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A Comparison of Two Engineering Models for Outdoor Sound Propagation: Harmonoise and Nord2000

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Summary
Two established engineering models for predicting environmental noise levels, the European “Harmonoise” and the Scandinavian “Nord2000”, have been compared for a number of test cases involving a variety of source and receiver configurations, terrain profiles, noise barriers, properties of the ground, and meteorological conditions. The predictions are compared with reference data from the literature, and with new experimental results. In most cases the models agree very well, but in some cases the predictions deviate significantly from each other. There are many similarities between the approximations used in the two models, but some parts of the modelling methods are clearly different. The most significant differences between the two modelling methods are pointed out, and it is attempted to explain the observed differences between the predictions.

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1. Introduction

Harmonoise and Nord2000 are two very similar engineering models for predicting environmental noise levels. Both models predict the sound pressure level at the receiver position in one-third octave bands from 25 Hz to 10 kHz from the sound power level of the source. The effects of various factors that influence the sound propagation are then calculated separately (in decibels) and subtracted from the sound power level. These factors are: i) spherical divergence, ii) air absorption, iii) reflections from the ground and diffraction from barriers, iv) energy losses during side reflections, and v) effects of scattering zones. Whereas the factors are the same in the two models, the approaches used to evaluate them can differ. The effects of spherical divergence, air absorption and energy losses during reflections are handled in the same way by the two models. On the other hand the methods used to estimate the effects of ground reflections, diffraction from barriers, and scattering zones are not the same in the two models. Both models also take account of the effects of meteorological conditions such as the vertical temperature and wind profiles and atmospheric instability, but the approaches used to simulate refraction and turbulence are very different.

The purpose of this paper is to compare the two models and, when possible, explain why they give different predictions for some configurations.

2. Differences between Harmonoise and Nord2000

The methods used to estimate the effects of ground reflections are similar. Both models calculate the effects from flat ground, valley shaped terrain, and hills and barriers separately. The results are then combined so as to obtain the total ground effect by the use of transitional parameters that represent the effect of each segment on the total ground effect. These transitional parameters are not estimated in the same way. Harmonoise calculates its parameter using a simple equation based on the sum of the Fresnel weights of the N different ground segments [1]. The corresponding parameters in Nord2000 are calculated on the basis of a number of cases that depend on frequency, positions of source and receiver, terrain configuration, dimensions of screens, and Fresnel weights of sections [2]. Both models calculate surface impedances from specified flow resistivity values using the Delaney and Bazley expressions [3].

The effects of hills and barriers are handled differently by the two models. The insertion loss caused by a screening object is calculated by Harmonoise from the Fresnel number N_f,

$$N_f = \operatorname{sgn}(h_{\text{eff}}) \frac{2(R_S + R_R - R)}{\lambda}, \tag{1}$$

where h_{eff} is the effective height of the barrier, R_S and R_R are the path lengths between the source and the top of the barrier, and the top of the barrier and the receiver, respectively, R is the direct path length in the absence of

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the screen, and λ is the wavelength. The attenuation due to diffraction is then determined from

$$A_{\text{diff}} = \begin{cases} 0 & \text{for } N_f \leq -0.25 \\ 6 - 12\sqrt{-N_f} & \text{for } -0.25 \leq N_f < 0 \\ 6 + 12\sqrt{N_f} & \text{for } 0 \leq N_f < 0.25 \\ 8 + 8\sqrt{N_f} & \text{for } 0.25 \leq N_f < 1 \\ 16 + 10\log(N_f) & \text{for } N_f \geq 1 \end{cases} \tag{2}$$

The method used to calculate the effect of multiple barriers is quite simple. The dominating diffracting edge, i.e., the edge for which N_f has the maximum value in the absence of all other diffracting edges, is found. The insertion loss A_{diff} is calculated for this edge using the source and receiver positions. Next the insertion loss is determined for the second edge using the first one as the equivalent source or receiver position, depending on the position of the second barrier relative to the first one, and the calculated insertion losses are summed up. This is repeated until all diffracting edges have been accounted for.

Nord2000 handles hills and screens in a slightly different way. To begin with it should be mentioned that whereas Harmonoise in principle has no restriction on the number of diffracting edges in Nord2000 the number of such edges is limited to the following three cases: i) one screen with one edge, ii) one screen with two edges, and iii) two screens each having one edge. If more than two screens appear along the propagation path only the two most significant screens are included in the calculation, and the remaining screens are regarded as reflecting surfaces. Diffraction effects are based on the wedge diffraction solution by Hadden and Pierce [4] and modified to include an absorbing wedge by assuming that it has a finite impedance; see Figure 1. A diffraction coefficient D is calculated for the wedge,

$$D = p_{\text{diff}} \frac{l}{\mathrm{e}^{\mathrm{j}kl}}, \tag{3}$$

where $l = R_S + R_R$, and R_S and R_R are the distances from the top of the wedge to the source and receiver, respectively, k is the wavenumber, and p_{diff} is the diffracted sound pressure at the receiver, which is a function of the reflection coefficient of the wedge sides, the angle of the wedge, and the total path length, calculated as described in reference [4].

In the two multiple-diffraction cases mentioned above the diffraction effect is calculated as proposed by Salomons [5]. The diffraction coefficients for the two edges, D_1 and D_2, are found in almost the same manner as before, but using the other edge as the effective source or receiver, depending on its relative position. One modification of the original method has been made in the case where there is one screen with two edges: the reflection coefficient of the segment between the two diffracting edges is equated with unity instead of its "real" value. This has been done to prevent cancellation of the diffracted rays at high frequencies when the top surface has as a finite impedance, in which case the reflection factor Q approaches -1. This is an *ad hoc* solution that may be subject to change [2], though.

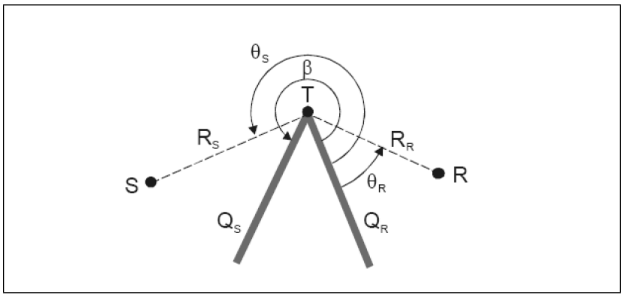

Figure 1. Diffraction effect of a wedge-shaped screen with a finite surface impedance.

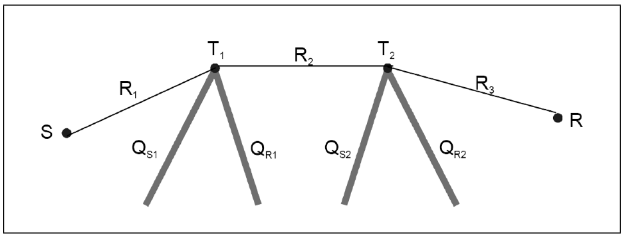

Figure 2. Diffraction from two wedge-shaped screens.

The diffracted sound pressure at the receiver, p, is calculated by expressing the combined effect of the two diffracting edges,

$$p = 0.5 D_1 D_2 \frac{\mathrm{e}^{\mathrm{j}kl}}{l}, \tag{4}$$

$$p = D_1 D_2 \frac{\mathrm{e}^{\mathrm{j}kl}}{l}, \tag{5}$$

using equation (4) for one screen with two edges and equation (5) for two screens each with one edge, where $l = R_1 + R_2 + R_3$ and R_1, R_2 and R_3 are defined in Figure 2.

Both models handle diffracted reflections from ground segments around the screens and from the screen sides in case of wedge-shaped screens in the same way; i.e., they calculate these effects using the method described in reference [4].

The way of dealing with scattering zones (e.g., zones with trees) is quite different; see references [6] and [2]. The theory for such effects is, however, not yet well established, and scattering zones are therefore not dealt with in this paper.

To take account of incoherence and frequency averaging effects both models define a coherence factor that describes the effects of frequency band averaging and turbulence. In Nord2000 effects from fluctuating refraction, surface roughness, and scattering zones are also taken into account.

Both Harmonoise and Nord2000 approximate the vertical sound speed profile by the same lin-log relationship,

$$c(z) = c_0 + Az + B\ln\left(\frac{z}{z_0} + 1\right), \tag{6}$$

where z is height above the ground and z_0 is the "roughness length". However, the effect of atmospheric refraction is handled in fundamentally different ways by the two models. Whereas Nord2000 replaces the straight rays in the model for a homogeneous atmosphere by curved rays, thereby simulating the actual phenomenon of refraction, Harmonoise uses straight rays and curves the ground instead to simulate the same effect. Moreover, the curvature is calculated differently. Harmonoise determines the radius of curvature from the maximum height of the curve [1], whereas Nord2000 uses a more complicated method of calculating the length of the curve and its angle relative to the ground [7]. The method used by Nord2000 is probably more correct from a theoretical point of view, but the Harmonoise method is much simpler since all calculations are performed using straight rays.

3. Results

More than one hundred test cases involving a variety of source and receiver configurations, terrain profiles, noise barriers, properties of the ground, and meteorological conditions have been tested [8]. Most of the test cases used here have been used for validation of the Nord2000 model [9], and the reference values used for comparison are also taken from this source.

A few test cases were designed specifically for this project. The reference data used in these cases are from measurements conducted with a 1:25 scale model. One of these cases is presented here, case 11.

In what follows a number of cases have been selected to illustrate similarities and differences between the two models. Apart from the new scale model results the data used for comparison are taken from reference [9], but the original sources are references [10] (calculations made with the Crank-Nicholson parabolic equation method, cases 1, 2, 4, 5, 6 and 7), [11] (measurements, case 3), and [12] (calculations made with the boundary element method, cases 8, 9 and 10). In all cases the temperature at the ground is 15°C, the wind speed (if any) is specified at a height of 10 m, and the roughness length is 0.1 m. Acoustically hard surfaces are modelled as having a flow resistivity of 10^9 Ns/m^4. All results are presented relative to free field and without the effect of atmospheric absorption, which is the same in the two models.

Figure 3 shows the results from test case 1, a simple example of sound propagation over flat and hard ground with no refraction and no turbulence. The results show that Harmonoise and Nord2000 agree very well with each other and with the reference data.

Similarly the agreement is also very good between the two predictions and the reference data in Figure 4, which shows results from test case 2. This is another simple example of sound propagation over flat ground with no refraction and no turbulence. In this case the ground surface is soft and uncompacted (as, e.g., a forest floor or a pasture field), and the propagation distance is 200 m.

Many similar cases without refraction, involving a variety of terrain surfaces and source and receiver configurations, have been examined. In all such cases the two models seem to predict sound propagation quite well. This implies that both models are accurate for simple cases without refraction, involving soft ground at short, medium and long propagation distances.

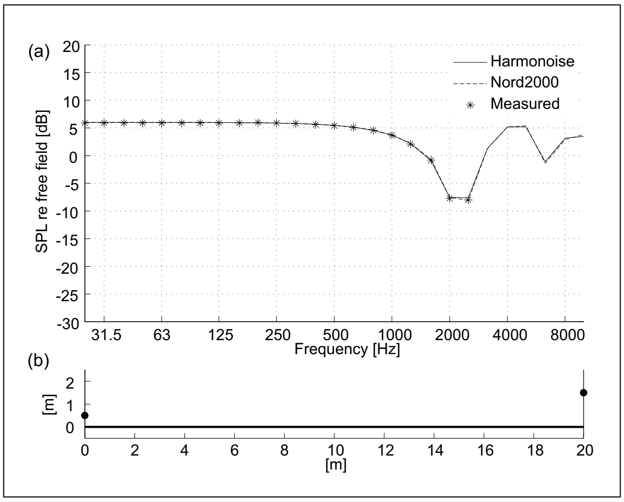

Figure 3. (a) Predicted results compared with reference data for test case 1: Sound propagation over 20 m of flat, acoustically hard ground with no refraction and no turbulence. Source height: 0.5 m; receiver height: 1.5 m. (b) Terrain profile.

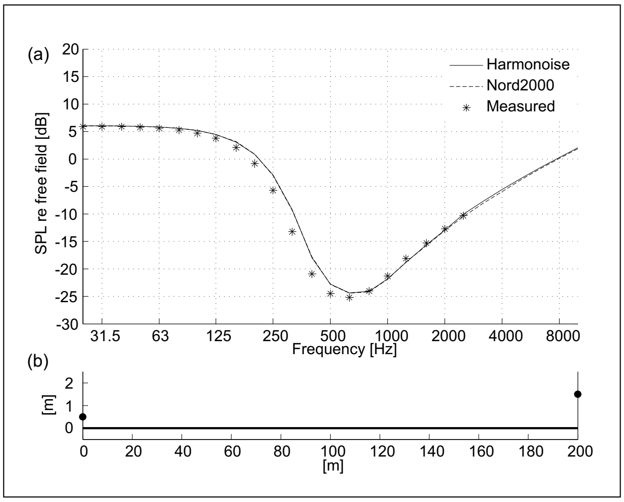

Figure 4. (a) Predicted results compared with reference data for test case 2: Sound propagation over 200 m of flat, acoustically soft ground with no refraction and no turbulence. Source height: 0.5 m; receiver height: 1.5 m; flow resistivity: 250 kNs/m^4. (b) Terrain profile.

Figure 5 shows the results from test case 3. This case involves a rigid barrier (e.g., a concrete wall) on a soft, uncompacted ground (e.g., a pasture field) without any effects of refraction but some turbulence. The source and receiver are close to the ground and fairly close to each other, and no direct sound can reach the receiver. Since there is no refraction all sound reaching the receiver will have been diffracted of the top of the barrier or scattered by turbulence. Harmonoise and Nord2000 agree very well in most of the frequency range. Below 100 Hz the Nord2000 prediction levels out at 6 dB as expected, whereas Harmonoise predicts a level of up to 10 dB relative to free

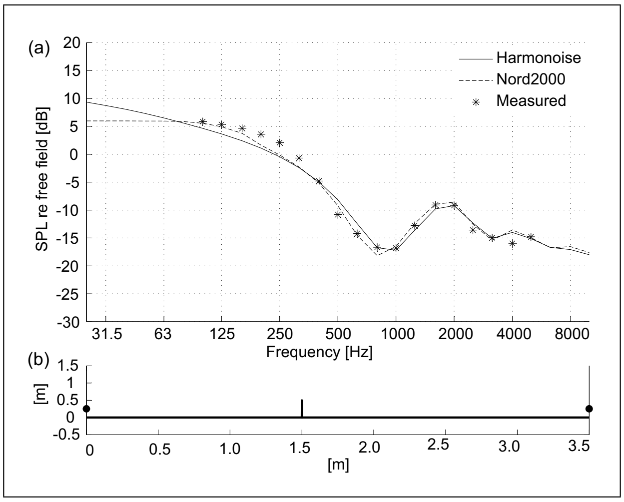

Figure 5. (a) Predicted results compared with reference data for test case 3: Sound propagation over 3.5 m of flat, acoustically soft ground with no refraction but some turbulence, and a thin, rigid barrier, blocking direct sound. Source height: 0.25 m; receiver height: 0.25 m; barrier height: 0.5 m; flow resistivity of the ground: 200 kNs/m^4; wind turbulence strength: 0.12 m$^{4/3}$/s^2; temperature turbulence strength: 0.008 K/s^2. (b) Terrain profile.

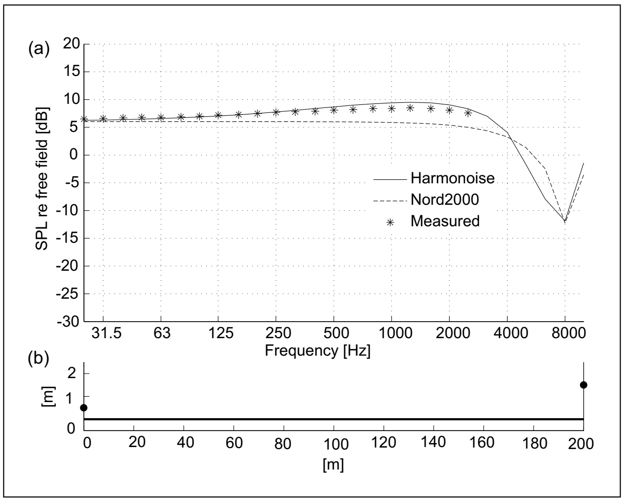

Figure 6. (a) Predicted results compared with reference data for test case 4: Sound propagation over 200 m of flat, acoustically hard ground with downwards refraction caused by a temperature gradient and no turbulence. Source height: 0.5 m; receiver height: 1.5 m; temperature gradient: 0.0846 K/m. (b) Terrain profile.

field below 63 Hz, even though the sound pressure level should clearly not exceed 6 dB relative to free field at any frequency. This is probably the result of approximating the total excess attenuation due to a diffracting obstacle by the sum of the insertion loss due to diffraction and the ground effect on either side of the obstacle [1].

A number of similar cases have been found to give similar results irrespective of the type of diffracting barrier separating the source and receiver.

Test cases 4 and 5 concern propagation over very hard and dense ground with refraction but no turbulence, see Figures 6 and 7. In case 4 there is a positive vertical temperature gradient resulting in downward refraction, and in case 5 there is a rather strong wind against the direction of propagation resulting in upwards refraction.

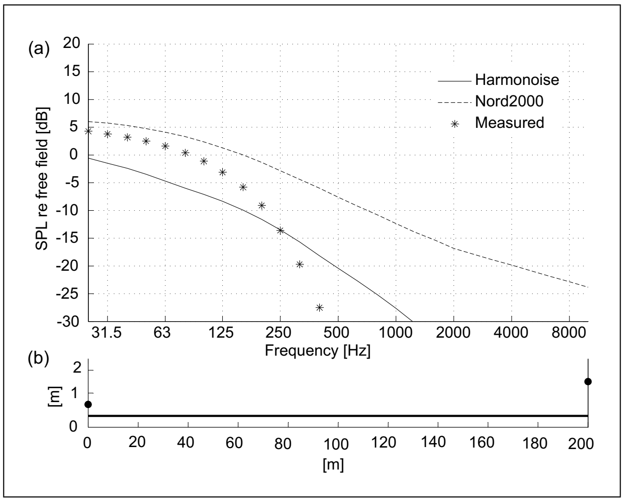

Figure 7. (a) Predicted results compared with reference data for test case 5: Sound propagation over 200 m of flat, acoustically hard ground with upward refraction caused by wind and no turbulence. Source height: 0.5 m; receiver height: 1.5 m; wind speed: −4.615 m/s. (b) Terrain profile.

Apparently, Nord2000 does not take account of the increase in sound pressure level resulting from multiple reflections caused by downward refraction over a hard surface in a proper way, presumably because of the complicated way refraction is handled by the model. On the other hand, Harmonoise bends the ground and therefore handles case 4 as if it were a valley with no refraction. This means that there is a focusing effect at the receiver, even though rays are not allowed to reflect from one ground segment to another by the Harmonoise model [1]. The difference between the two models can be seen in the results; the predictions made with Harmonoise are in relatively good agreement with the reference data, whereas the Nord2000 prediction never exceeds 6 dB relative to free field.

In case 5 the direction of the wind is against the direction of propagation resulting in upward refraction. For this case with upward refraction both models predict sound pressure levels that decrease rapidly with the frequency, but the results deviate significantly, both from each other and from the reference data. Results from a number of similar test cases suggest that neither model can predict the effects of strong upward refraction at medium and long distances with acceptable accuracy.

Figures 8 and 9 show results from test cases 6 and 7, respectively. These cases are analogous to cases 4 and 5, but here the ground is soft and uncompacted. It can be seen that the predictions are in much better agreement than before. The differences between the predictions in the presence of refraction thus seem to be reduced when the ground is soft compared to predictions where the ground is hard. This has also been observed in a number of other cases where the ground is soft. The explanation is that when the ground is softer the attenuation of the reflec-

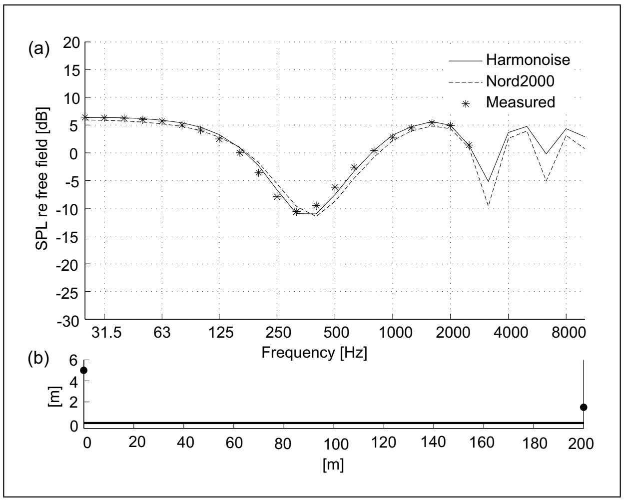

Figure 8. (a) Predicted results compared with reference data for test case 6: Sound propagation over 200 m of flat, acoustically soft ground with downward refraction caused by a temperature gradient, and no turbulence. Source height: 5 m; receiver height: 1.5 m; flow resistivity: 250 kNs/m^4; temperature gradient: 0.0846 K/m. (b) Terrain profile.

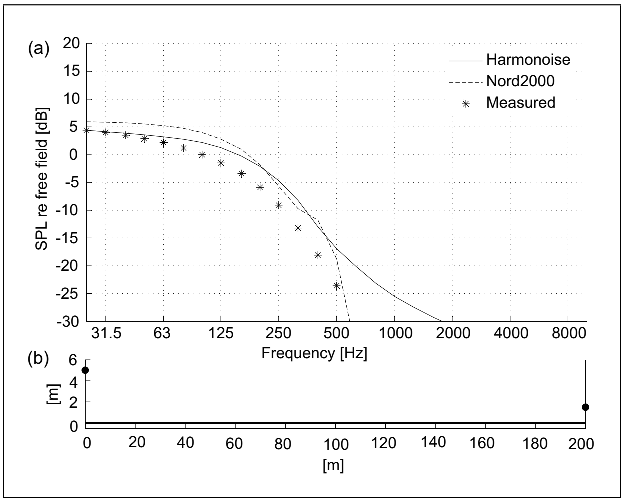

Figure 9. (a) Predicted results compared with reference data for test case 7: Sound propagation over 200 m of flat, acoustically soft ground with upward refraction caused by wind, and no turbulence. Source height: 5 m; receiver height: 1.5 m; flow resistivity: 250 kNs/m^4; wind speed: -4.615 m/s. (b) Terrain profile.

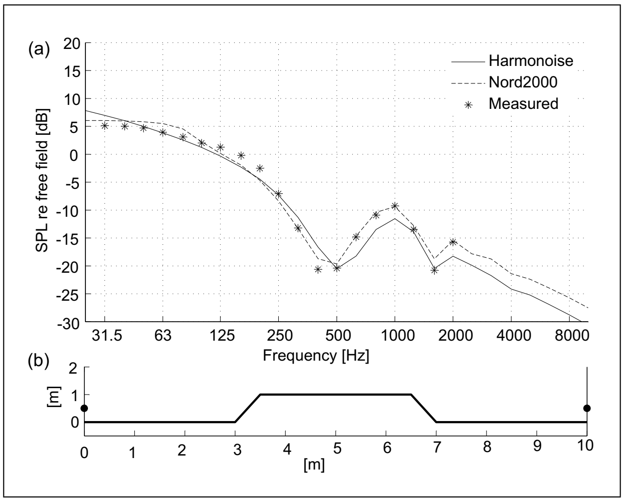

Figure 10. (a) Predicted results compared with reference data for test case 8: Sound propagation over 10 m of flat, acoustically soft ground with no refraction and no turbulence, and a 4 m wide, 1 m high hill with two diffracting edges and a 3 m wide acoustically hard top surface, blocking direct sound. Source height: 0.5 m; receiver height: 0.5 m; flow resistivity of the ground and sides of the hill: 200 kNs/m^4. (b) Terrain profile.

tions reduces the overall importance of the reflections, and therefore the effect of refraction become less pronounced. It should also be noted that for refraction over short distances the accuracy of the predictions is comparable to that seen in very simple cases without refraction. This, of course, is due to the fact that as the propagation distance is reduced, the effects of refraction are reduced; hence at very short distances there is little or no effect of refraction.

Figures 10 and 11 show the results of two simple examples of sound propagation over flat ground with no refraction and no turbulence, test cases 8 and 9 respectively. In both cases the source and receiver are 10 m apart and close to the ground. Both cases include a double edged hill, blocking direct sound. The only difference between these two cases is the top segment of the hill, which is acoustically hard in case 8 and acoustically soft in case 9.

The predictions agree reasonably well with each other and the reference data in most of the frequency range in case 8. Some deviations between the two predictions can be seen at high frequencies, but the difference between the results is moderate and seems to be fairly constant with frequency. In case 9, however, the models agree reasonably well up to 1 kHz above which they deviate significantly. The difference between the results seems to increase with increasing frequency.

The results shown in Figure 12 are from test case 10, which is very similar. In this case all surfaces are soft but the hill is wedge-shaped, i.e., there is no top segment. In this case Harmonoise and Nord2000 give almost the same result in the entire frequency range. This shows that the difference between the predictions stems from how the models handle the top segment of the hill.

A number of similar cases have revealed that the deviations become more prominent as the ground segment on the top of the hill becomes softer. Nord2000's behaviour is a direct result of a modification made to the way diffractions of a double edged barrier are handled by the model, as mentioned earlier. No similar modification has been made to Harmonoise. Because of the limited frequency range of the reference data presented here, very little can be said about whether one model is more accurate than the other. Therefore some measurements were carried out to compensate for this lack of data. Results from one such a case can be seen in Figure 13.

Case 11 is similar to case 9. The results, presented in Figure 13, look similar to those shown in Figure 11, i.e., there is a significant difference between the two predic-

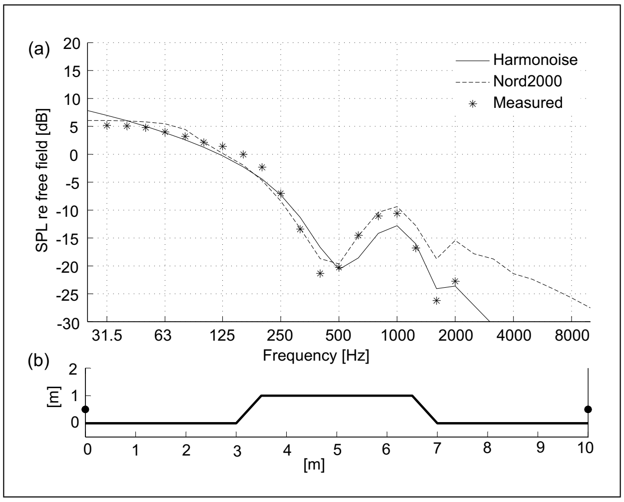

Figure 11. (a) Predicted results compared with reference data for test case 9: Sound propagation over 10 m of flat, acoustically soft ground with no refraction and no turbulence, and a 4 m wide, 1 m high hill with two diffracting edges and a 3 m wide acoustically soft top surface, blocking direct sound. Source height: 0.5 m; receiver height: 0.5 m; flow resistivity of all surfaces: 200 kNs/m^4. (b) Terrain profile.

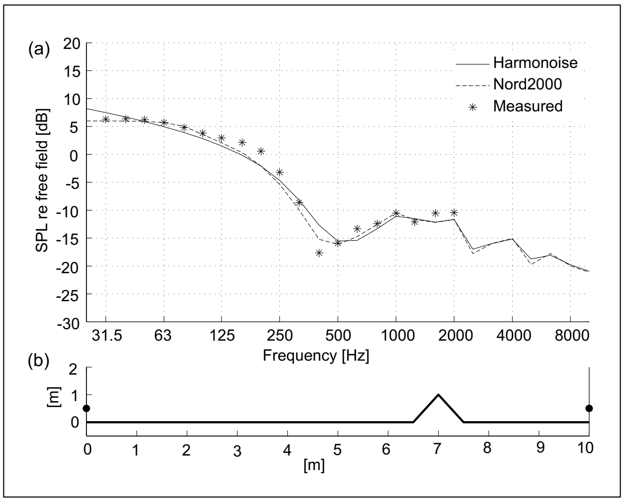

Figure 12. (a) Predicted results compared with reference data for test case 10: Sound propagation over 10 m of flat, acoustically soft ground with no refraction and no turbulence, and a 1 m high, 1 m wide wedge-shaped hill with one diffracting edge, blocking direct sound. Source height: 0.5 m; receiver height: 0.5 m; flow resistivity of all surfaces: 200 kNs/m^4. (b) Terrain profile.

tions. The experimental results clearly agree better with the Harmonoise prediction than with the Nord2000 prediction.

Other similar cases confirm that the Harmonoise model is better than the Nord2000 model at predicting sound propagation at high frequencies over a barrier with two edges and an acoustically soft top segment. It is difficult to estimate the uncertainty of the results from the scale model experiments, but there is nothing that indicates that it should exceed 3 dB. It seems, therefore, that the amendments made to Nord2000 should have to be much more moderate.

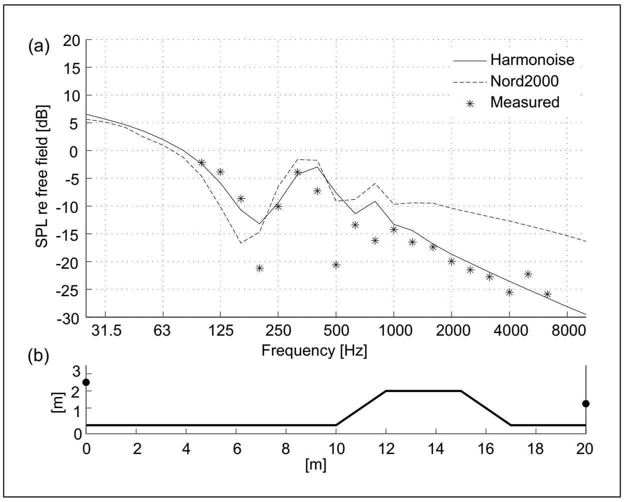

Figure 13. (a) Predicted results compared with reference data for test case 11: Sound propagation over 20 m of flat, acoustically hard ground with no refraction and no turbulence, and a 7 m wide, 2 m high hill with two diffracting edges and a 3 m wide acoustically soft top surface, blocking direct sound. Source height: 2.5 m; receiver height: 1.25 m; flow resistivity of top of hill: 63 kNs/m^4. (b) Terrain profile.

4. A-weighted sound pressure levels

In addition to the graphical results presented in the previous section, A-weighted sound pressure levels have been calculated. In these calculations the source is assumed to emit pink noise. This is a reasonable assumption that simplifies the calculations considerably. The A-weighted levels are calculated from the predicted one-third octave band values relative to free field, but only for the one-third octave bands where there are reference data.

The A-weighted levels for all the cases that have been simulated are presented in Table I, in which cases 1 to 11 are numbered as 1005, 1011, 28, 1016, 1018, 1022, 1024, 113, 117, 121, and 2021, respectively.

The A-weighted values calculated from the predictions are in general fairly close to the reference A-weighted values. This can be seen in Table II, where the percentage of A-weighted predictions that are within 1 dB and 3 dB of the corresponding reference values are shown. It can be seen that the predictions from both models are within 1 dB of the reference values in just over half of the cases. The predictions are within 3 dB of the reference values in most cases. It is therefore reasonable to conclude that both models can predict A-weighted sound pressure levels within 3 dB for a wide variety of cases.

Finally, Table III shows the average differences between the A-weighted values calculated from the predictions and the references. The average differences between either model and the reference values or the models themselves are rather low, but the standard deviations are fairly high. This confirms what can be observed in Table I, that is, the

Table I. A-weighted values calculated for simulation results from both Harmonoise and Nord2000 as well as reference data for all test cases.

Case	Harm.	Nord.	reference	Case	Harm.	Nord.	reference	Case	Harm.	Nord.	reference
1	0,3	2,0	2,2	81	-34,2	-29,7	-26,8	1031	-16,0	-16,0	-17,9
2	-9,1	-13,2	-11,8	82	-19,0	-17,8	-18,6	1032	-16,0	-15,7	-16,6
11	-1,0	-1,0	-1,3	83	-13,6	-13,9	-12,6	1033	-6,8	-7,2	-9,4
12	-1,1	-0,9	-0,7	84	-1,3	-6,9	-7,9	1034	-32,4	-21,3	-25,0
13	-1,2	-1,1	-1,0	91	-13,3	-13,2	-13,0	1041	-9,7	-10,0	-10,0
14	-1,6	-1,5	-1,2	92	-10,4	-10,4	-8,9	1042	-5,9	-7,1	-6,3
15	-7,8	-7,9	-7,1	93	-8,0	-4,7	-3,7	1043	-2,1	-4,4	-6,7
16	-11,2	-10,8	-9,3	111	-15,2	-12,6	-13,9	1044	-22,6	-19,4	-23,3
17	-8,8	-8,8	-8,9	112	-15,7	-13,3	-14,3	1045	1,8	1,9	2,0
18	-10,9	-10,7	-9,5	113	-17,2	-15,8	-15,7	1046	2,3	1,3	2,0
23	-1,1	-1,0	-1,2	114	-21,5	-22,0	-21,5	1047	-0,3	-1,1	-2,8
24	-1,2	-1,0	-1,3	115	-15,4	-12,8	-13,9	1048	-12,2	-7,5	-22,7
25	-1,2	-1,2	-1,1	116	-16,1	-13,4	-14,5	1051	-11,6	-10,7	-11,9
26	-1,8	-1,7	-2,3	117	-18,0	-15,8	-16,5	1052	-4,7	-6,3	-6,5
27	-7,9	-8,0	-8,8	118	-22,2	-22,0	-22,2	1053	2,1	-0,7	-1,3
28	-11,3	-11,0	-10,5	121	-14,5	-14,4	-13,4	2001	1,2	1,2	-1,1
29	-8,8	-8,8	-9,2	122	-14,3	-13,9	-13,2	2002	-0,8	-0,4	-1,8
30	-11,1	-10,9	-10,2	123	-13,5	-12,0	-12,5	2003	-0,8	-0,4	-1,9
31	-5,1	-7,6	-8,7	124	-12,9	-10,9	-10,7	2004	-1,5	-1,2	-3,1
32	-13,3	-10,6	-13,0	125	-14,2	-14,0	-13,2	2005	-1,5	-1,4	-4,0
33	-7,3	-8,7	-10,4	126	-13,3	-11,4	-12,1	2006	-1,2	-0,7	-5,4
34	-12,3	-10,4	-12,8	127	-13,2	-10,3	-10,7	2007	1,2	1,3	0,0
35	-0,4	-1,3	0,0	1001	-3,0	-2,8	-2,7	2008	-0,7	-0,8	-0,7
36	-17,1	-14,8	-13,4	1002	-2,9	-2,8	-2,7	2009	-17,2	-14,4	-15,9
39	-17,9	-16,5	-14,6	1003	-2,2	-2,5	-3,0	2010	-15,8	-12,4	-16,8
40	-18,9	-17,9	-20,9	1004	-4,1	-3,8	-3,7	2011	-20,7	-15,9	-21,2
41	-1,9	-1,6	-1,6	1005	-1,4	-1,4	-1,4	2012	-18,9	-13,3	-19,7
42	-3,6	-3,1	-5,9	1006	-1,4	-1,4	-1,5	2013	-20,2	-14,5	-23,1
43	-2,3	-2,1	-3,3	1007	-1,2	-1,9	-1,4	2014	1,4	1,4	0,2
44	-4,2	-4,0	-4,4	1008	-0,9	-0,1	0,7	2015	-0,7	-0,5	-1,6
45	-15,2	-15,0	-16,2	1011	-14,8	-14,8	-15,5	2016	-0,7	-0,9	-1,4
46	-15,5	-18,8	-16,3	1012	-9,7	-11,8	-10,4	2017	-0,4	-0,8	-0,1
47	-15,1	-14,7	-15,6	1013	-1,4	-3,8	-4,4	2018	-0,6	1,4	-1,0
48	-15,0	-16,5	-15,7	1014	-30,5	-22,6	-24,7	2019	-2,6	-0,3	-2,8
49	-14,2	-13,9	-14,4	1015	2,1	2,2	2,2	2020	-2,7	-6,7	-5,0
50	-14,4	-15,0	-14,6	1016	5,3	1,9	4,4	2021	-14,5	-10,7	-17,1
51	-1,8	-2,9	-2,2	1017	4,0	0,6	5,5	2022	1,2	1,2	-0,1
52	-13,3	-11,8	-10,6	1018	-26,2	-14,0	-25,0	2023	-0,5	-0,6	0,1
53	-1,4	-0,7	-1,5	1021	-1,6	-1,5	-1,3	2024	-15,5	-13,7	-15,7
54	-12,2	-11,0	-11,9	1022	-0,8	-1,5	-0,9	2025	-19,8	-15,0	-20,2
71	-2,2	-2,0	-1,7	1023	-1,4	-2,8	-5,3	2026	-18,3	-13,2	-19,9
72	-1,5	-1,2	-0,9	1024	-18,6	-18,3	-22,4	2027	-19,3	-14,0	-22,8
73	-0,1	1,0	0,7	1025	-1,5	-1,4	-1,4	2028	1,6	1,7	1,0
74	-1,9	-1,4	-0,8	1026	-0,7	-1,7	-0,9	2029	1,2	1,3	-0,1
75	0,4	1,0	2,7	1027	0,4	-1,1	-3,0	2030	1,4	1,5	-0,1
77	-1,9	-1,8	-0,3	1028	-4,9	-1,3	-20,7				

model predictions are in general relatively close to each other and the reference results although they can deviate significantly in some cases.

5. Conclusions

Results calculated with two engineering models for predicting environmental noise levels, Harmonoise and Nord 2000, have been compared for a large number of test cases for which accurate calculations or experimental data are available. Furthermore, some scale model experiments have been conducted to supplement the reference data for some cases of special interest.

Table II. Percentage of A-weighted predictions within 1 dB and 3 dB of the corresponding reference data.

	< Δ 1 dB	< Δ 3 dB
Harmonoise	51.8%	86.9%
Nord2000	50.4%	88.3%

Table III. Average difference (A. d.) between calculated A-weighted values from the two model predictions and the reference data. S. d.: Standard deviation.

Comparison between:	A. d.	S. d.
Harmonoise - Reference data	0.3	2.5
Nord2000 - Reference data	1.0	3.0
Harmonoise - Nord2000	-0.7	2.4

There are many similarities between the two models, but also a number of differences. In particular the two models handle diffraction and refraction quite differently. In simple cases without refraction the two models agree very well both with each other and with the reference data. The agreement between the two models deteriorates for more complicated configurations, and in some cases the results have been found to be very different. The largest differences have been observed in cases where there is a diffracting hill or barrier and in cases of strong refraction. At very low frequencies Nord2000 seems to predict diffraction better than Harmonoise, which overestimates the lowest frequencies considerably. Harmonoise, on the other hand, seems to give better predictions at high frequencies in cases where there is a hill with two diffracting edges, particularly when the top segment of the hill is acoustically soft. Harmonoise also seems to handle downward refraction better than Nord2000, at least in cases where the surface is very dense and hard. Neither model can handle upward refraction satisfactorily.

Overall, both Harmonoise and Nord2000 have been found to predict sound propagation reasonably well for a variety of different cases. The accuracy of the predictions varies between different cases, and the predictions are in general very accurate for the simplest cases, but often rather inaccurate for more complex cases. A-weighted levels calculated with the two models are fairly accurate in general, but can vary significantly for complex cases. Neither model gives better predictions in all cases, and although the two models are able to predict sound propagation reasonably well in most cases, there is still room for improvement.

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