Predictions of Noise Generated by Elevated Sources in Industrial Environments

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***Abstract*— Industrial facilities typically include equipment installed (1) in a free field at some elevation above the terrain (e.g. wind turbines, vents, exhaust stacks, flares etc.) and (2) on top of floating screens (e.g. standard equipment on steel decking). Noise impacts from such equipment are routinely assessed with the ISO 9613-2 prediction method for the purposes of noise control design and occupational noise studies. There are, however, certain assumptions and limitations inherent to this method which are directly linked to the ground effect attenuation mechanism. The main concern is that the noise assessments are made at very short distances (typically less than 100 m) thus potentially undermining the stated accuracy of the prediction method. Furthermore, ISO 9613-2 is ambiguous in its definition of source emission properties and ways to account for the apparent increase in sound power of sources located close to reflective surfaces.**

Research presented in this paper relies on an idealized test case and a realistic industrial scenario, both modelled to examine the ISO 9613-2 ground effect calculation methods as implemented in SoundPLAN v7.3. The results indicate that both specified methods fail to perform as expected when simulating the unobstructed short-range sound propagation over hard ground and at sharp angles of sound incidence (due to elevated and closely spaced sources and receivers).

***Index Terms*— industry noise; environmental noise; outdoor sound propagation; noise mapping; facility design.**

I. Introduction

During the last two decades significant efforts were made to harmonize and modernize methods for predicting the noise emissions from the industry: Harmonoise, Imagine, Nord2000, Cnossos etc. [1]. Despite these efforts, the longstanding empirical and semi-empirical methods still prevail in practical engineering assessments, with ISO 9613-2 [2] being the one most widely used internationally. There are, however, limitations to using these semi-validated schemes in the acoustical design of industrial facilities [3][4][5][6].

Specifically, most algorithms have not been thoroughly validated for very short propagation distances and elevated sources and receivers. Unfortunately, it is under these conditions that the dissimilarities in ground effect schemes (as implemented in prediction standards and commercial software) may considerably impact the noise assessment outcomes. An example where short-range noise propagation from elevated sources is common is depicted in Figures 1 and 2. Here, an offshore industrial facility is shown in a conceptual General Arrangement 3D model as well as an acoustical model developed for the Front End Engineering Design (FEED) stage of a platform project. The figures show platform decking above the ocean surface at heights of up to 50 m (helipad deck) and noise sources located as high as 100 m (vent stacks, flare tips, crane equipment etc.).

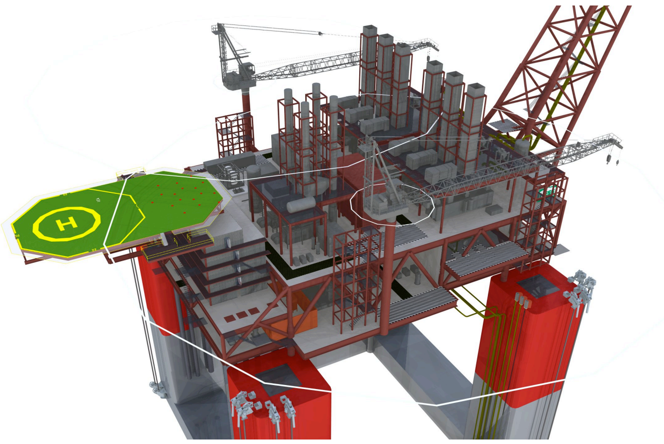

Fig. 1. A conceptual General Arrangement 3D model of an offshore facility depicting noisy equipment distributed across the sound-reflecting (plated) and sound-transparent (grated) platform decking.

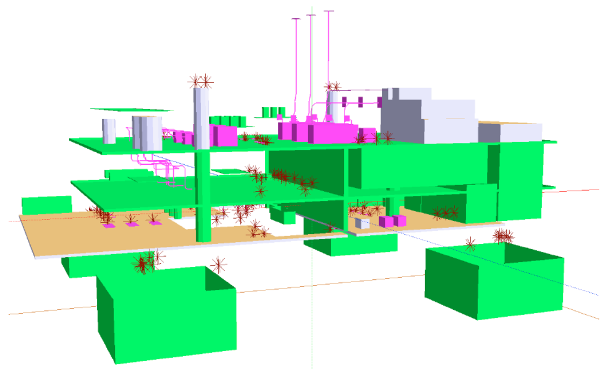

Fig. 2. An acoustical model of an offshore facility depicting elevated noise sources. For calculation purposes, the model was split into the Main Deck Model, Production and Mezzanine Deck Model and Hull Model.

As the design progresses from FEED to Detailed Design the acoustical models are extensively used to determine the noise control measures required for maintaining a healthy noise climate. For example, to meet the Australian occupational noise regulations the noise levels should remain below 82 dB(A) at 1 m from equipment package boundaries. This criterion should be met everywhere on the platform to effectively manage the risks associated with noisy plant. If, however, the predictions show that exceedance of noise criteria is likely, the operators are required to implement a set of costly noise control measures so as to reduce the risks in accordance with the As Low As Reasonably Practicable (ALARP) philosophy. The ALARP

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principle allows certain equipment to exceed the project noise criteria, but only for as long as all feasible ways of controlling the risks have been considered and/or implemented into the design.

The remainder of this paper discusses some of the problems encountered in practice when developing noise models to meet the project demands described above.

II. Industrial Noise Predictions

A. *Overview of Standardized Calculation Methods*

An outdoor sound propagation model simulates the attenuation of sound as it traverses across a predefined ground terrain from the emission point to the receiver. Along its propagation path, a sound wave will encounter a number of attenuation mechanisms (geometrical divergence, atmospheric absorption, ground effects, reflection from surfaces, screening by obstacles and meteorological effects) which should all be incorporated into a standardized prediction method. In order to sucessfuly utilize such a prediction method for industrial facility design projects it is important to correctly determine: (1) the position and placement of noise sources in relation to ground and other reflecting planes; (2) the source emission properties (sound power, directivity, angle of radiation, apparent increase in sound power due to presence of reflecting planes etc.); (3) the conditions along the propagation path; and (4) the conditions at the receiver.

The next step in the noise modelling process is to select a propagation algorithm best suited for the acoustical conditions determined in previous steps (i.e. the one that models all relevant physical phenomena in required detail). The following methods have been proven to deliver satisfactory results when predicting noise emissions from the industry: VDI 2714/2720 (Germany), ISO 9613-2 (international), Nordic General Prediction Method (GPM) (Scandinavia) and CONCAWE (international). Other relevant standards that are extensively used are: BS 5228 (UK), Nord2000 (Scandinavia) and NMPB08 (France). The above standards often overlap in content and methodology, and focus here will only be on ISO 9613-2 as the most widely used scheme which offers a compromise between complexity, accuracy and practicality of implementation and use.

In general terms, the above listed prediction methods are used to calculate the average downwind sound pressure level at the receiver (notation used here follows the ISO-9613-2 terminology):

$$L_{ft}(DW) = L_w + D_c\text{-}A \tag{1}$$

L_W is the sound power level of the source (ideally in octave bands or alternatively as an overall level), D_c is the source directivity correction and A is the combined correction index due to different attenuation mechanisms:

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \tag{2}$$

A_{div} is the attenuation due to geometrical divergence, A_{atm} is the attenuation due to atmospheric absorption, A_{gr} is the attenuation due to ground effects, A_{bar} is the attenuation due to a barrier and A_{misc} is the attenuation due to other effects.

According to ISO 9613-2 the source directivity term (D_c) combines the directivity index (D_i) and an additional correction to account for sound propagation into solid angles less than 4π steradians (D_Ω):

$$D_c = D_I + D_\Omega. \tag{3}$$

The inclusion of D_Ω as a source property is ambiguous, as the physical phenomena it models is already incorporated in the ground effect scheme inherited from the GPM. This can become an issue when defining the emission properties for sources placed above reflective ground since there is a risk of applying the D_Ω correction twice: once via the propagation algorithm and once more through the definition of the source directivity. Further complications may arise from different ways of handling the floating screens and sound propagation from sources mounted on top of them [4] [5]. Again, there is a risk of applying more corrections than required: once for the source directivity to account for its immediate environment (the presence of a floating screen) and then once again to account for ground reflections along the propagation path.

Commercial software packages have varying solutions to this issue and may not always approach the problem from the same perspective. The source definition properties, therefore, may not be translatable from one software environment to another and should be revised each time there is a change in software, prediction standard or even a calculation setting within the same software/standard (as demonstrated later in this paper).

B. *Ground Effect*

The ground effect requires special attention since this attenuation mechanism is notorious for introducing substantial uncertainties in noise predictions. Physical principles behind the ground-wave interaction phenomena are too complex to be considered here in any detail (refer to Attenborough [6] for a comprehensive overview of the topic). Instead, the focus here is on simplified implementations of this attenuation mechanism into empirical prediction methods and commercial software packages. ISO 9613-2 provides two such methods for calculating the ground effect: the Traditional Method and the Alternative Method.

The Traditional Method is similar to the scheme implemented in the Nordic GPM in that it specifies three regions where ground attenuation is observed: the source region A_s (when $30h_s<d_p$), the receiver region A_r (when $30h_r<d_p$) and the middle region A_m (between the source and the receiver regions). The middle region is omitted if the following condition is met: $d_p<(30h_s+30h_r)$. Here, d_p is the propagation distance, h_s it the source height and h_r is the receiver height. The total attenuation due to ground effect is then calculated as:

$$A_{gr} = A_s + A_m + A_r \tag{4}$$

Ground factors associated with these three distinct regions are used to compute the total ground attenuation contribution via expressions defined in Table 3 of the ISO 9613-2. The Traditional Method relies on the frequency dependent ground attenuation and thus the contributions are calculated for 1/1 octave bands between 63 Hz and 8 kHz. SoundPLAN extends this range to 1/3 octave bands between 25 Hz and 10 kHz (even down to 1 Hz and up to 20 kHz in version 7.4). Yet it is unclear how the corrections are calculated for frequencies outside of the range defined by ISO 9613-2 and in narrower frequency bands than intended by the design. Most importantly, the Traditional Method incorporates the D_Ω correction in an impedance-based ground effect estimation mentioned earlier (i.e. the GPM approach) and does not require further source directivity modifications.

The Alternative Method is applicable to flat and constant-slope terrains with a porous ground type and when the noise sources are broadband and defined with an overall A-weighted sound power level. If these conditions are met, Equation 5 can be used to calculate the ground attenuation based on the average source-receiver height:

$$A_{gr} = 4.8 - (2h_m/d)[17 + (300/d)] \geq 0 \text{ dB} \tag{5}$$

This prediction scheme, however, does not account for the hemispherical radiation due to the presence of reflective planes and this should be compensated for with the D_Ω correction:

$$D_\Omega = 10\log\left[1 + \left(d_p^2 + (h_s\text{-}h_r)^2\right)/\left(d_p^2 + (h_s + h_r)^2\right)\right] \tag{6}$$

In summary, even when the same propagation method/standard is used, the definition of source properties will be dependent on the choice between the Standard and Alternative Methods for calculating the ground effect. Failing to consider this early in the modelling stages may have considerable impact on the final noise prediction outcomes (as demonstrated in Sections III and IV).

C. Apparent Increase of Sound Power due to Reflecting Planes

Norton [7] argues that there are in fact two different mechanisms which contribute to the emission properties of a source located close to a reflecting plane. He distinguishes between the correction for hemispherical sound radiation (termed D_Ω in most standards) and the correction for the apparent increase in sound power of sources (also termed D_Ω in standards). Based on this observation, it seems that two different physical phenomena are attributed the same parameter in the ISO 9613-2 prediction method.

Norton handles this issue by introducing three different sound power models to account for variations in the acoustic radiation impedance of a source [7]: (1) a constant power model (for which the source position does not affect its radiated sound power and a standard D_Ω applies yielding a correction of + 3 dB to account for the presence of hard reflective ground); (2) a constant volume model (where reflecting surfaces increase the radiated sound power of a source yielding a double D_Ω correction at + 6 dB); and (3) a constant pressure model (where reflecting surfaces decrease the radiated sound power of the source by 3 dB arriving at no D_Ω correction at all). Norton [7] also mentions that the choice of a sound power model will be dependent on the source dimensions and its geometry, which is in contrast with the usual approach of reducing a complex source to a point source. The implications of this approach to this three-fold definition of sound power will be discussed in a follow-up paper.

D. Limitations

Facility design projects may potentially make use of the Alternative Method due to uncertainties otherwise introduced via the source emission data provided by the equipment vendors. Sound power levels used in the predictions are typically A-weighted and estimated from basic theoretical principles, often without an indication whether the hemi-spherical propagation has been accounted for. Also, the emission data is often derived directly from non-standardized spot measurements taken at 1 m from equipment installed in manufacturing shops rather than standardized laboratory environments. The emission data obtained in this way is thus non-compliant with the sound power testing standards and great care should be taken when interpreting the information supplied by equipment vendors.

III. Testing Methods

This section describes the modelling scenarios devised to test the ISO 9613-2 ground effect schemes: (1) an idealized Test Case and (2) a realistic scenario of an industrial facility.

A. Test Case Description

A simple sound propagation model was developed to test the ISO 9613-2 ground effect schemes as implemented in SoundPLAN v7.3. The aim was to investigate disparities that stem from different calculation settings rather than to determine the validity of the calculation method or its implementation in a given software package.

The Test Case was designed to enable: (1) observation of general trends in sound attenuation over relatively short distances and for elevated sources and receivers and (2) examination of the performance of various ground effect methods when modelling scenarios of interest for industrial facility design projects (i.e. the impact of different calculation settings on the overall predicted levels).

At this stage of testing (a) frequency dependent results were not considered (although the calculations were conducted in 1/3 frequency bands from 25 Hz to 10 kHz), (b) frequency A-weighting was not applied and (c) complex propagation phenomena associated with the ground-wave interaction was ignored (as in the considered prediction method). The reported simulation outcomes include all of the sound attenuation mechanisms although their impact was observed to be negligible due to simplicity of the Test Case.

Test Case presented here does not fully address the quality requirements and quality assurance described in the ISO/TR 17534 group of standards [9][10][11]. In fact, the inclusion of formalized test cases and scenarios which serve to validate the implementation of a given calculation method has only recently been considered by software developers. Prior to this, the prediction methods were mostly validated on non-standardized test cases.

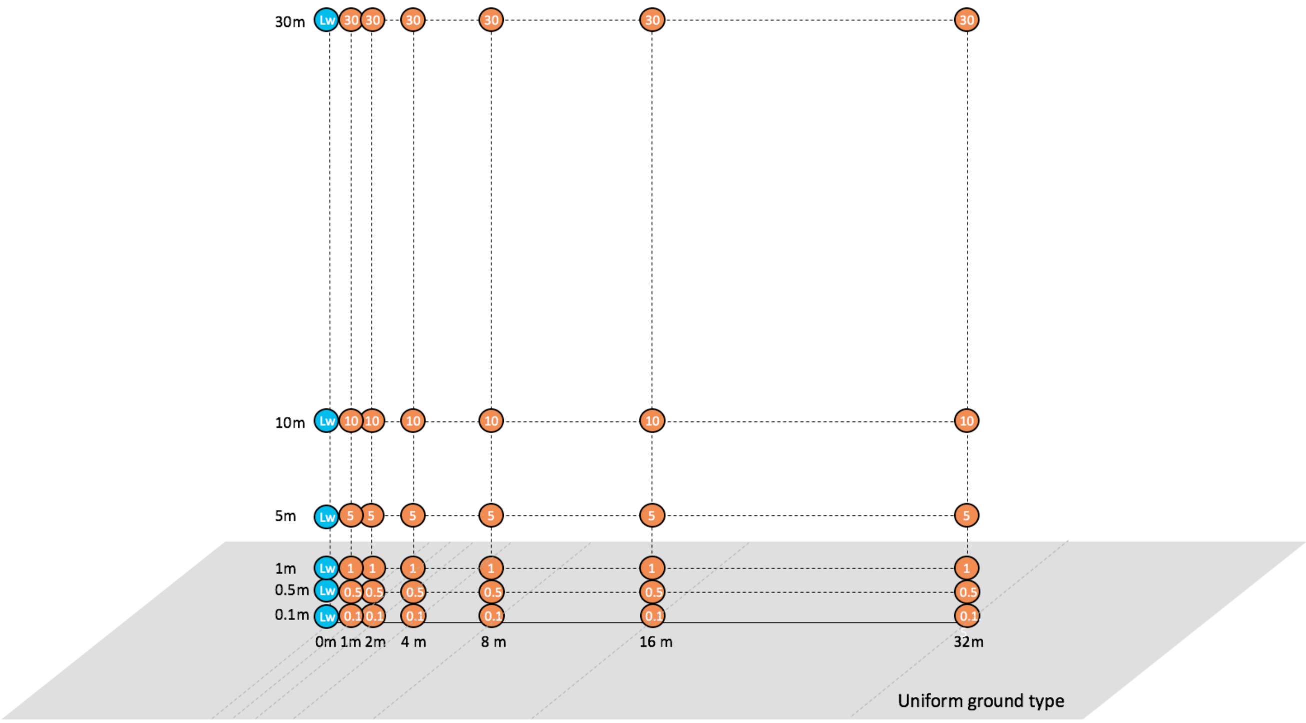

Fig. 3. Test Case source-receiver grid above a flat terrain with a uniform ground type (absorbing or reflecting).

To complicate matters further, the prediction methods are often combined into hybrid schemes to counter-act the shortcomings of one or both of the employed methods. In such cases, it is difficult to appoint any observations made during the testing to a specific method. For this reason, the Test Case considered here was designed to avoid attenuation mechanisms which may require these hybrid schemes (e.g. handling of attenuation due to diffractions around barriers).

B. *Test Case Model Setup*

The Test Case comprises a flat terrain modelled without any obstacles to sound under downwind propagation conditions (see Figure 3). The homogenous ground type was set to two extreme settings: G=0 for hard reflective ground and G=1 for porous absorbing ground. A point source was defined with an unweighted uniform spectral content across the frequency range available in SoundPLAN. Point receivers were assigned to the model at locations away from the source at 0.5 m, 1 m, 2 m, 4 m, 8 m, 16 m and 32 m. These locations were chosen to exemplify the attenuation of sound by 6 dB with every doubling of distance and due to spherical divergence from a point source radiating sound into a free-field. The sources and receivers were assigned the following heights above the terrain: 0.1 m, 0.5 m, 1 m, 5 m, 10 m and 30 m.

The simulations were performed for each source/receiver height and point responses computed to arrive at a total of 36 responses for each of the tested prediction methods. Two sound propagation algorithms were employed: ISO 9613-2 (with two different ground effect schemes) and the Nordic GPM (comparable to the ISO 9613-2 Traditional Method for calculating the ground effect). The GPM prediction outcomes are not reported here as they closely match the results obtained with the ISO 9613-2 Traditional Method (i.e. GPM was only used to validate the SoundPLAN implementation of the ISO 9613-2 Traditional Method).

C. *Practical Example Model Setup*

In this instance, implications of the ISO 9613-2 ground effect calculation method are demonstrated on a practical example. Detail shown in Figure 4 depicts a complex equipment package (Solar Titan 130 Gas Turbine Generator - GTG) modelled in considerable detail to include the equipment housing, all associated piping, vents and exhaust stacks etc. This equipment package is typically installed in numbers greater than one and is recognized as one of the main contributors to excessive noise levels associated with offshore platforms. The GTG packages were modelled on top of the Main Deck at 44 m above the ocean surface. The Main Deck was composed of steel plates modelled as hard reflective planes via SoundPLAN's digital ground model. The platform also comprised a number of grated (and thus sound transparent) decks for which separate noise models were developed (i.e. Production Deck, Mezzanine Deck and Cellar Deck).

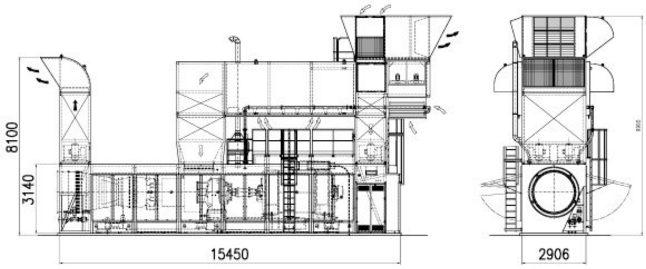

Fig. 4. Generic configuration of a Solar Titan 130 Gas Turbine Generator package specified for an offshore facility.

IV. SIMULATION RESULTS AND COMMENTS

A. *Test Case Simulation Results*

Table 1 shows the total ground effect correction levels to be added to the remaining attenuation mechanisms considered as part of the ISO 9613-2 prediction scheme. The corrections were calculated for Test Case conditions described above by employing the Alternative Method which separately accounts for ground attenuation (A_{gr}) and hemispherical radiation above a reflecting plane (D_{Ω}). The results demonstrate that for source-receiver heights above 0.5 m only the D_{Ω} correction is relevant. The corrections calculated for h = 30 m resemble the free-field propagation conditions with minimal contribution to the overall attenuation. It is interesting to observe how the D_{Ω} correction increases with distance for heights above 5 m, thus proving to be sensitive to the path length difference. Correction values for the Traditional Method were not computed separately in this investigation.

TABLE I
GROUND EFFECT CORRECTIONS CALCULATED WITH THE ALTERNATIVE METHOD OF ISO 9613-2

h	h=0.1 m			h=0.5 m			h=1.0 m		
d [m]	A_{gr} [dB]	D_o [dB]	SUM [dB]	A_{gr} [dB]	D_o dB	SUM [dB]	A_{gr} [dB]	D_o dB	SUM [dB]
1	0	2.9	2.9	0	1.8	1.8	0	0.8	0.8
2	0	3.0	3.0	0	2.6	2.6	0	1.8	1.8
4	0.2	3.0	2.8	0	2.9	2.9	0	2.6	2.6
8	3.4	3.0	-0.4	0	3.0	3.0	0	2.9	2.9
16	4.4	3.0	-1.3	2.6	3.0	0.4	0.3	3.0	2.6
32	4.6	3.0	-1.6	4.0	3.0	-1.0	3.2	3.0	-0.1
h	h=5.0 m			h=10.0 m			h=30.0 m		
d [m]	A_{gr} [dB]	D_o dB	SUM [dB]	A_{gr} [dB]	D_o dB	SUM [dB]	A_{gr} [dB]	D_o dB	SUM [dB]
1	0	0	0	0	0	0	0	0	0
2	0	0.2	0.2	0	0	0	0	0	0
4	0	0.6	0.6	0	0.2	0.2	0	0	0
8	0	1.4	1.4	0	0.6	0.6	0	0.1	0.1
16	0	2.4	2.4	0	1.4	1.4	0	0.3	0.3
32	0	2.8	2.8	0	2.4	2.4	0	0.9	0.9

The Test Case prediction outcomes are shown graphically in Figure 5 for hard ground and in Figure 6 for soft ground. Both figures show the combined attenuation due to varying source-receiver distances and heights for the two considered ground effect schemes. The results are shown as deviations from the theoretically predicted sound attenuation due to free-field spherical divergence (i.e. 6 dB attenuation per distance doubling).

The Traditional Method predicts that caution should be used when modeling equipment and receivers very close to horizontal reflective surfaces (e.g. 0.1 m), particularly when larger source-receiver distances are of interest. As the height increases above 0.5 m (which is a common modelling height for pumps, electric motors, pipes etc.) all tested hard ground scenarios appear to qualify for a uniform ground effect correction of + 3dB. This is not in line with the expectations for this method seeing how the correction is also applied to sources located as high as 30 m above the ground. This means that if a vent stack is modelled as a point source above a solid platform deck, it will pick up the D_{Ω} correction regardless of its elevation, thus leading to an over-prediction of platform noise levels. For a soft ground type (Figure 6 - left plot) the Traditional Method performs as expected, with corrections not exceeding 1 dB for the considered source-receiver heights and distances.

In contrast with the Traditional Method, the Alternative Method correctly predicts the free-field conditions beyond a certain height for both ground types. This means that sources modelled on top of elevated solid decks should be corrected for the restricted angle of radiation when using this ground effect scheme, while stacks and chimneys will not require the D_{Ω} correction to be added. The exact height at which the free-field conditions prevail should be tested thoroughly by means of a standardized test case.

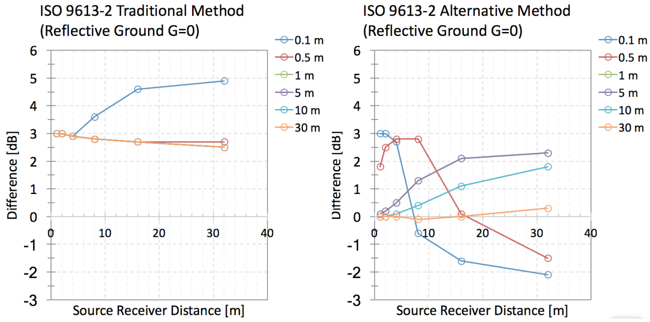

Fig. 5. Traditional vs. Alternative ground effect for hard (reflective) ground: difference in dB between the theoretical free-field spreading and simulated total attenuation at various source-receiver heights and distances.

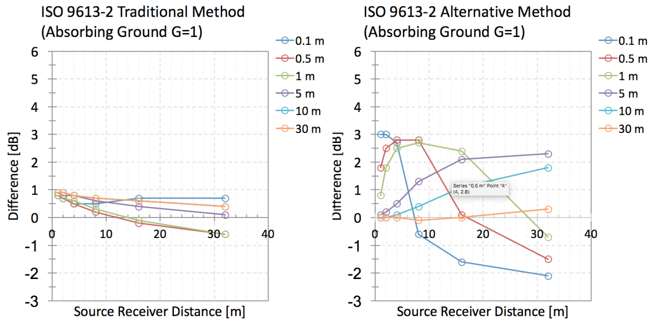

Fig. 6. Traditional vs. Alternative ground effect for soft (absorbing) ground: difference in dB between the theoretical free-field spreading and simulated total attenuation at various source-receiver heights and distances.

B. Practical Example Simulation Results

Figure 7 shows a total noise map which combines all significant sources active on the Main Deck (including the three GTGs). In order to better visualize the differences between Traditional and Alternative ground effect schemes, a single GTG was modelled in isolation and noise levels observed in the vicinity of the package.

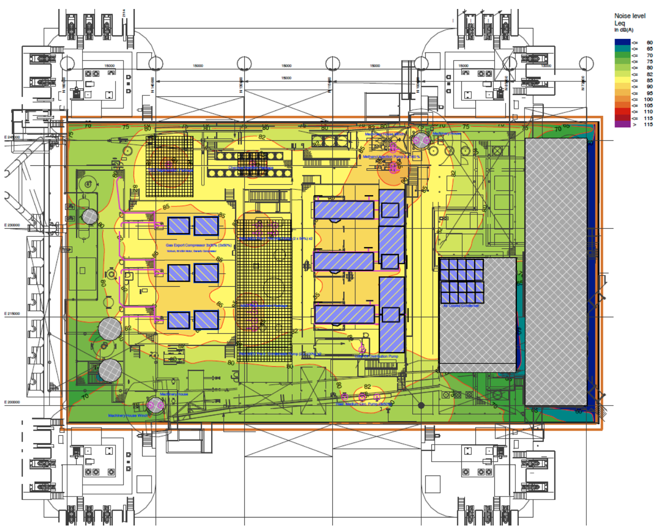

Fig. 7. Combined noise levels predicted on the Main Deck of an offshore platform. The noise sources comprise gas turbine generators, gas export compressors, pump packages (including motors) and piping.

The results are shown in Figure 8 and Figure 9 where the 82 dB(A) noise criteria contour was colored in yellow for easier identification of hazardous areas. It is clear from these plots that a much louder GTG package was predicted with the Traditional Method: Figure 8 demonstrates non-compliance while Figure 9 demonstrates compliance with the project noise criteria. The predictions made with the Traditional Method can thus potentially lead to over-specification of noise control measures which may not be justified in reality. If the algorithm is switched to the Alternative Method, the model predicts that noise risks associated with the GTG package will not require further attention and that all noise levels are below the action limits.

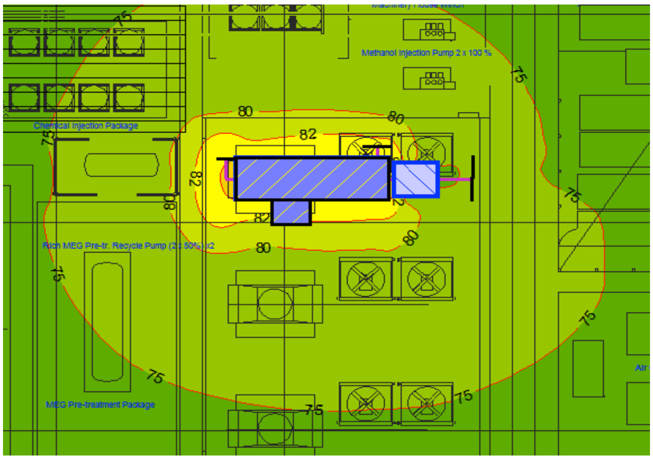

Fig. 8. Noise levels predicted on the Main Deck for an isolated GTG package comprising a number of point, line and area sources. Noise levels are over-predicted with the Traditional Method for ground effect attenuation.

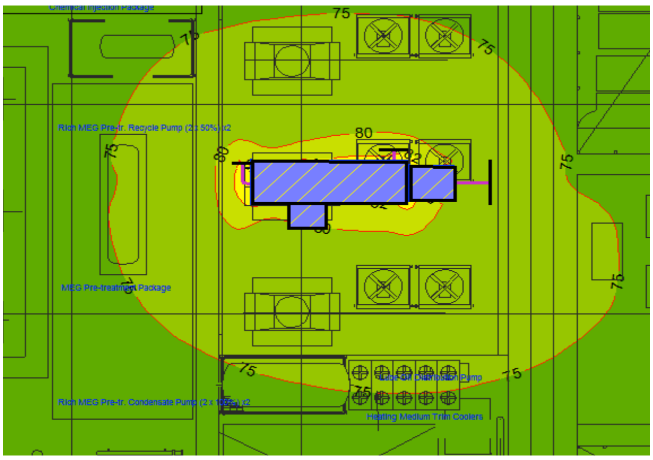

Fig. 9. Noise levels predicted on the Main Deck for an isolated GTG package comprising a number of point, line and area sources. Noise levels are realistically predicted with the Alternative Method for ground effect attenuation.

This does not necessarily mean that the Alternative Method is always preferred to the Traditional Method. The situation may be reversed under different acoustical conditions, and this example only serves to demonstrate how easily the decision making process can be driven in various directions by a simple software setting.

V. Conclusion

The results reported here can be viewed as engineering-grade validation cases serving one major goal: to demonstrate via idealized and practical scenarios how an ambiguous software setting can have a significant impact on the noise assessment outcomes. Both noise models considered here have shown this to be the case. The observed inaccuracies may not be critical for large-scale noise mapping, but can significantly influence the direction of facility design projects (i.e. where the noise impacts are routinely assessed as close as 1 m from equipment packages).

Currently, there is no indication that the empirical and semi-empirical methods will be replaced in practice by more accurate numerical methods and sophisticated ground effect schemes. Until this happens, the end-users are advised to consider in detail all limitations that apply to the chosen propagation standard and understand its implementation within a given commercial software package. For close-range predictions in industrial settings, this will require an in-depth understanding of the software algorithms to determine, for example, whether the D_Ω corrections are to be manually applied by the end-user or if they will handled automatically by the software.

In global terms, this means that one cannot simply define the absolute properties of noise sources and then determine which method to employ for the predictions. Source emission properties should be revised each time a prediction method is changed and, as the current study shows, even when the standard remains constant but some of the software settings are changed.

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