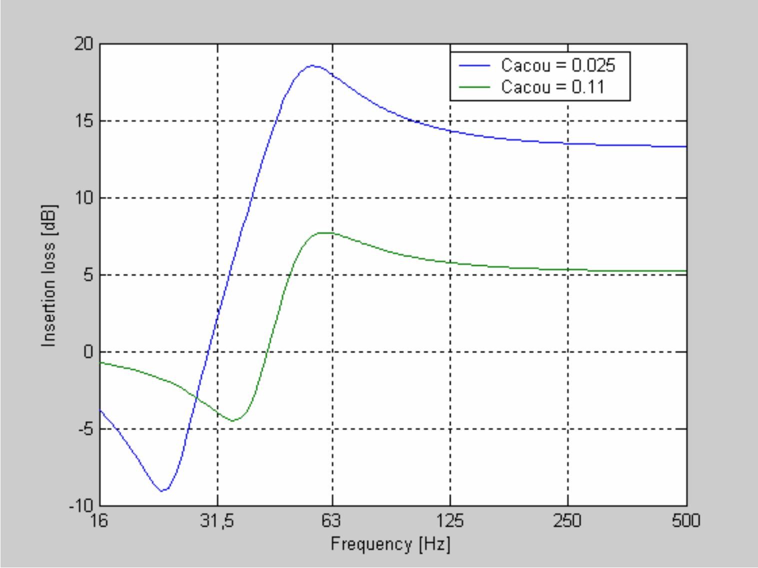
s_M, s_s and s_p is the acoustic stiffness of the ballast mat, the ballast and the gravel respectively. f_o is the resonance frequency for the unsprung bogie mass on the track without the ballast mat.

In the work from Wetschureck the sub grade was considered to be an elastic half space, which may be valid when the track is installed on ground in open lines. In rock tunnels the terminating impedance is a layer of gravel between the ballast mat and the rock surface. The terminating impedance becomes :

$$\frac{1}{Z_a} = \frac{j2\pi f}{s_p}(1 - jd_p)$$

The stiffness of the ground, s_p, is the E modulus of the gravel divided by the thickness, and d_p is the loss factor of the gravel.

In fig.7 is shown calculated noise reduction for the stiff ballast mat, $C_{stat} = 0.06$ N/mm^3 and a soft ballast mat having $C_{stat} = 0.01$ N/mm^3. The acoustic stiffness for these mats are around $C_{acou} = 0.11$ N/mm^3 and $C_{acou} = 0.025$ N/mm^3 respectively.



Figur 7. Calculated noise reduction for ballast mats having stiffness according to the old ($C_{acou} = 0.11$) and the new requirements ($C_{acou} = 0.025$).

It can be seen that the stiff mat only gives around 5-6 dB noise reduction. This is not acceptable for long parts of the tunnels. Another solution then would be required. The soft ballast mat gives 13-15 dB noise reduction which is satisfactory for most parts of the tunnels.

It was found necessary to collect experiences on soft ballast mats to see if softer mats could be used in the new tunnels.

For the most critical section of the tunnel calculations and measurements showed that ballast mats alone would not be sufficient, even if the softest ballast mats was used. In this section more rock was taken out of the tunnel, so that the tunnel floor was reduced by approximately 2 meters. Then full scale measurements were made in the tunnel by testing different kinds of masses and remedial actions, in order to find the best solution for these 2 meters. A fully loaded freight wagon for which one of the axles were connected to a big vibration exciter was used in the tests. The conclusion was that backfill of rock gave the best results, the additional insertion loss was measured to 4-6 dB. Two papers from the test have been submitted in this conference. (R.Cleave et al. 2005)

8 EXPERIENCES FROM BALLAST MATS SOFTER THAN THE REQUIREMENTS

On the airport line from Oslo City to Oslo Airport Gardermoen soft ballast mats have been installed in a long tunnel. Before the installation test was made with these soft ballast mats on a 325 m long track in a line for heavy rail traffic up to 160 km/h. The ballast mats was from Rockdelta, static stiffness is less than $C_{stat} = 0.01$ N/mm^3. The airport line opened in 1998, and the test track was established in 1995. We therefore have relatively long experience with soft ballast mats. The possible railway constraints from soft track is shown in table II :

Safety	Passenger comfort	Maintenance
Derailment of train Lateral stability of track	Non-compensated transverse acceleration in curves Dynamic car-body acceleration	Ballast crushing Rail corrugation Rail fatigue

Tabell II. Possible railway constraints from soft track.

The lines have been in service for many years, and measurement trolleys have passed the ballast mat sections many times. The conclusions is that it is not possible to detect the soft ballast mat sections on the recordings. This is also confirmed from the train drivers. The movements of the track because of the soft ballast mats is far away from values were derailment and instability of the track may occur. The arguments concerning passenger comfort and safety have been found not to be any problem.

Concerning the maintenance arguments no increased ballast crushing have been found until now. In the airport line some corrugations have been found in the tunnels. However there is no correlation with the positions of the ballast mats, which means that the soft ballast mat do not give increased corrugations in this tunnel.

The most relevant argument against soft ballast mats seems to be the fatigue and life time of the rail which is correlated to the rail deflection. On the test track extensive measurements of rail deflections have been made. The measurement system was a laser on the tunnel wall and a reflector on the sleeper or the rail. In fig.8 is shown the distribution of deflections of the sleeper during 24 hours.

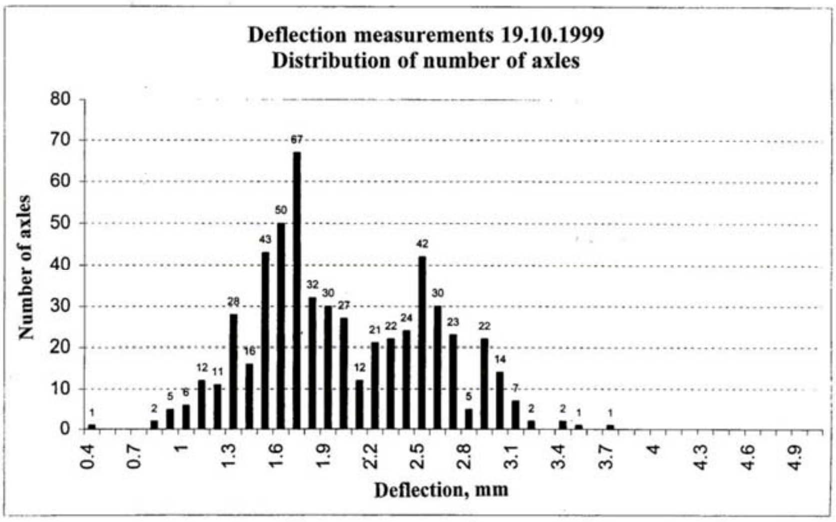


Figure 8. Measured deflection values of sleeper in 24 hours.

Measurements have been made may times in the period 1995 – 2000. The maximum deflection is defined as the 95 % confidence value. In fig 9 the measured maximum sleeper deflections in the period is shown.

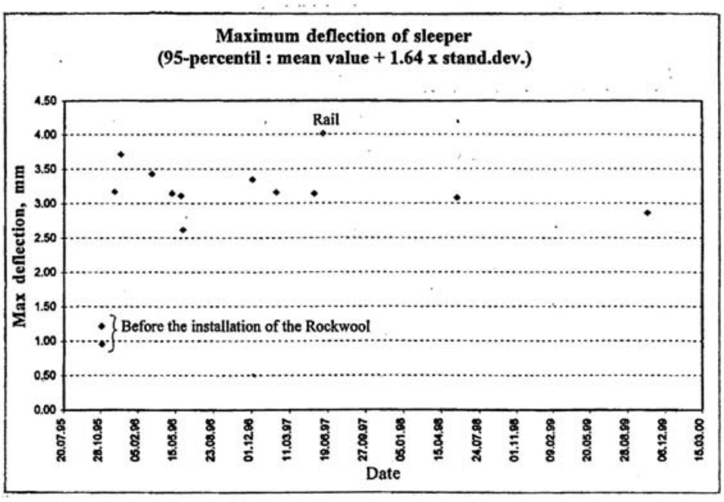


Fig 9. Maximum deflections of sleeper measured in the period 1995 – 2000.

The rail deflection is the sum of the contribution from the railpad, the ballast, the ballast mat, and the gravel between the ballast mat and the rock. The rail deflection have been calculated from traditional Zimmermann method. The resulting stiffness of the ground, k_{eff} is :

$$\frac{1}{k_{eff}} = \frac{1}{k_{pad}} + \frac{1}{k_{ballast}} + \frac{1}{k_{ballastmat}} + \frac{1}{k_{gravel}}$$

In fig 10 is shown calculated deflection for the test track..

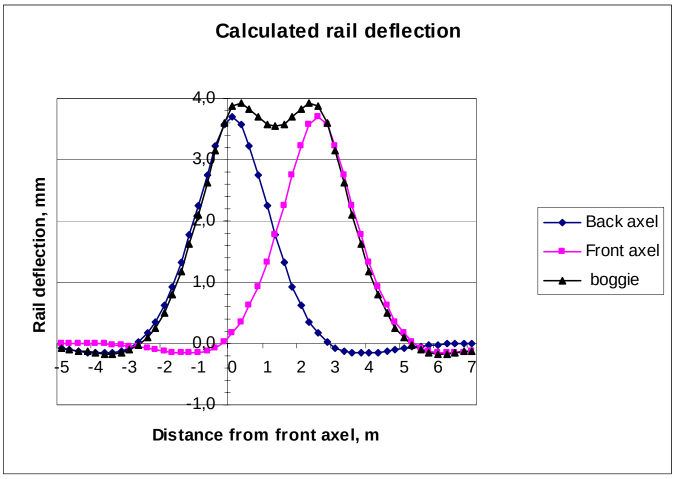


Figure 10. Calculated rail deflection in the tunnel having soft ballast mat. 225 kN axle load

The calculated deflections are about the same as was measured in the tunnel. It can be stated that the maximum rail deflections were around 4 mm, and the mean value around 2.5 mm. When looking at traditional fatigue limits for steel and the number of passages 4 mm is well within the limit for fatigue, and further, for fatigue calculations mean values are more relevant. Fatigue of the rail should therefore not be a strong argument against soft ballast mats in Norwegian lines. In the Norwegian railway lines there is not a tradition for refitting of rails when certain limits for passing tonnage is reached. In such cases with very strong and heavy traffic, the theoretical rail life time may be reduced for tracks having soft ballast mats.

9 REVISED REQUIREMENTS FOR BALLAST MATS

From the experiences and considerations of the tracks having soft ballast mats the Norwegian National Rail Administration have decided to allow ballast mats having $C_{dyn} = 0.01$ N/mm^3 in the sections for which high noise reduction is required. However there is a requirement that there shall be a 550 mm layer of ballast between the sleeper under side and the ballast mat surface. The maximum calculated rail deflection becomes 3.2 mm for this case. For some products the stiffness is considerable lower in the track than is measured in laboratory when there is a flat steel plate above the mats. This should be corrected for. The most correct method in lab. should be to use a steel plate which simulates the ballast surface, in German called “Schotterplatte”.

Two classes of ballast mats have been installed in the tunnels, dependant on the need for noise reduction. The classes are :

Class 1 : $C_{dyn,3Hz} = 0.01$ N/mm^3
Class 2 : $C_{dyn,3Hz} = 0.02$ N/mm^3

Data for $C_{dyn,3Hz}$ in according to DB-BN 918 071-1 was required from the suppliers. In addition data for acoustic stiffness in octave bands from 31.5 to 250 Hz measured according to ISO 10846-2 was required. (ISO 10846-2, 1997). Preload should be 0.03 N/mm^2.
5 suppliers of ballast mats were invited to give offer for the project. Emphasise was given to the relevance of data, to the documented acoustic stiffness, and to the price. A framework agreement was written with two suppliers.

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