The United Nations University

GEOTHERMAL TRAINING PROGRAMME
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Reports 2001
Number 8

PRELIMINARY STUDY OF NOISE PROPAGATION BEHAVIOUR AT THE NESJAVELLIR GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

A study of noise propagation was carried out at well sites NV-16, NV-21, NV-22 of the Nesjavellir geothermal field in SW-Iceland. Silencer equipment was used as noise sources, through which a double phase flow was discharged to the atmosphere. These sources emit noise levels with low frequency characteristics and according to measured noise, need distances longer than 160 m to reach reduced noise values on the order of 50-55 dB (A), the values recommended by the environmental legislation for residential areas. However, at Nesjavellir there are no communities located close to the well sites; therefore, the noise emissions do not constitute an environmental impact, except for the recreational areas close to Nesjavellir. The study also included calculation of noise using the Sound Plan Software, where noise levels were determined by modifying environmental variables such as ground type, relative humidity and inserting acoustic barriers close to the sources. The results indicated that a combination of soft ground at all well sites and acoustic barriers placed very near to the sources can attenuate the noise levels at short distances, when it is too expensive to modify the source design in operation projects. Therefore, it is recommended to carry out experimental testing of noise propagation by modifying environmental conditions for the purpose of verifying real noise values, and then to apply environmental measures to attenuate the noise impact produced by geothermal development.

1. INTRODUCTION

One of the most commonly observed emissions to the environment is noise produced during the development and operation of industrial projects. Geothermal projects are an example of this. The noise emission to the air constitutes an environmental impact when there are people or animal communities living near the project sites. When those conditions are present it becomes necessary to design strategies focused to develop projects and at the same time to protect the environment, necessitating the inclusion in design planning of noise reduction programmes and environmental monitoring.

The study of environmental noise produced by geothermal activities should include the analysis of the noise source, the propagation of the noise toward the receiver and impact reduction. When technology has been developed without taking into account environmental conditions, it becomes necessary to look at alternative noise reduction measures. Instead of changing the technology design of the noise sources which would be very expensive, it is possible to attenuate the propagation of noise toward the receiver by inserting appropriate acoustic barriers and modifying some environmental variables around the site.

The main objective of this preliminary project is to carry out a study on the emissions of environmental noise and the attenuation forms, for the application and prevention of environmental impacts caused by noise in geothermic projects. Within the scope of the study, work includes mapping the noise propagation behaviour in a geothermal field by noise measurement, and calculating noise levels using software that changes environmental conditions such as vegetation covering, ground types, temperature, wind and humidity, and allows for inserting acoustic barriers close to the sources.

2. DESCRIPTION OF THE ELECTRIC PRODUCTION PROCESS OF THE NESJAVELLIR GEOTHERMAL POWER PLANT

2.1 Geothermal energy at Nesjavellir

The Nesjavellir geothermal field is within the Hengill area. It belongs to the Hengill high-temperature system and is located some 20-30 km east of Reykjavík. This is one of the largest high-temperature areas in Iceland (see Figure 1).

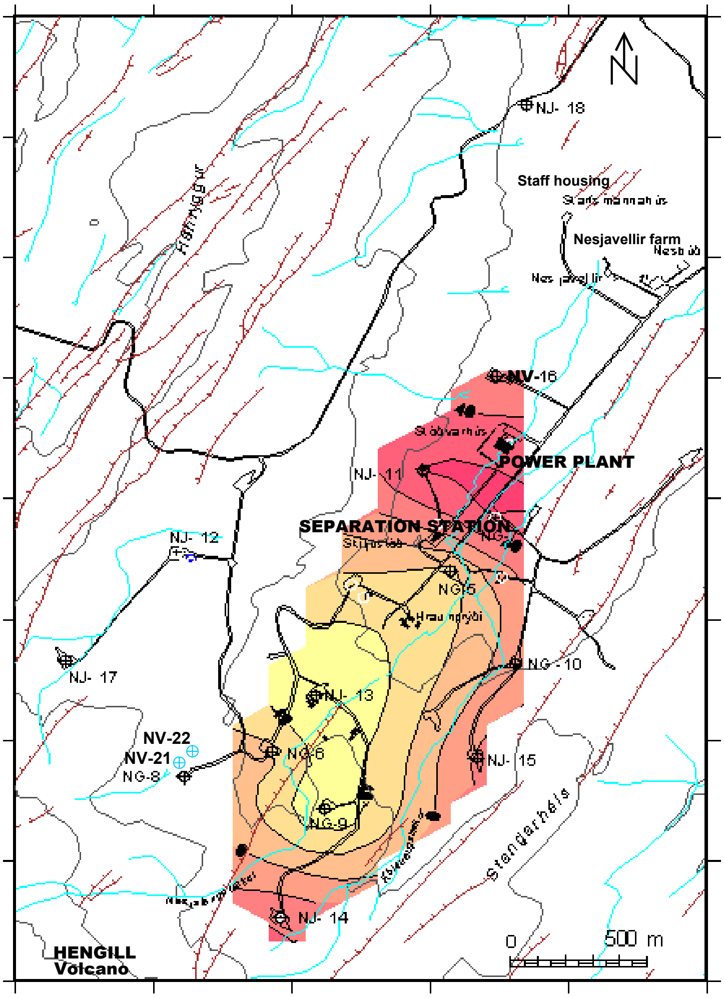

FIGURE 1: The location of Nesjavellir geothermal field

General studies begun in the Hengill geothermal area in 1947-49. With the high surface geothermal activity found south of the Nesjavellir farm in the NE-Hengill area, research was to some extent concentrated towards that part. These general studies and exploration drilling continued intermittently at Nesjavellir. In the mid-eighties an extensive exploration programme was carried out at Nesjavellir including geological, geochemical and geophysical studies and many deep exploration wells. All exploration wells were designed so as to function as production wells later. The extent of the geothermal system at a depth of 1-2 km was also studied to the east, west and north.

Results were good. On average, each well has a thermal power of 60 MWt, which would yield a net output of 30 MWt from a thermal power plant and be sufficient to supply hot water for space heating for a community with 7,500 inhabitants. Of 18 wells drilled so far at Nesjavellir, 13 are production wells (Gíslason, 2000).

The City Council of Reykjavík decided on 20 November 1986 to begin construction of a geothermal power plant at Nesjavellir. The first stage in this development was a thermal power plant with a capacity of 100 MWt for heating in Reykjavik,. The plant went into operation in September 1990. With recent extensions the Nesjavellir Power Station provides at present 90 MWe of electricity (from three turbines 30 MWe) and 200 MWt of thermal power. The plant and the transmission pipelines are designed for a maximum capacity of 400 MWt.

2.2 The Nesjavellir power plant operation

Production process of the geothermal plant at Nesjavellir is summarized here below (Gíslason 2000). The plant can be divided into five sub-systems all of which have separate functions, including

- Geothermal fluid supply;
- Electricity generation;
- Cold water supply;
- Heating and treatment of cold groundwater;
- Transmission of hot water by pipeline to Reykjavík.

Table 1 presents the total discharge of geothermal fluid and the production of heated water for space heating. Table 2 shows the conditions of energy production contained in the hot water and in electric form and the production of steam and gases that are discharged to the atmosphere (before the electric production was increased to 90 MWe).

TABLE 1: Production conditions for the Nesjavellir plant

Year	Month	Discharge (tons × 10^3)	Production (tons × 10^3)
1994	3	1219	4045
1995	12	4963	15528
1996	12	5717	14331
1997	12	6456	15266
1998	12	4231	8445
1999	12	10470	14646

TABLE 2: Hot water production at the Nesjavellir plant in 2000

Hot water	
Average flow rate	700 kg/s
Temperature of heated water	82ºC
Average return temperature	32ºC
Average energy output	147 MWt
Electricity	60 MWe
Total energy	**207 MW**
Steam	
Average steam flow	126 kg/s
Average CO_2 concentration	3.3 g/kg
Average release of CO_2	416 g/s
Emission of CO_2 from plant	**7.2 g/kWh**

A mixture of steam and geothermal brine is transported from the wells to a central separation station at 200˚C and 14 bar. After being separated from the brine, the steam is piped through moisture separators to steam heat exchangers inside the plant building. The steam can be piped to steam turbines for co-generation of electricity. Unutilised steam is released through a steam exhaust.

The steam heat exchangers consist of 295 titanium plates. In them the 120˚C steam is cooled under pressure into condensate whose heat is then transferred to cold fresh water in condensate heat exchangers. The condensate cools down in the process to 20˚C. Separated geothermal brine has its heat transferred to cold fresh water by geothermal brine heat exchangers. Cold water at 4˚C is pumped from wells at Grámelur, near the shore of Lake Thingvallavatn, to a storage tank by the powerhouses. From there, it is pumped to the steam heat exchangers where its temperature is raised to 85-90˚C.

The hot water production reaches 1100 l/s. This water is pumped from the power station into a tank near Hengill (406 m above sea level). Through a pipeline 90 cm in diameter and about 30 km long the water goes by gravity from the tank to Reykjavík. The pipeline is made of steel, insulated with rock wool and covered by plastic and aluminum on the outside. Good insulation and large flow rate are the main reasons of only 2˚ temperature loss during pumping from Nesjavellir to Reykjavík (Gunnarsson et al., 1992).

The fresh water is saturated with dissolved oxygen that would cause corrosion after being heated. It is passed through de-aerators where it is boiled at low vacuum pressure to remove the dissolved oxygen and other gases, cooling it to 82-85˚C. For this reason, a small amount of geothermal steam containing acidic gases is also injected into the water to rid it of any remaining oxygen and lowering its pH, thereby preventing corrosion and scaling. A flow diagram of the process is shown in Figure 2.

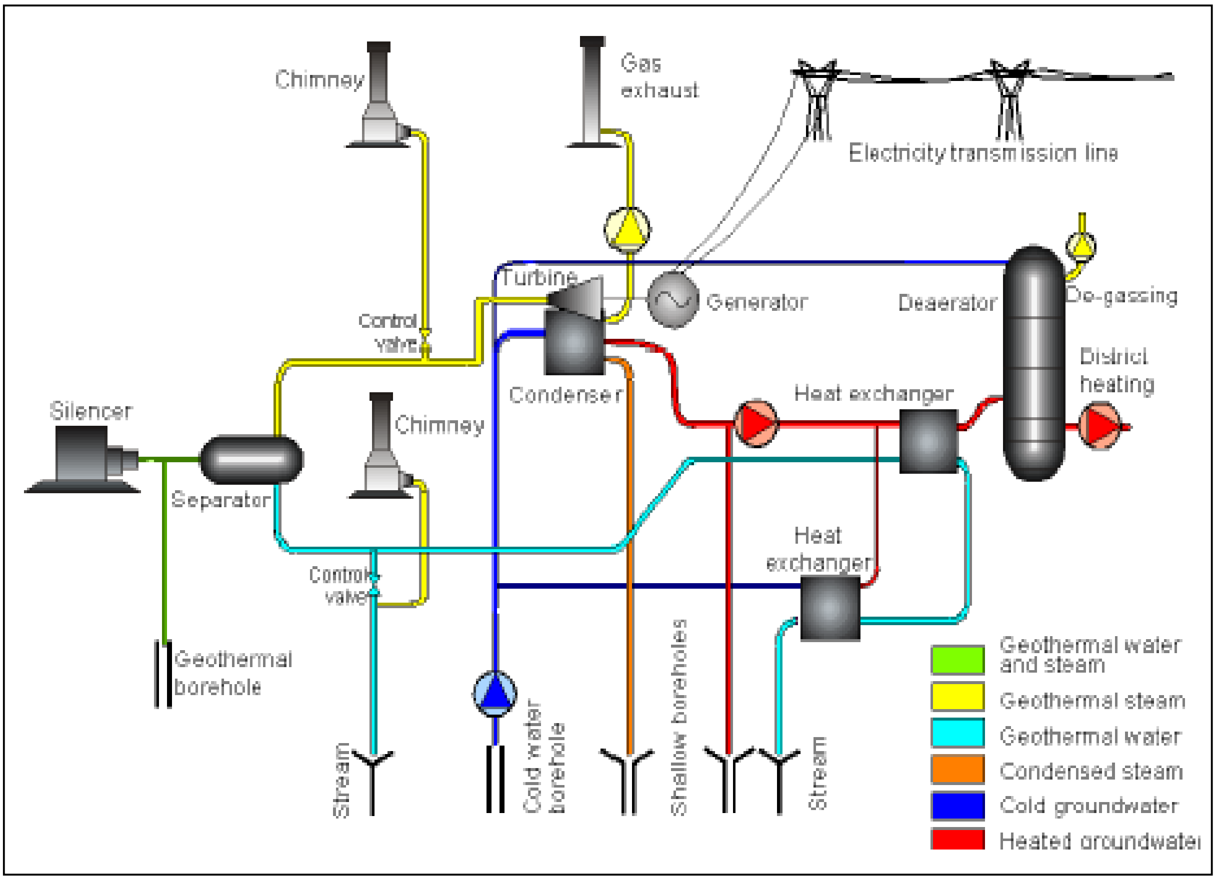

FIGURE 2: Design of the Nesjavellir plant (Gíslason, 2000)

3. THE AREA SURROUNDING THE NESJAVELLIR GEOTHERMAL POWER PLANT

As a part of the project of investigation, it is necessary to characterize the environmental and climatologic conditions of the field area. The information of the environmental conditions is decrypted as follows:

3.1 Geology

The Nesjavellir geothermal field belongs to the Hengill high-temperature geothermal area, and is located in the northern sector of the Hengill central volcano, within a SW-NE trending fracture zone, which intersects the volcano. In the uppermost part of the lava pile (above 400 m b.s.l.), basaltic hyaloclastite formations dominate the rock sequence, while the lower part is characterized by basaltic lava series, with sparse hyaloclastite formations interbedded. Magmatic intrusions become more frequent with depth, composing less than 5% of the rock sequence above 400 m b.s.l., around 20% at 400-1300 m b.s.l. and more than 50% at 1300-1600 m b.s.l. The majority of these intrusive rocks are of basaltic composition with apparent thicknesses of less than 30 m. Below 1400 m b.s.l. intermediate intrusive rocks have been found (Franzson et al., 1986).

The area of surface geothermal manifestations in the Hengill area covers about 40 km^2. The geothermal area is characterized by low resistivity, some 110 km^2 in areal extent at 200 m depth below sea level. Its central part contains a high-resistivity body below the low-resistivity layer, caused mainly by change in alteration minerals from low-temperature minerals to high-temperature minerals and a transition from water-dominated to a two-phase system at depth. A negative magnetic anomaly caused by hydrothermal alterations of the magnetite in the basaltic rocks correlates well with outlines of the geothermal area (Árnason et al., 1986).

Aquifers are often found on the peripheries of intrusions, and also at faults that can't be seen at the surface, but boreholes show clearly that occur. Rock temperature is highest next to the recently active volcanic fractures. At sea level, the temperature is approximately 100˚C. It increases with depth, and at 2 km depth it exceeds 350˚C (Steingrímsson et al.,1990).

3.2 Ground type

The ground in Nesjavellir geothermal field is the same as in the lands that are located around Thingvallavatn lake. The soil is mostly of Aeolian origin, well drained, with a low content of clay and a mineral fraction consisting mainly of volcanic ash. These soils are very susceptible to water and wind erosion.

The grounds in Nesjavellir are mostly well drained on highly permeable bedrock such as glacial deposits, palagonite rock and postglacial lavas (Agricultural Research Institute, 1982; Thorsteinsson and Arnalds, 1992). The dry land grounds are predominantly formed of Aeolian materials resting upon bedrock of various origins. There are limited occurrences of alluvial flats or water deposits along the few surface rivers and brooks in the area. The Aeolian soils are mainly characterized by the following:

- Average soil thickness is around 1 m, which is common for soils of this origin in Iceland.
- The soils are gravel free with a very low content of clay. The texture is mostly sandy loam and silt loam, which makes the soils highly permeable and also very susceptible to wind and water erosion. The mineral fraction is likely to be predominantly tephra (volcanic ash).
- The profile is homogenous and without distinct horizons.
- The soils have weak structure.
- The organic matter content is high, as commonly occurs in cold and cold-temperate climate. This causes relatively high cation-exchange capacity in spite of low content of inorganic colloids.
- The pH is relatively high due to the patchy basaltic, Aeolian addition, which compensates for the loss of cations by leaching and for organic build-up.

3.3 Vegetation type

The characteristics in the present state of the vegetation in places located southwest of the Thingvallavatn lake such as the Nesjavellir geothermal field, are due to the combined effects of woodland destruction, grazing of livestock, cold climatic spells and volcanic activities causing a drastic deterioration some 1100 years ago. This deterioration was followed by extensive soil erosion, which has greatly reduced the agricultural value of the land in Nesjavellir area, as well as in the country as a whole (Saemundsson, 1992). The vegetation which had developed for centuries without interference changed drastically because of the stress which human activities and grazing of herbivores imposed upon the fragile ecosystem. Gradually the trees and shrubs were destroyed by chopping, burning and grazing and the remaining vegetation became less vigorous and more sensitive to the harsh climate, colder climatic spells and natural catastrophes such as volcanic eruptions. This soon resulted in large scale soil erosion which has continued up to this date (Thorsteinsson and Arnalds, 1992).

The vegetation of the area is characterized by the absence of trees. As shown in Figure 3, it is classified into six main plant communities, based on species dominance: Moss heath, dwarf shrub heath, graminoid heath, cultivated grassland, lava bedrock and a small area of barren land. The areas classified as barren land on the map usually carry some, although very scattered, plant cover, either remnants of earlier vegetation not yet fully eroded, secondary growth on eroded land, or vegetation classified as alpine (Agricultural Research Institute, 1982). Figure 3 shows the vegetation map of the Nesjavellir area.

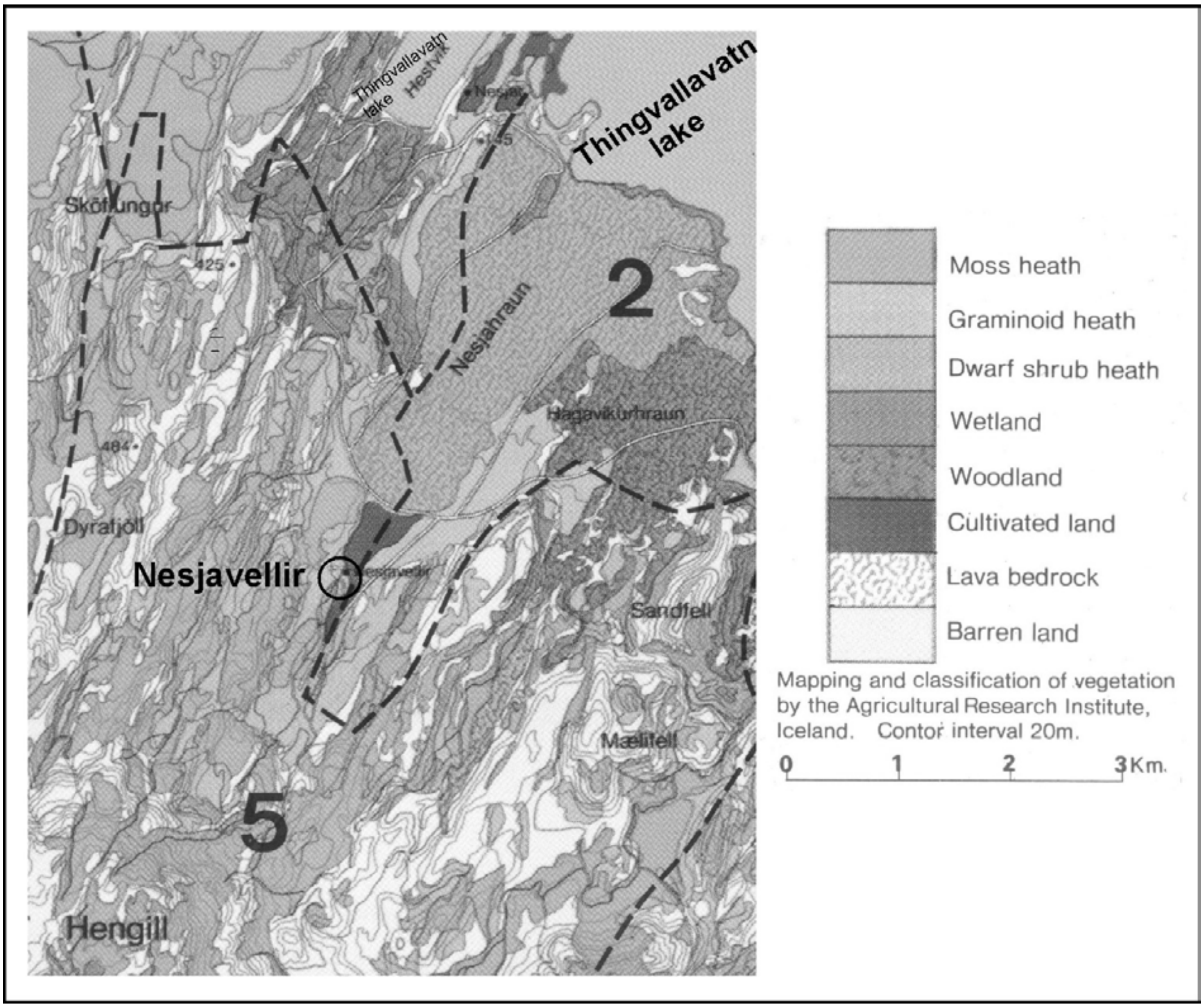

FIGURE 3: Ground type in the Nesjavellir area (Agricultural Research Institute, 1982)

3.4 Weather

The data of total accumulated precipitation, mean temperature, mean wind speed and relative humidity from the beginning of 1999 to June, 2001 have been prepared by the Icelandic Meteorological Office, based on measurements at a site located west of the Nesjavellir geothermal power plant (Icelandic Meteorological Office, 2001).

The total accumulated *precipitation* varied between 1709 and 1754 mm per annum. The monthly data are presented in Table 1 in Appendix I.

The mean *temperature* monthly data varied from –1.5 to 11.6°C. In the winter the data varied between –1.5 and 2.7°C and in summer between 1.0 and 11.6°C. The monthly data of maximum and minimum temperature registered are presented in Table 1 in Appendix I.

The mean *wind* speed in a month varied from 3.1 to 7.5 m/s. In the winter the data varied between 3.3 and 7.5 m/s and in summer between 3.1 and 6.2 m/s. According to the presented data, the mean wind speeds can be considered as quite slow winds. The monthly data are presented in Table 1 in the Appendix I. Figure 4 shows wind direction at the Nesjavellir geothermal field. The figure was obtained from "Environmental impact assessment to Nesjavellir geothermal power plant. Project of expansion from 56 to 90 MWe", by VGK Consulting Engineers Ltd. and published with the permission of Reykjavík Energy Co. (Egilsson et al., 2000).

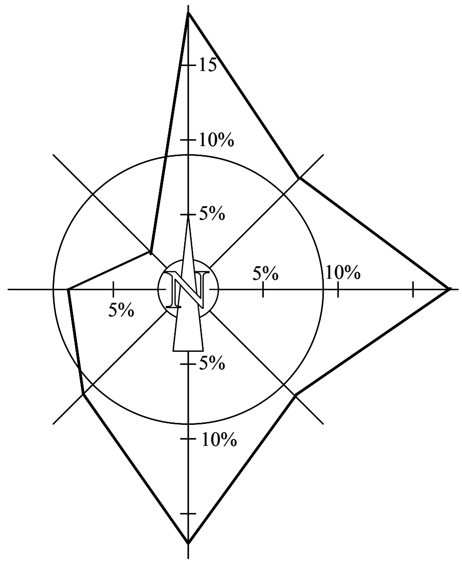

FIGURE 4: Wind direction in the Nesjavellir area (Egilsson et al., 2000)

The mean *relative humidity* varied from 65% to 84% on a monthly basis. In winter the data varied between 65 and 82% and in summer between 71 and 84%. The monthly data are presented in Table 1 in Appendix I.

4. NOISE PROPAGATION AND MEASUREMENTS

4.1 Theoretical background

4.1.1 Fundamental concepts on noise

The fundamental concepts on environmental noise found in different books that study this parameter type indicate that the noise is a succession of travelling pressure waves moving away from a source. Although there exists no pressure gradient between a source and its surroundings, pressure waves are transmitted through medium (usually air) and since pressure is a force, there must be a flow of momentum and hence energy. Consequently, sound waves must transmit energy. As this energy is dispersed over a wide area it is more usual to refer to the intensity of sound at a point. Intensity, I, is the amount of energy passing through a unit area per unit time and can be expressed in W/m^2. There is a direct relationship between the intensity of a sound and its acoustic pressure, p (in N/m^2). Therefore, as sound measuring instruments measure pressure directly, it can be expressed as a value of intensity and the total acoustic power produced by the source can be easily calculated (MWD, 1983; Davis and Cornwell, 1991). The acoustic intensity, I, at a point is given by

$$I = \frac{p^2}{\rho c} \tag{1}$$

where ρ = Density [kg/m^3], in air at 20°C and standard pressure it is 1,185 kg/m^3;
c = Sound velocity [m/s].

The total power, W, of the source is simply the intensity times the area of radiation, A (in m^2), or

$$W = \frac{p^2}{\rho c} \times A \tag{2}$$

Then the sound power level, L_W of a source can be defined as

$$L_W = 10 \times \log_{10}((Sound\,power)/(Reference\,power)) \tag{3}$$

In acoustic engineering, the scale which is used is based on the logarithm of the proportions of the measured quantities compared to specific quantities of reference. The commonly used sound reference power level is 10^{-12} W and the sound power level of the source is expressed in decibel (dB). The sound power, W, is proportional to the square of the sound pressure, with the sound pressure expressed in Pascals (Pa). The sound pressure level, L_p, is actually measured as 10 times the logarithm of the ratio of squared sound pressure compared to the square of some constant reference pressure. The reference used is the pressure corresponding to the lowest sound pressure that the ear can detect, 20 µPa, thus, L_p is defined as

$$L_p = 10 \times \log_{10}((Sound\,pressure)^2/(Reference\,pressure)^2) \tag{4}$$

or, consequently,

$$L_p = 20 \times \log_{10}((Sound\,pressure)/(Reference\,pressure))$$

4.1.2 Equivalent continuous sound pressure level - L_{eq}

According to general agreement about noise analysis, the units used to express noise measurement appropriately are decibels or dB(A), which approximates perceived sound by human hearing. However, the noise levels frequently vary with time, and it becomes very complicated to keep track of the data during a measurement period. For that reason, it is not convenient to use the instantaneous sound pressure level, L_p as a measure parameter for the study of noise propagation behaviour. Rather the equivalent continuous sound pressure level, L_{eq}, is used which represents the energy-average of fluctuating noise during a time period. L_{eq} is a parameter proposed by ISO (1996, 1971).

The mathematical expression is

$$L_{Aeq} = 10\log_{10}\left[\frac{1}{T}\int_0^t p(t)^2/p_0^2\,dt\right] \tag{5}$$

where T = Period of time during which L_{Aeq} is calculated;
$p(t)$ = Instantaneous sound pressure;
p_o = Reference sound pressure (20 µPa);
A = Refers to a weighting of the sound level in order to simulate human hearing;

Equation 5 can be written as

$$L_{Aeq} = 10 \log_{10} \left(\frac{1}{T} \int_0^t 10^{0.1 L_p} dt \right) \tag{6}$$

where L_p $= 10 \log_{10} (P(t) / P_o)^2$

and if the sample methodology is discrete, then L_{Aeq} is given by

$$L_{Aeq} = 10 \log_{10} \left(\frac{1}{T} \sum_{i=1}^{n} 10^{0.1 L_i} t_i \right) \tag{7}$$

where n = Number of samples,
L_i = Sound level in sample *i*, and
t_i = Time fraction of sample *i*.

4.1.3 Noise frequency

The frequency is the number of complete variations of pressure or cycles per second and is given by

$$P = 1/f \qquad or \qquad \lambda = c/f \tag{8}$$

The frequencies of audible sounds vary from 0.015 to 15 kHz. At frequencies smaller than 15 Hz the sound is not audible, although if it is sufficiently strong it is perceived as a vibration (infrasonic frequencies). The human voice contains frequencies in the range 80 Hz - 8 kHz, but concentrates at the interval 0.5 - 2 kHz. In practice, it is not usual to find high levels of sounds at a higher frequency than 8 kHz. Therefore, sounds above 8 kHz are ignored in environmental control.

The audible sound spectrum is divided into octave bands. An octave band is the frequency interval between a determined frequency and the double of the same frequency. The analysis of the octave bands requires a set of octave filters that can be incorporated into the sound level meter. Hearing is most sensitive in the frequency range from 1 to 5 kHz. To compensate the dependence of sensitivity to the frequency, the sound level meter incorporates electronic pondering filters that correspond to the answer of hearing. Two main filters A and C have been established and the more important is filter A. There is a general agreement that noise from traffic, the industrial sector and the communities can be measured suitably using this filter (Harris et al., 1995; Beranek, 1971).

4.2 Sound level meters

4.2.1 Type NL-05

For the measurement of environmental noise levels the integrating sound level meter type NL-05 was used. It is a small piece of equipment for easy handling, manufactured in Tokyo Japan for Higashimotomachi, Kokubunji, and distributed world wide by RION Co., Ltd. The equipment is designed to measure sound parameters in different environments using Quantifier Notation according to International Standard and JIS (excerpts from ISO 1996, 3891, IEC Pub. 804 JIS Z8202, 8731). The sound level meter allows not only conventional sound level measurements, but also incorporates processing functions, which make it possible to determine L_p (instantaneous sound pressure level) L_{eq} (equivalent continuous sound pressure level), *LE* (sound exposure level) and L_{max} (maximum sound pressure level).

The equipment calculates the L_{eq} for different measurement times, such as 10 seconds, 1, 5, 10, 15, and 30 minutes, 1, 8 and 24 hours. Once the calculation has been completed the data is automatically stored in the memory of the unit. Stored data can be called up on the display to be used for noise analysis. Before starting a measurement, the sound meter is calibrated using an electrical calibrating method; here, one need only press the *cal* button to activate calibration mode and the indication "Cal 94.0 dB" appears on the display. The controls and functions and operation processing can be seen in the instruction manual (Rion Co., Ltd., 1996).

4.2.2 Type B & K 2218

The B&K 2218 is an analog sound level meter with a wide dynamic range and an integrating sound level meter or L_{eq} meter with digital readout. It is used to obtain all conventional sound level meter values, plus a single number description of traffic noise, community noise, industrial noise (ISO noise dose), as well as noise emission of cyclical machines. It can, in addition, compute the *SEL* value for characterizing single events. The 2218-meter is also of great benefit on the type of fluctuating signal where the dB(A) "slow" reading is not stable. Both the integrated sound level and the elapsed time over which the integration takes place can be displayed. The integration time may be pre-selected. The 2218-meter also functions as an impulse precision sound level meter with peak hold facility, and has optional frequency analysis and tape recording capabilities.

The main uses of this equipment are determination of L_{eq} for assessment of risk of hearing loss or noise annoyance, measurement of cyclical machine noise, short duration noise dose measurements, investigation of noise dose distribution versus locality and time noise and vibration measurements and analyses. Before starting a measurement the sound meter should be calibrated using the electrical calibrating method and acoustic calibration method. The controls and functions and operation processing can be seen in the instruction manual (Brüel & Kjaer, 1999).

5. NOISE PROPAGATION BEHAVIOUR AT THE NESJAVELLIR FIELD

5.1 Selected noise sources

Three sites located at the Nesjavellir geothermal field were selected as noise sources. These are wells NV-16, NV-21 and NV-22, all operating with the use of the equipment silencers. Measurements of the equivalent continuous sound pressure level (L_{eq}) data were carried out with the silencer equipment used as the sound sources. The sites can be described as follows:

- The first site is at the NV-16 geothermal well located 250 m to the northeast of the power plant. The well produces a *two-phase fluid* of 13.1 kg/s, of which 7.6 kg/s is steam and the rest water, which together are discharged to the atmosphere through the silencer equipment.

- The second site is the NV-21 geothermal well located approximately 1,500 m to the west of the power plant. The well produces a *two-phase fluid* of 15.6 kg/s. The steam flow is 13.2 kg/s but the rest, 2.4 kg/s, is water, which together are discharged to the atmosphere through silencer equipment.

- The third noise source is the NV-22 geothermal well, located 40 m to the east of the NV-21 geothermal well, and is approximately 1,500 m to the west of the power plant. The NV-22 well has a directional design and produces a *two-phase fluid* of 34 kg/s. A flow of 18.2 kg/s is steam and water is 15.8 kg/s, which together are discharged to the atmosphere through silencer equipment.

Figures 5 and 6 show the well sites, including elevation lines and types of ground surrounding the well sites.

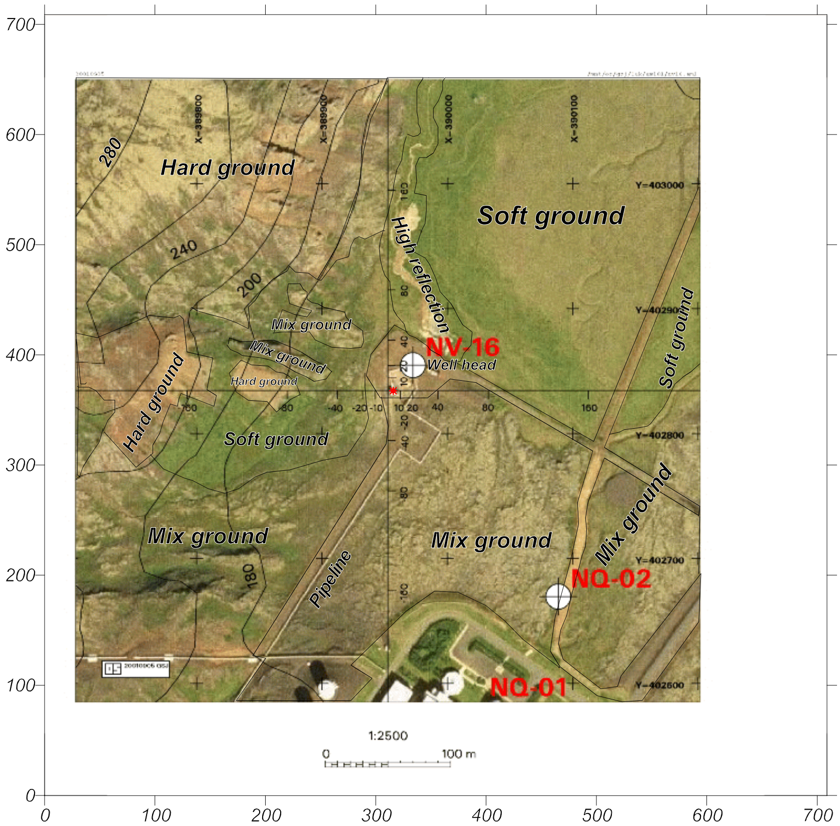

FIGURE 5: Well site NV-16 and the surroundings with elevation lines and ground types

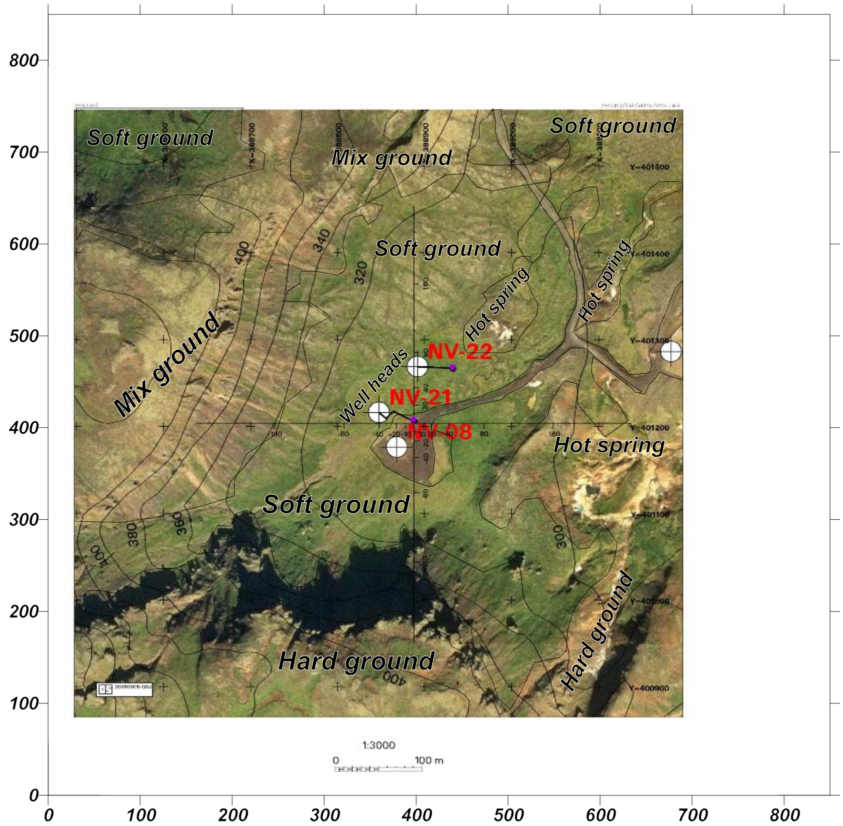

FIGURE 6: The well site for NV-21 and NV-22 and the surroundings with elevation lines and ground types

5.2 Mapping of noise propagation

The mapping of noise level propagation at different locations and different distances was carried out by measuring at 8 selected directions from the sound sources (silencer equipment of NV-16, NV-21 and NV-22). The spacing of the measurement points was such that each time the distance from the sound sources was doubled; with radii of 5, 10, 20, 40, and 80 m and a maximum one of 160 m. This means a maximum of 6 points in all eight directions. The measurement time at every point was 10 seconds. These measurements were carried out using the sound level meter NL-05. The distribution of the measured points is shown in Figures 7 and 8.

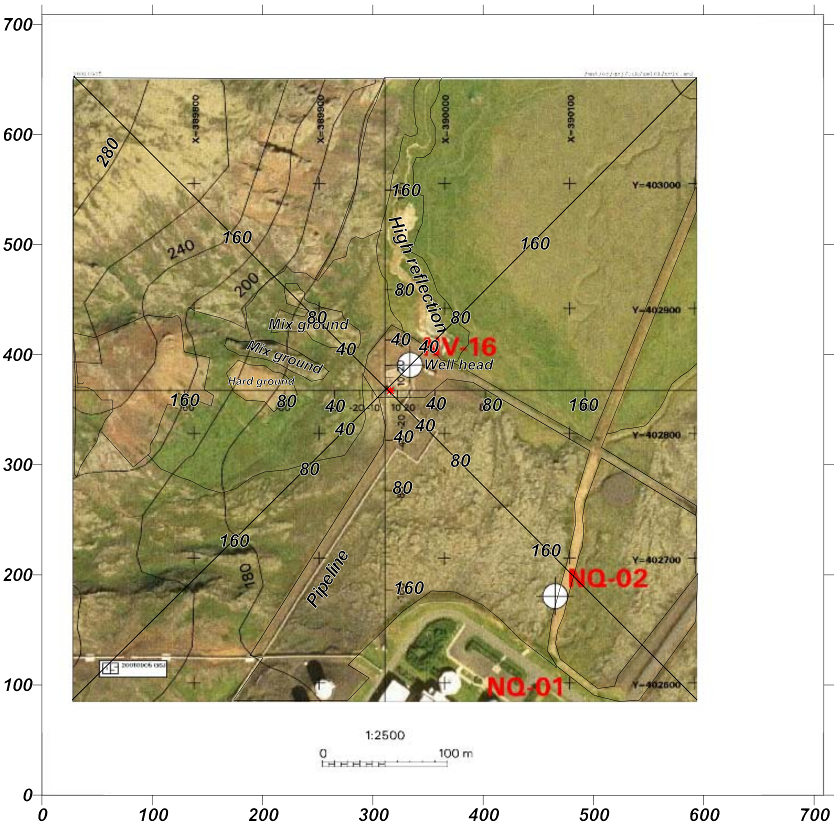

FIGURE 7: Measurement points around NV-16

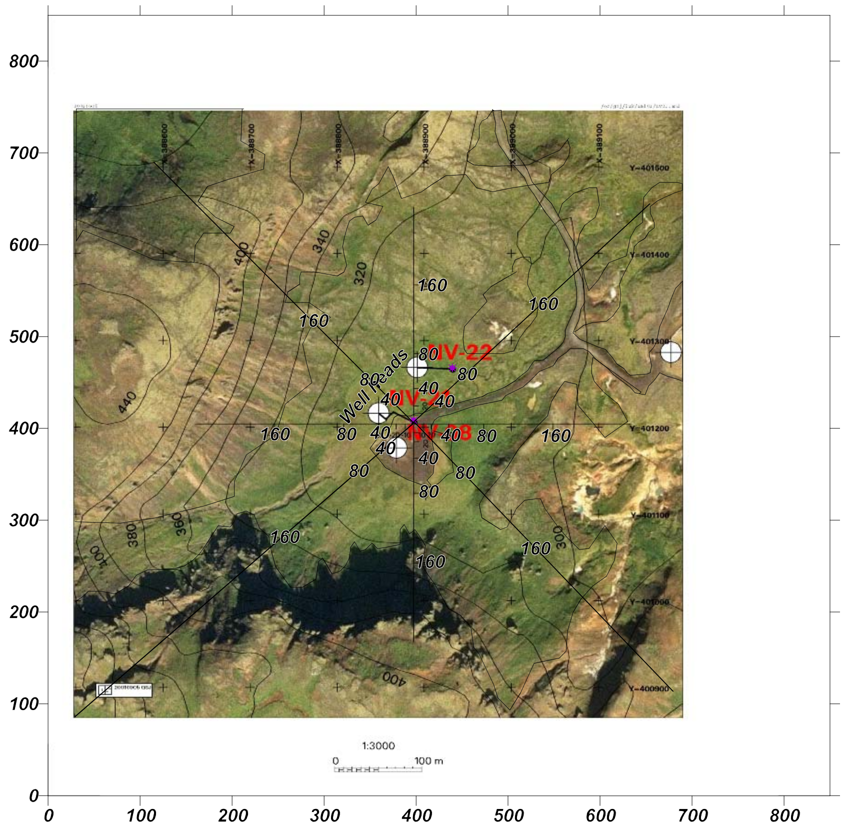

FIGURE 8: Measurement points around NV-21/NV-22

5.3 Measured noise levels

5.3.1 Well site NV-16

At the time (August 17, 2001) when the noise measurement was carried out, meteorological conditions at well site NV-16 were 80% relative humidity, a temperature of 12˚C and the wind direction was to the west with a wind velocity of 2 m/s (Data from Icelandic Meteorological Office, 2001).

In Figure 9 the measured noise levels at well site NV-16 are presented (noise data see Appendix II). The figure shows high-noise values close to the source (centre of figure) and low-noise values far from it (edges of figure). The variations in sound level are mainly due to variations in the elevation of the land (Figure 5). If the land is high and overlooking the source, the sound level is high. If the land is low and natural screens found which act as sound-shadow zones, the sound level is low. The type of ground has also some influence, as the sound is attenuated when propagating over soft ground.

The northwest part of the area shows values in the range 68-70 dB(A) even beyond the distance of 160 m. These are the highest values obtained at this distance. This area is mainly composed of rocks and overlooking the source. As the rocky ground has a high reflection, this ground type can be classified as hard ground (Figure 5), which has low-noise absorption and high-noise reflection (Harris et al., 1995). Therefore, the noise propagation is less dampened in this part. Towards other directions, south, east and west of well site NV-16 and at distances of 160 m from the silencer equipment, low-noise values, in the range 58-62 dB(A), are recorded as seen at the edges of Figure 9. Here the ground type is composed of land with some small vegetation and volcanic lava with high porosity (see Figure 5), which can be classified as soft ground (Harris et al., 1995) with high-noise absorption. Hence, in these areas the noise propagation is low and the natural attenuation of noise high (Stephens and Saenz, 1996).

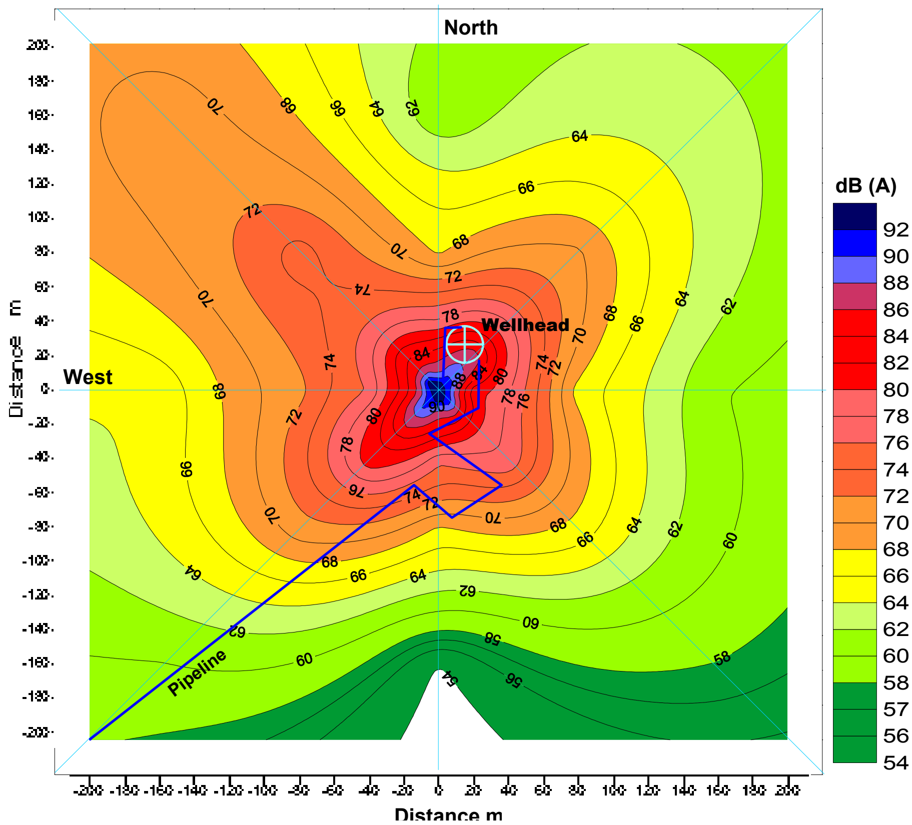

FIGURE 9: Measured noise levels around well site NV-16

5.3.2 Well sites NV-21 and NV-22

At the time (August 18, 2001) when the noise measurement was carried out, the meteorological conditions at well sites NV-21/NV-22 were 80% relative humidity, the temperature was 10ºC and the wind direction was to the west with the wind velocity 4 m/s (Data from Icelandic Meteorological Office, 2001).

Figure 10 presents noise levels measured at the well sites (noise data see Appendix III). Generally, Figure 10 shows high-noise values close to the sources (centre of figure) and low-noise values far from the sources (edges of figure). At the edges, about 160 m from the sources, Figure 10 shows the highest values towards south, in the range 88-92 dB(A). This increment in noise levels is due to this part being located at a high elevation 400 m a.s.l. with regard to the sound sources (310 m a.s.l.) (see Figure 6). This high zone is mainly composed of bare rocks. As bare rock ground has a high reflection, this ground type can be classified as hard ground with low-noise absorption (Stephens and Saenz, 1996). This south part is really a cliff, which constitutes a barrier that produces high-noise reflection between the cliff and the noise sources. For this reason, the noise reflection is increased, such as is shown in Figure 10. Also the chart shows an increment of noise levels to the southeast due to the reflection effect produced from the hill.

To the east, northeast, and north parts of the well sites, the measured values are in the range 82-86 dB(A). Although the ground here has vegetation with some noise absorption it also has a high noise reflection effect produced by hot water located in these areas. Generally, water has a high noise reflection, and for this reason the noise propagation is increased. The lowest noise values at distances up to 160 m, from the well sites are in the range 76-78 dB(A) and are observed to the northwest, west and southwest. This area has ground type constituting of volcanic lava with small vegetation that can be considered soft ground which presents some noise absorption. Hence, the natural attenuation of noise is increased.

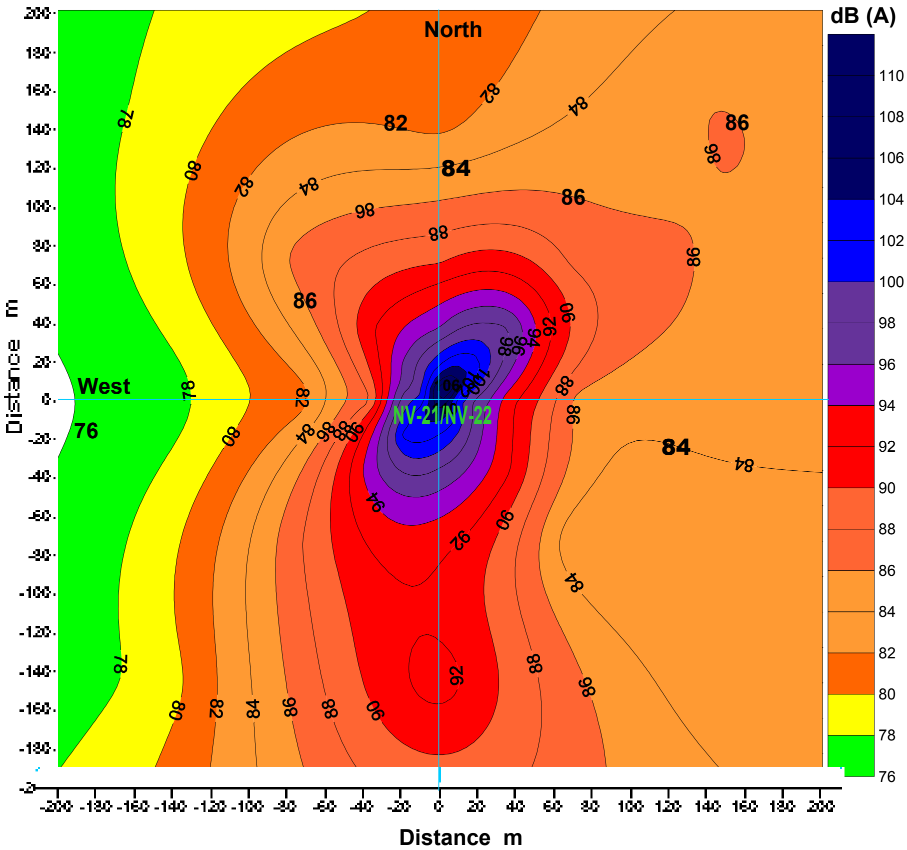

FIGURE 10: Measured noise levels at well sites NV-21/22

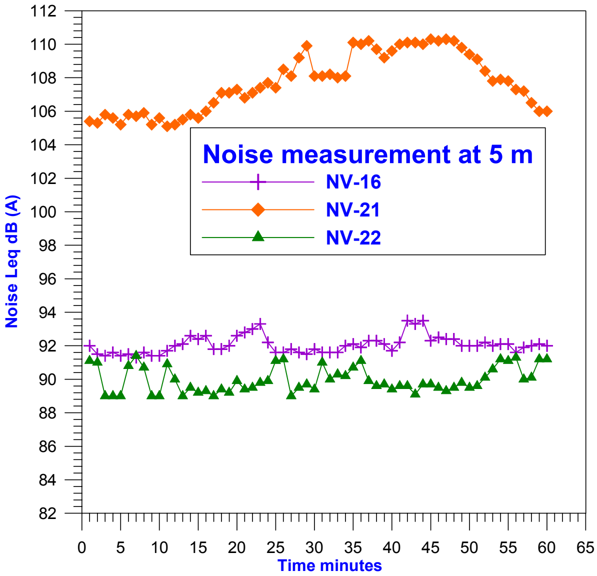

FIGURE 11: Noise variation over time, dB(A), at a distance of 5 m from the sources

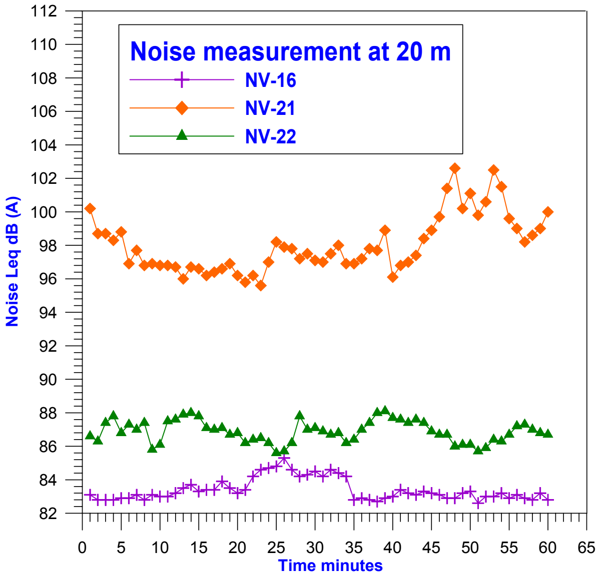

FIGURE 12: Noise variation over time, dB(A), at a distance of 20 m from the sources

5.4 Noise level variation with time

For these noise measurements the sound meter NL-05 was used, and measurements were carried out according to the following procedures. At each noise source, one direction was selected and for this direction 2 points were selected at distances of 5 and 20 m. The sound level was measured with a measurement time of 1 minute over 60 minutes, continuous at each point, until complete 2 hours of monitoring at each noise source were recorded. The results are presented in Figures 11 and 12 (see also Appendix IV).

The noise levels measured at 5 m distance from NV-16 and NV-22 well sites (Figure 11) show a variation of approximately 3 dB(A) over time during the 60 minutes measured at each source. The borehole NV-21 presents a different behaviour and the noise levels have a variation of 5 dB(A), during the 60 minutes of continuous measurement. For the noise values at 20 m distance (Figure 12), NV-16 and NV-22 show again a variation of approximately 3 dB(A), but for well NV-21 the variation is approximately 8 dB(A). These results may reflect that thermodynamic conditions at the boreholes are not stable (Table in Appendix V), but vary over time, leading to variations of the noise levels. Also, meteorological conditions like the wind present variations with time for sound propagation.

The high noise levels measured at NV-21 compared to the other wells are because this well has a higher percentage of steam flow rate than the other. The steam flow rate is always associated with high velocities of flow and this phenomenon increases the noise levels. The noise levels measured 20 m from well NV-22 are higher than at NV-16 due to the added influence from well NV-21, which is located only 40 m from NV-22.

5.5 Characterization of the frequency spectrum emitted by the noise sources

To characterize the frequency spectrum of the sound emitted by the silencer equipment at the NV-16, NV-21 and NV-22 well sites, sound meter type *B&K 2218* was used, and the noise was measured at distances of 5 m and 20 m from the sources to one direction. The noise was measured at different frequencies with a measurement time of 30 seconds. The frequency bands used were the centre octave band 31.5, 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz, as human hearing is most sensitive in this frequency range. The results of the measured frequencies at 20 m are shown in Figures 13 and 14 (after A-weighting). From

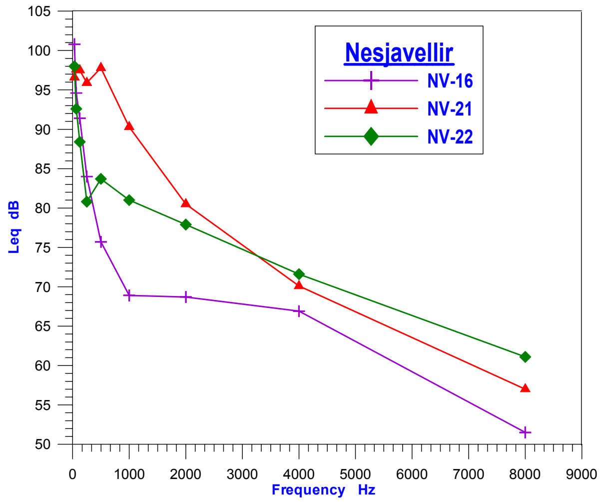

FIGURE 13: Measured octave levels at different well sites, in dB

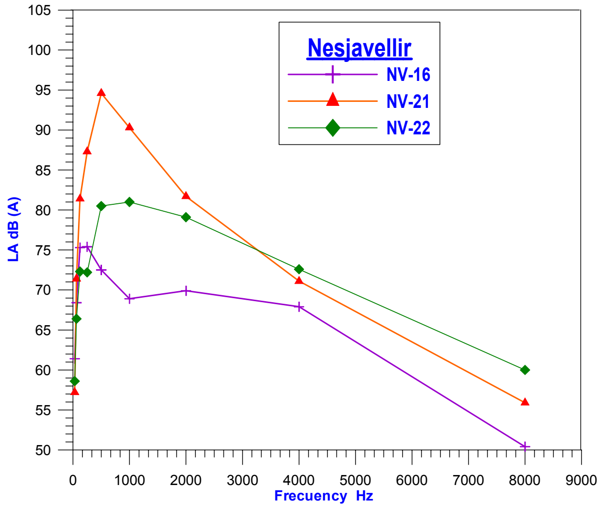

FIGURE 14: Measured octave levels at different well sites after A-weighting, in dB

the figures it can be seen that there are high noise values at the low frequencies from 31.5 to 1000 Hz, at all the noise sources. This indicates that the flow types produced by wells NV-16, NV-21 and NV-22 emit a noise with characteristics of low frequency when discharged to the atmosphere (see noise data in Appendix VI).

The noise levels were calculated from the sound power levels measured at different frequencies at 5 m distance from the silencer equipment of NV-16, NV-21 and NV-22. To calculate the sound power level, L_w, the following equation was used:

$$L_W = L_p + 20\log r + 11 \tag{9}$$

where L_p = Sound pressure level measured at 5 m at different frequencies (dB);
r = Distance form the source (m)

To calculate the noise levels at distances of 10, 40, 80, and 160 m, the same basic equation was used, or

$$L_p = L_W - 20\log r - 11$$

Equation 9 is used to analyse spherical noise propagation outdoors, and it can be applied when a source radiates noise uniformly in all directions.

Figures 15, 16 and 17 show the noise levels at different frequencies over distance. Most important in these figures is to observe the tendencies of the frequency curves over distance. The noise emissions for the low frequencies 31.5 and 250 Hz are high and, therefore, the noise needs longer distances than 160 m to be reduced to acceptable values. On the contrary, the frequency curve of 2000 Hz shows lower noise values and therefore smaller distances are needed for reduction of these noise values.

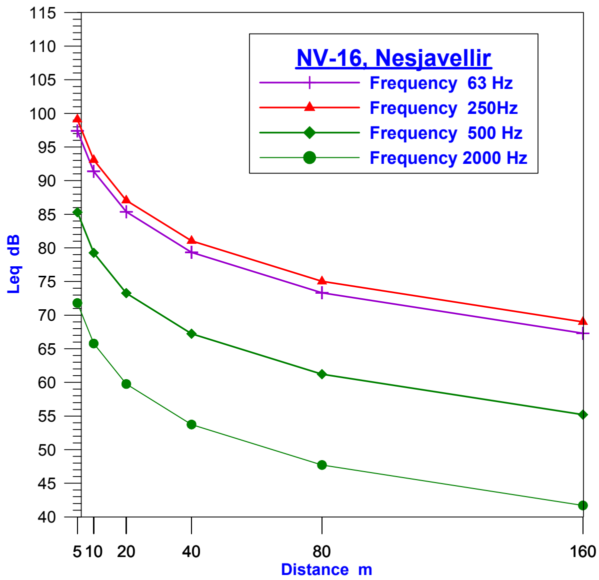

FIGURE 15: Measured octave levels at different distances at well site NV-16

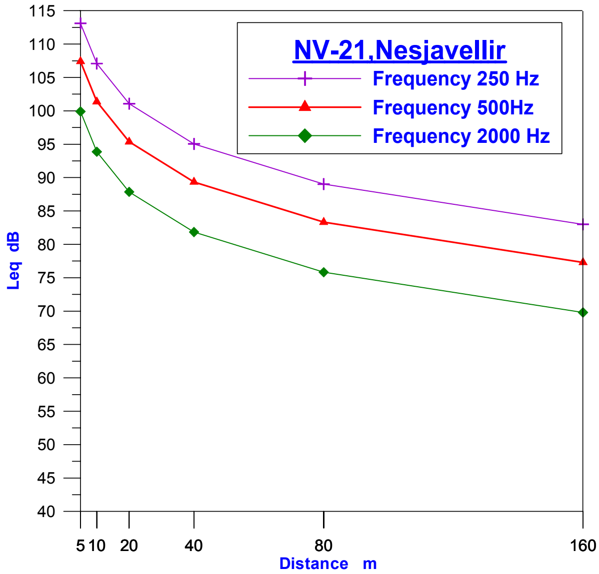

FIGURE 16: Measured octave levels at different distances at well site NV-21

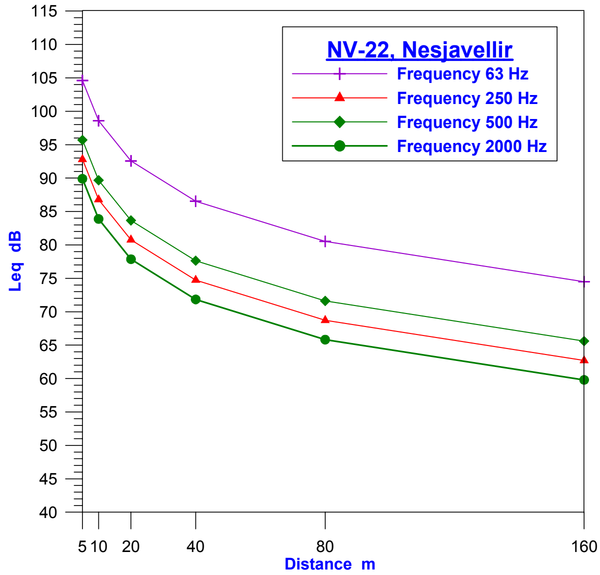

FIGURE 17: Measured octave levels at different distances at well site NV-22

6. CALCULATION AND PREDICTION OF SOUND LEVELS WITH SOUND PLAN SOFTWARE

6.1 The basic structure of Sound Plan

The Sound Plan software consists of a set of individual programs and dynamic link libraries that cooperate to make up a suitable tool to calculate and predict the noise levels emitted from traffic and industrial sources and the influence upon a receiver. The model data are generated in compliance with standards selected by the user, the results are presented in tabular or in graphical form. The main parts of the program are can be divided into: Geo-database, library, calculation, documentation and graphics. The Sound Plan software is the pivot point joining all sub programs. Aside from functioning as a switchboard, it starts a new project, opens older projects and presets numerous acoustical parameters that are valid only for the specific project (Braunstein and Berndt GmbH, 2001).

Permission to use this software was obtained from Línuhönnun Consultants Company, who have a license to use the program. They also kindly facilitated their offices, so that the required processing with the software was carried out inside the company. The use of the Sound Plan software was purely for academic purposes, but is an important part of the research project presented here.

6.2 Description of the use of Sound Plan for the well sites at the Nesjavellir geothermal field

The Sound Plan software was first used to carry out the calculation of the noise levels produced by the silencer equipments of well sites NV-16, NV-21 and NV-22 at the Nesjavellir geothermal field and to estimate the noise propagation at these well sites. To use the software the procedures were the following:

First input files were created to calculate the noise levels at each one of the sources (silencer equipment), all files were stored in a big file called *Situation* file, which was named *Noise propagation at Nesjavellir*, after which the following input files were created:

i *Elevation line*: In this file were stored the files related to the topographic map of the area, composed of elevation contour lines and the coordinates at Nesjavellir geothermal field (Figures 5 and 6). These files were created first with the AutoCAD program and were later imported to Sound Plan to create the *elevation line* file, which is a base data later used in the calculation of noise levels.

ii *Ground type*: In this file was stored the information relating to ground types existing at well sites NV-16, NV-21 and NV-22 (Figures 5 and 6). The ground types were classified as soft ground (ground composed of land with vegetation), mixed ground (ground composed of land with vegetation, volcanic lava and rocks) and hard ground, which is constituted mainly of rocks. Each one of these ground types was assigned a value corresponding to noise absorption, so the soft ground was assigned the value of 1 (100% absorption), the mixed ground was assigned 0.5 (50% absorption) and the hard ground 0 (0% of absorption), as is recommended by the Sound Plan manual.

iii *Road file*: In this file were characterized the existing roads around the NV-16, NV-21 and NV-22 well sites. They were also classified as mixed ground and assigned a value of 0.5 (Figures 5 and 6).

iv *Water*: In this file were grouped the areas where hot water ponds are found around the well sites of NV-16, NV-21 and NV-22. They were also classified as areas with high values of noise reflection and assigned 0% noise absorption, see Figures 5 and 6.

v *Building*: In this file were grouped the wellhead houses NV-16, NV-21 and NV-22 and assigned values of 0% noise absorption.

vi *Barriers*: In this file were grouped the pipelines of NV-16, NV-21 and NV-22, and assigned values of 0% noise absorption.

vii *Sources*: In this file were grouped the silencer equipment of NV-16, NV-21 and NV-22.

viii *Noise emission*: These files were created in the file *sources* of each geothermal well.

ix *Calculation* file. When all files had been created, the next step was to calculate the noise level propagation for each noise source (silencer equipment). For this, it was necessary to create the *calculation* file, containing the results of the calculated noise levels.

In the *noise emission* file, the following parameters were set:

- *Day histogram,* was set at 100% operation time of silencer equipment.
- *Values,* were set as the sound power levels calculated from measured noise values at different frequencies at 5 m distance from the silencer equipments, see Table 3.
- *Comments*, was set as descriptive information about the noise measurements at NV-16, NV-21 and NV-22 well sites.
- *Group*, referred to the corresponding noise emission files.
- *Directivity*, was not set to a specific value so the noise propagation is given as equal in all directions.

TABLE 3: Measured noise values at different frequencies for wells NV-16, NV-21, NV-22

Frequency type (Hz)	NV-16 Sound power level (dB)	NV-21 Sound power level (dB)	NV-22 Sound power level (dB)
31.5	134.0	130.5	135.0
63	122.4	130.5	129.6
125	122.1	129.3	125.4
250	124.1	138.1	117.8
500	110.3	132.4	120.7
1000	101.2	133.9	118.0
2000	96.8	124.9	114.9
4000	91.3	114.8	108.6
8000	74.4	107.8	98.1

It is important to mention that every time a file is created, it needs to be saved immediately on a *situation* file, which was created at the beginning. This *situation* file converts all files created from a temporary file to a permanent file and so can be used later for other calculations.

6.3 Calculation of noise levels around well site NV-16

6.3.1 Comparison between measured and calculated noise around well site NV-16

Table 4 shows a comparison of noise values at well site NV-16, between measured noise and calculated noise using Sound Plan. The same conditions as for the actual measurements were chosen for calculation of noise levels using Sound Plan software. This meant setting the meteorological conditions to 80% relative humidity, and the temperature at 12˚C. The columns for measured and calculated noise show the ranges of noise values at each distance, taking into consideration that the noise was measured in different directions for the same distance; therefore, the noise levels are variable at each distance. The last column shows the resulting mean difference between the mean measured noise and mean calculated noise values using Sound Plan for the various distances; and it can also be seen that the average mean difference is approximately ± 3.5 dB(A). This difference can be due to various reasons such as:

- The noise values are point values, measured for only 10 seconds at each point, and therefore not average values measured over a long time, for example for 24 hours as is recommended.
- Noise values measured over at least 24 continuous hours are more representative than noise values only measured for 10 seconds, as meteorological conditions can change from one hour to the next.
- Likewise the flow rate produced by NV-16 is not constant, and the thermodynamic conditions from borehole NV-16 change with time.
- Another important aspect is that the Sound Plan software does not consider all meteorological conditions. The input file only considers the temperature and the relative humidity, but does not include wind conditions.

All these aspects can affect the precision of the results, leading to the average mean difference of ± 3.5 dB(A). However, these results can not be considered bad; on the contrary, they should be considered good as the difference is small and acceptable.

The calculated values from the software can clearly be considered a good prediction of noise propagation behaviour from the sound source to the area around well site NV-16. They should allow prediction of noise propagation behaviour when modifying environmental conditions around well site NV-16, such as ground type, topography and or by inserting different kinds of sound barriers at different distances from the silencer equipment of NV-16.

TABLE 4: Measured and calculated (by Sound Plan) noise values at well site NV-16

Distance (m)	**Measured noise (dB(A))**	**Calculated noise using Sound Plan (dB(A))**	**Difference (dB(A))**	**Mean measured noise value (dB(A))**	**Mean calculated noise value (dB(A))**	**Mean difference (dB(A))**
5	91 - 94	88 - 94	3 - 0	92.5	91	1.5
10	86 - 90	82 - 88	4 - 2	88	85	3
20	81 - 88	79 - 82	2 - 6	84.5	80.5	4
40	76 - 81	70 - 79	6 - 2	78.5	74.5	4
80	67 - 75	64 - 70	3 - 5	71	67	4
160	54 - 71	52 - 64	2 - 7	62.5	58	4.5
Average mean difference						**± 3.5**

Figure 18 shows the distribution of the calculated noise around well site NV-16 using Sound Plan. It shows a noise propagation behaviour similar to the one presented before in Figure 9, which was based on the measured noise values around well site NV-16. The area close to the sound source (centre of figure)

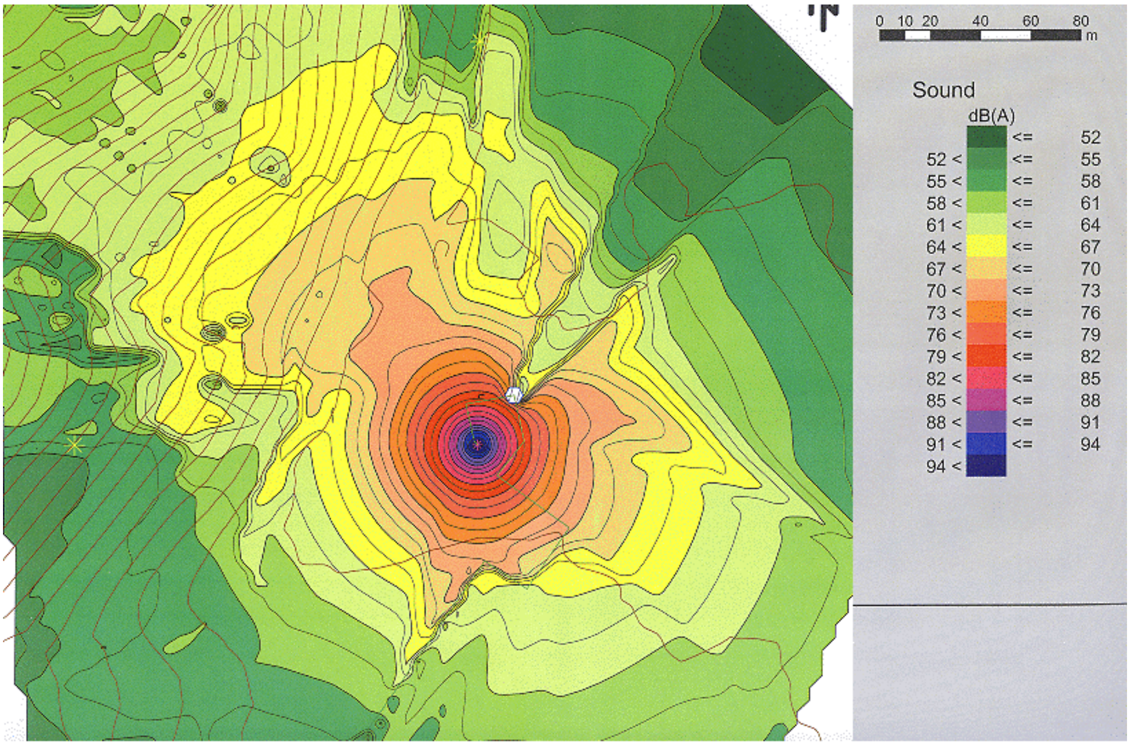

FIGURE 18: Calculated noise levels at well site NV-16 by Sound Plan

has high noise values and low noise values are seen for the area far from the source (edges of figure). Noise values between 64 and 70 dB(A) can be seen towards northwest of the well site NV-16, extending to distances of 80-160 m. These values are the highest obtained at this distance. This effect is because of the rising elevation of the land toward northwest from well site NV-16 and its surface being mainly of rocks, which have high noise reflection. Therefore, the noise is highest in this part of the area around NV-16. In other part the ground is lower and softer with more noise absorption, such as was indicated in Figure 9. In Figure 18 a screening effect of noise produced by the wellhead house and the pipeline can also be seen. The noise screening effect decreases at increased distances.

6.3.2 Noise level calculations modifying the ground type

In order to assess the effect of the ground type, all ground types around well site NV-16 were changed to soft ground and with these new conditions noise levels were recalculated. Figure 19 shows the noise propagation for the modified ground conditions. The reflection effect of noise in the area northwest of well site NV-16, as seen in Figure 18, has mostly disappeared and the noise propagation is reduced by the soft ground, which has high absorption of noise and constitutes a natural environment of noise attenuation. The noise levels obtained at a distance of 80 m are between 55 and 61 dB(A). Figure 19 demonstrates that soft ground has a good capacity for noise absorption and can be used as a natural source to attenuate noise levels.

The opposite situation is observed in Figure 20, which shows the noise propagation calculated around well site NV-16 with all ground types changed to hard ground. The reflection effect of noise has been extended to all the areas around the well site within distances of 160 m and the noise values are between 64 and 67 dB(A). The hard ground produces a spherical noise propagation around the area of the well site, with the exception of the effect produced by the wellhead house, which reduces the noise levels behind it.

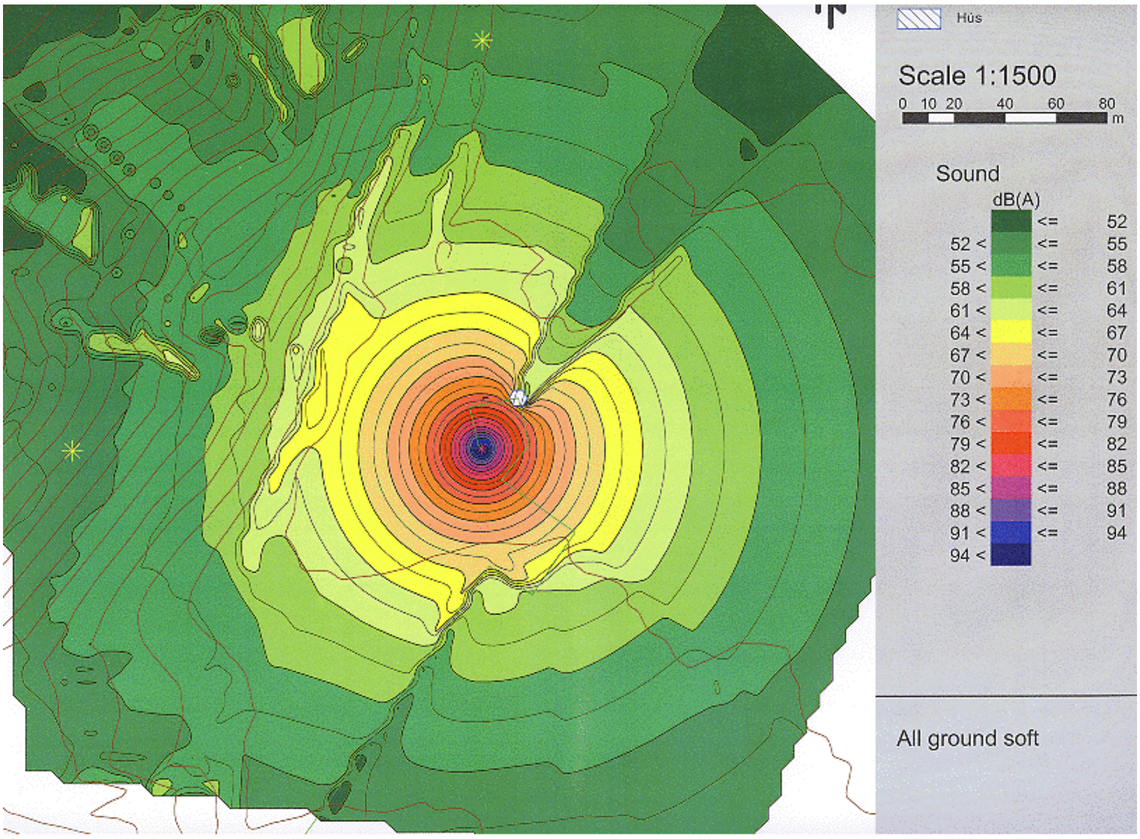

FIGURE 19: Calculated noise levels with all ground soft at well site NV-16

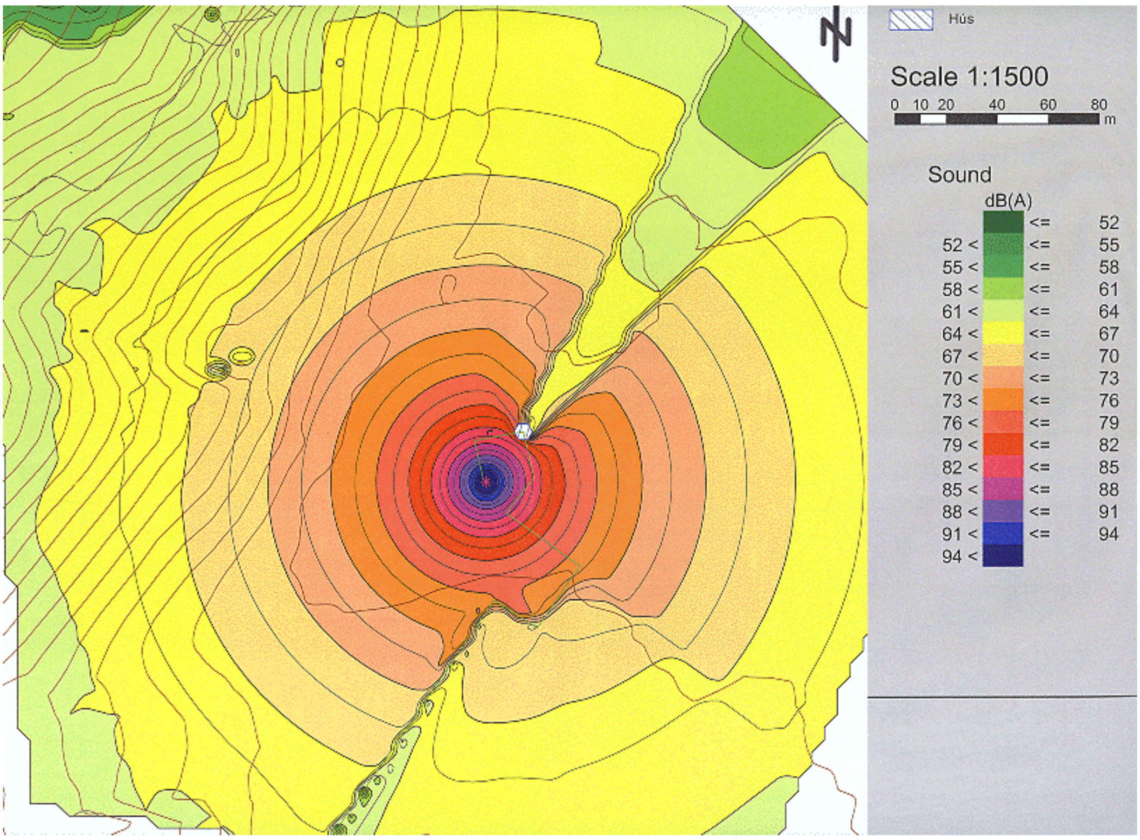

FIGURE 20: Calculated noise levels with all ground hard at well site NV-16

6.3.3 Noise level calculations inserting a sound barrier

A sound barrier was inserted at 1 m distance from the silencer equipment at NV-16. The barrier is a box, with 4 walls of 6 × 6 m and 0.1 m of thickness, and the construction material was considered to have high noise absorption. The calculated results of the effect of the barrier are observed in Figure 21, which shows a big reduction of noise propagation around well site NV-16. This figure indicates noise values of 61 dB(A) at a distance of 40 m and at 160 m the noise levels are between 52 and 55 dB(A). This result is very important as it shows that a barrier placed very close to the sound source, can effectively reduce the noise levels, when it is not possible modify the design of the noise source or when it would be too expensive to abandon communities living close to the well sites (Stephens and Saenz, 1996).

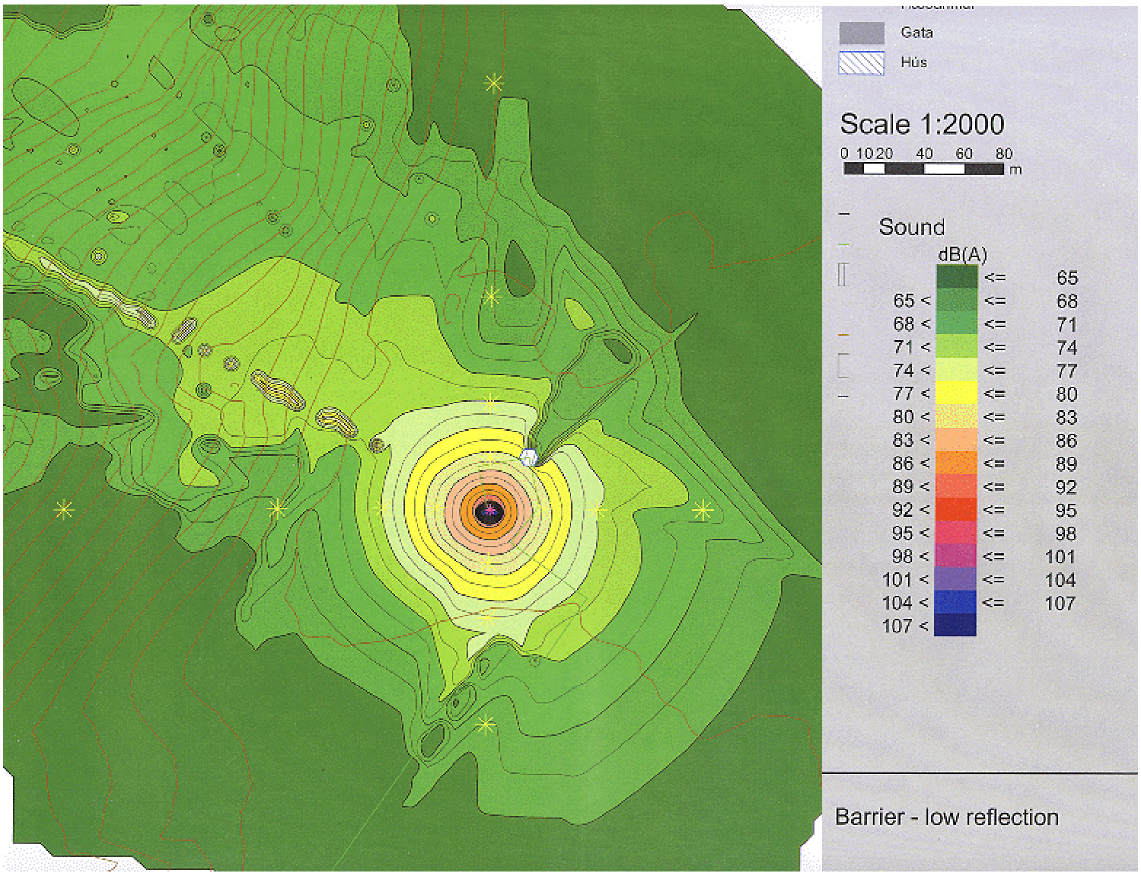

FIGURE 21: Noise levels with inserted barrier at silencer equipment of borehole NV-16

6.4 Calculation of noise levels around well site NV-21/NV-22

6.4.1 Comparison between measured and calculated noise around well site NV-21/NV-22

Table 5 shows the caomparison of measured noise values and noise values calculated using Sound Plan around well sites NV-21 and NV-22, similar as Table 4 did for NV-16. The calculation of noise levels was carried out setting meteorological conditions the same as during measurements, i.e. 80% relative humidity and the temperature at 10ºC. Again, the columns for measured and calculated noise do not show point values but value ranges for each distance, as the noise was measured for different directions at the same distance, and the noise levels are variable with regard to each direction. The last column shows the resulting mean difference, between the mean noise measured and the mean noise calculated using Sound Plan. The average of the mean difference is approximately ± 2 dB(A). The reasons for this difference were discussed in Section 6.3.1.

The resulting mean difference, ± 2 dB(A), can be considered good, being small and, thus, acceptable. Also the calculated values from Sound Plan clearly permit an assessment of the noise propagation behaviour from the source to the area around well sites NV-21 and NV-22, and also prediction of the noise propagation by modifying the environmental conditions around the well sites, for example ground type and topography and by inserting different types of barriers at different distances from the silencer equipment of NV-21 and NV-22.

TABLE 5: Measured and calculated noise values for well sites NV-21, NV-22

Distance (m)	Measured noise (dB(A))	Calculated noise using Sound Plan (dB(A))	Difference (dB(A))	Mean measured noise value (dB(A))	Mean calculated noise value (dB(A))	Mean difference (dB(A))
5	104 - 111	104 - 107	0 - 4	107.5	105.5	2
10	99 - 107	101 - 104	2 - 3	103	102.5	0.5
20	96 - 103	98 - 101	2 - 2	99.5	99.5	0
40	88 - 98	92 - 98	4 - 0	93	95	2
80	81 - 93	83 - 92	2 - 1	87	87.5	0.5
160	77 - 93	77 - 83	0 - 10	85	80	5
Average mean difference						**± 2**

Figure 22 presents the calculated noise using Sound Plan at well sites NV-21/NV-22. The noise emission is similar to the measured noise values around well sites NV-21/NV-22 seen in Figure 10. The figure shows high noise values, between 83 and 86 dB (A), at distances of 160 m south of the well sites. The higher noise values obtained here are due to the fact that here is a cliff composed mainly of bare rocks, which constitutes a barrier and, thus, a noise reflection effect is produced between the noise sources and the cliff. Other areas around the well sites have lower noise levels, as explained in Figure 10.

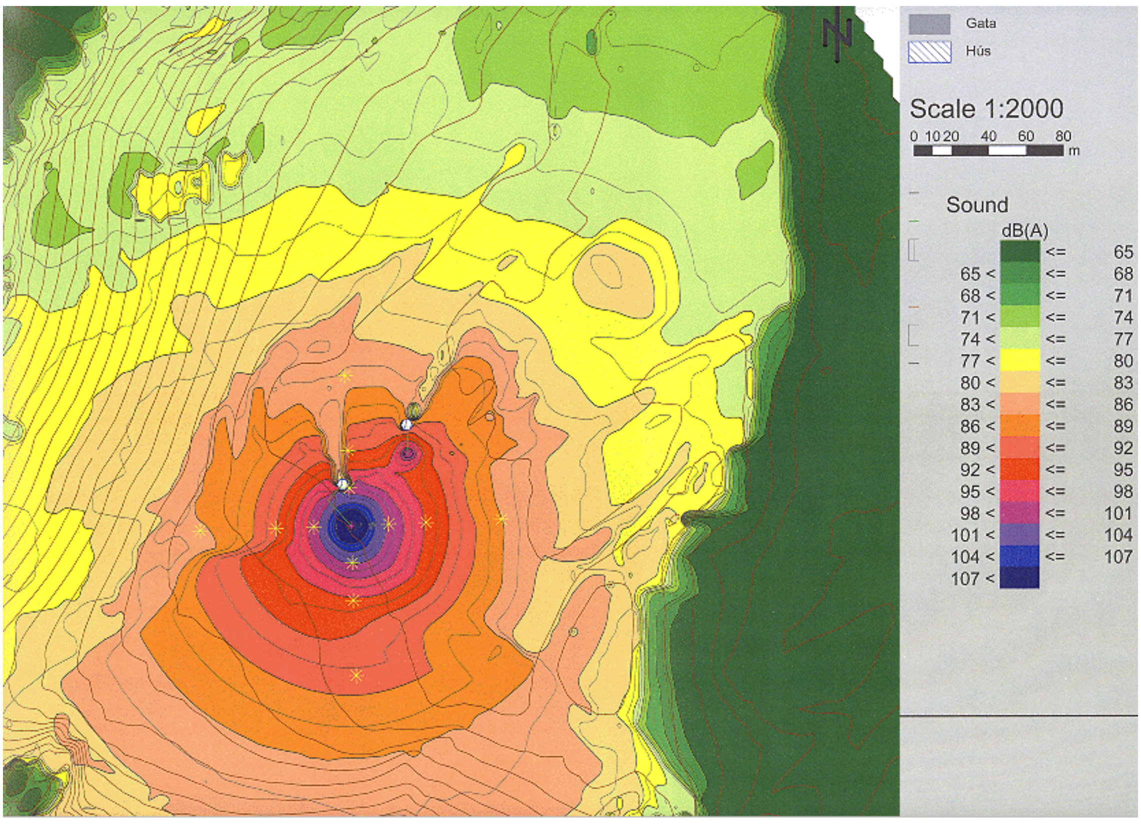

FIGURE 22: Calculated noise levels around well sites NV-21 and NV-22

6.4.2 Noise level calculations modifying the ground type

Figure 23 shows the calculation of noise propagation around well sites NV-21/NV-22, when all ground types at the well sites are modelled to be soft . The noise levels are lower, especially in the south, compared to those seen in Figure 22, as is to be expected. The values obtained at distances of 160 m in the southern part are in the range 77-80 dB(A), which is a reduction of 6 dB(A) compared to the natural conditions shown in Figure 22.

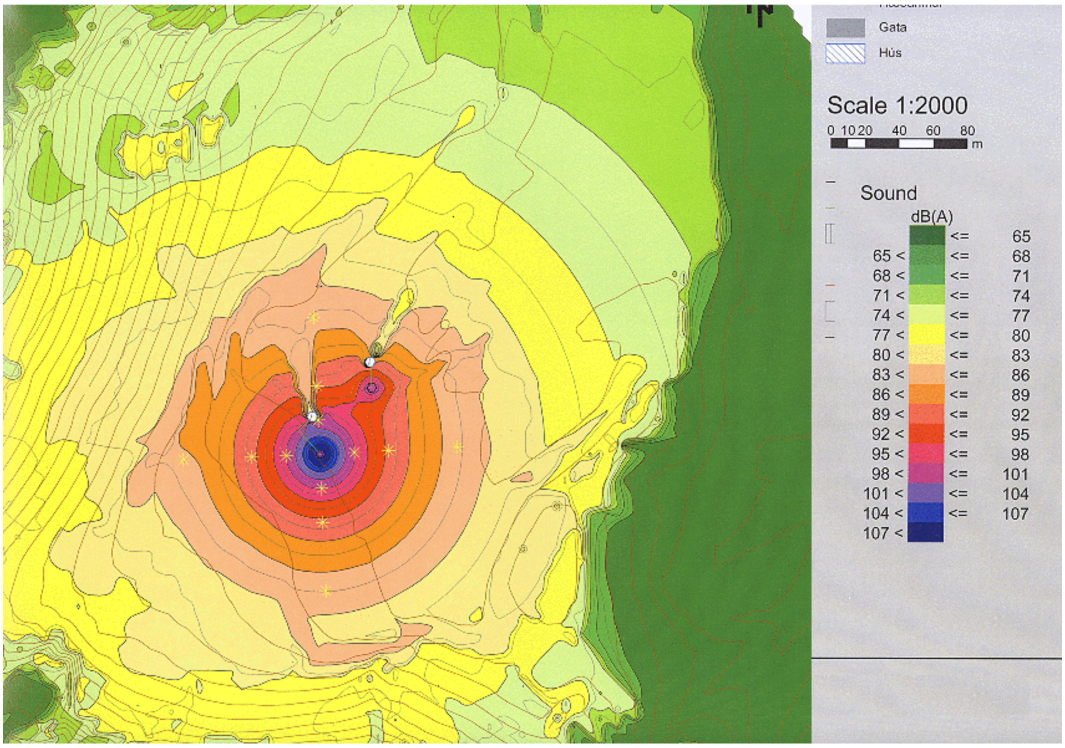

FIGURE 23: Calculated noise levels with all ground soft around well sites NV-21 and NV-22

A different situation can be seen in Figure 24, which shows the ground conditions modelled as hard ground around the well sites. Now the noise levels in other areas around the well sites have increased, from the range of 77-80 dB(A) shown in Figure 22 to 83-86 dB(A).

6.4.3 Noise level calculations inserting a sound barrier

The noise propagation obtained for the natural environment shown in Figure 22, is reduced when ground conditions are changed to soft ground such as was discussed above, and the noise levels can be reduced even further when a barrier is inserted to mitigate the noise.

The silencer equipment of borehole NV-21 was closed using a barrier with a box form placed at a distance of 1 m from the equipment; the size of the 4 walls used was 6 × 6 m and the thickness 0.1 m. Figure 25 shows the effect produced by the barrier. The noise values obtained 160 m south of the well sites are in the range 71-74 dB(A), a reduction of 12 dB(A) compared to values shown in Figure 23. The values in the range 71-74 dB(A) can still be considered high, and the reason is that a barrier was only placed close to the silencer equipment of borehole NV-21. The silencer equipment of the other borehole NV-22, also in operation, was not closed by a barrier.

Figure 26 presents a different effect produced by a barrier. In this case the barrier was placed 40 m to the southwest of the silencer equipment of borehole NV-21. The barrier has one wall 40 × 6 m and another 80 × 6 m and the thickness 0.1.

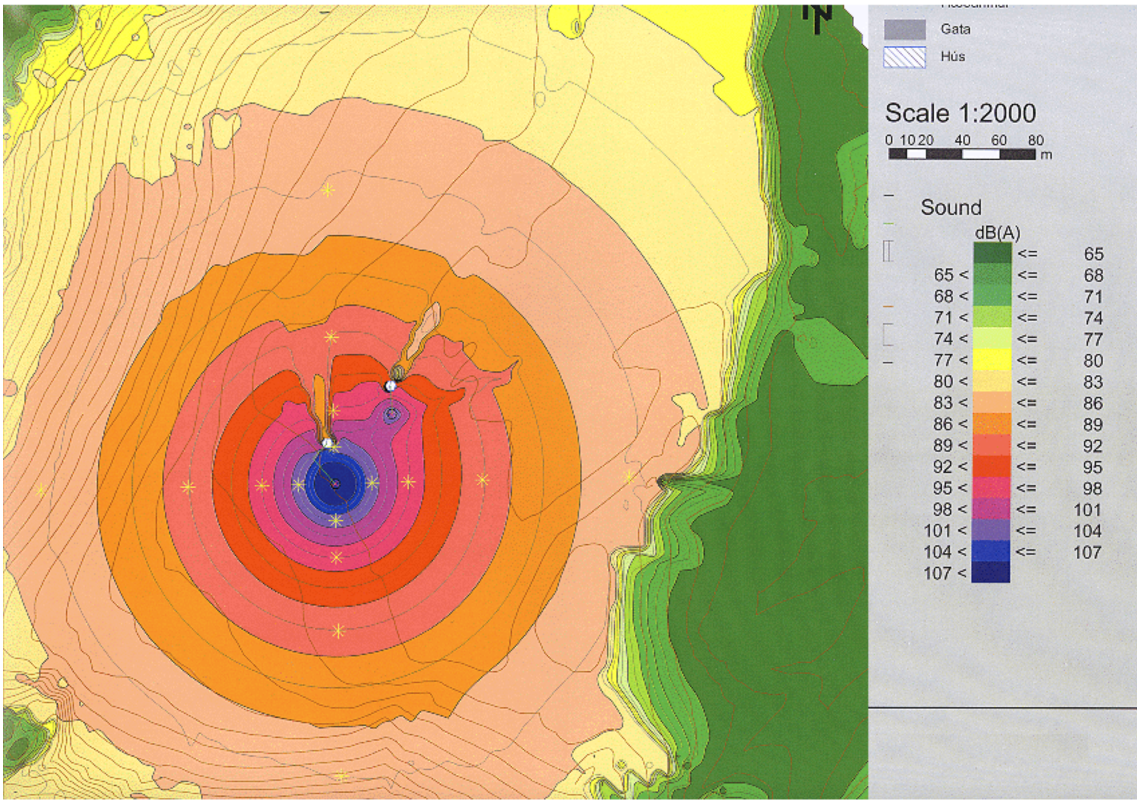

FIGURE 24: Calculated noise levels with all ground hard
around the well sites NV-21 and NV-22

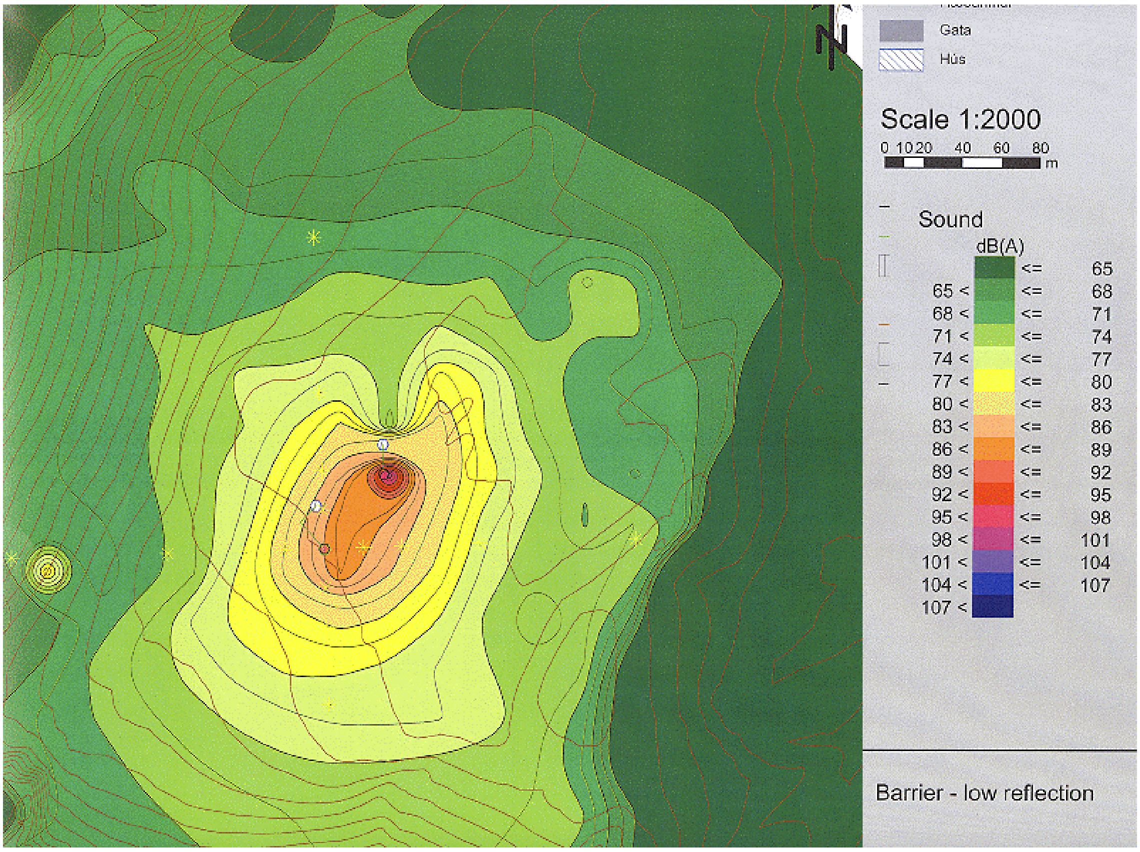

FIGURE 25: Calculated noise levels with inserted barrier
at silencer equipment of well NV-21

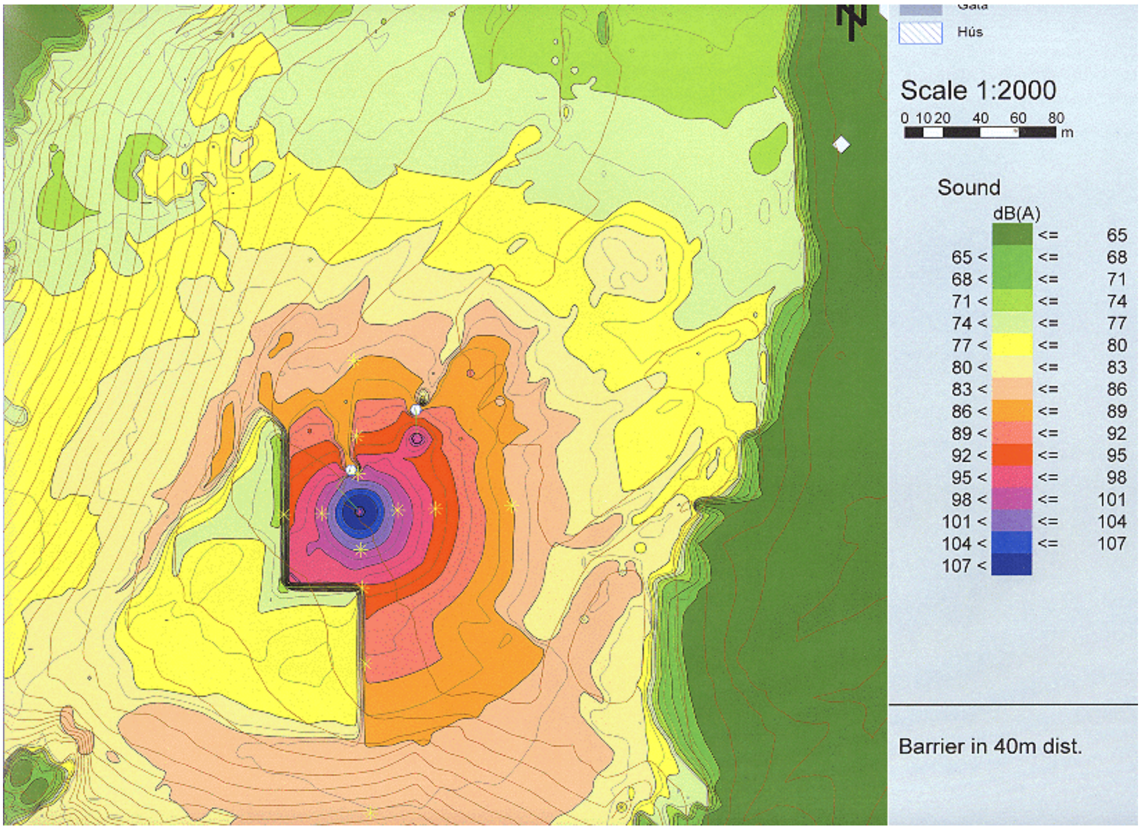

FIGURE 26: Calculated noise levels with a barrier inserted at 40 m distance to the southwest from the silencer equipment of borehole NV-21

The noise values obtained indicate a noise reduction of 15 dB(A) behind the barrier. But at distances above 40 m from the barrier, the noise levels start to increase again, by 3 dB(A), and at a distance of 160 m the values are increased by 6 dB(A). The noise propagation behaviour seen in Figure 26 indicates that when a barrier is placed far from a source, the size of the barrier needs to increase, and the mitigation effect is not as efficient as up close to the source.

For a good mitigation effect to be produced by a barrier, the barrier has to be tight and made of heavy, sound-insulating material of approximately 20 kg/m^2. It must also be high and either placed close to the source or the receiver. It is also good if the surface of the barrier (in the direction of the source) has good sound absorption. If the barrier is reflective, the sound is reflected towards the source and the sound level on that side of the barrier increases when the barrier is built. A barrier is also more effective at a high frequency source than at a source with a dominating low frequency, as here. When the wavelength of the sound is equal to the height of the a barrier, the sound waves can go over the top of the barrier more easily and the sound reduction of the barrier is reduced (Maekawa and Lord, 1994; Beranek, 1971).

7. CONCLUSIONS AND RECOMMENDATIONS

1. With the elaboration of this research report it has been possible to recognise distinct environmental variables that affect noise propagation behaviour in geothermal fields. A suitable combination of these variables can help to attenuate, in natural form, noise impacts when it is too expensive to modify the design of noise sources in operation projects.
2. The scope of this study was focussed on noise sources located in outdoor environmental settings and sources located inside buildings were not included. The purpose was to study the attenuation forms of outdoor noise levels produced from a point source such as silencer equipment at well sites which might have communities living close by.

3. A similar study can also be applied to the drilling of boreholes where there are several simultaneously active noise sources. It can also be applied to all kinds of geothermal activities that emit noise and affect communities living close to the work areas.
4. No noise source emitting dominant high frequency noise was found in the Nesjavellir geothermal field.
5. The present report can be considered a preliminary stage in studying the noise propagation behaviour for geothermal projects. The obtained results and information can help to improve and develop environmental management aimed at low cost measures for the mitigation of environmental impacts.
6. Experimental testing of noise propagation is recommended, modifying environmental conditions such as ground type, and inserting acoustic barriers of different sizes and construction materials for the purpose of obtaining low noise values. These could later be applied to environmental measures for noise attenuation.
7. It would be advisable to carry out studies of noise propagation for different designs of silencer equipment using construction materials with high noise absorption, for the purpose of improving current designs and to obtain an equipment design that might be classified as ecological with low noise levels in accordance with environmental legislation.
8. Finally, it is recommended when carrying out noise measurements at test points to use a longer measuring time, about 24 hours, in order to obtain good representative noise values from the source.

ACKNOWLEDGMENTS

First, my deepest gratitude to God and Jesus Christ for giving my dear wife Sonia del Carmen de López, my dear daughter Yadid Eloany Lopez and myself the necessary support during my geothermal training for the six months in Iceland. I want to express my gratitude to the government of Iceland, United Nations University and Geotérmica Salvadoreña S. A. de C. V. for permitting me to attend the Geothermal Training Programme. Thanks to those who coordinate the programme, Dr. Ingvar B. Fridleifsson, director, Mr. Lúdvík S. Georgsson, deputy director and Mrs. Gudrún Bjarnadóttir, administrative assistant, for their efficient help and kindness during training.

Great thanks to Dr. Steindór Gudmundsson, my supervisor, for comments, ideas and patient revision of the draft of this report. Also I want to thank Dr. Halldór Ármannsson, for his unconditional support and Reykjavík Energy Co., especially Mr. Gestur Gíslason, for all the assistance given at Nesjavellir Power Plant. Likewise, I am very grateful to Línuhönnun Consulting Engineers Company, who kindly facilitated their offices, for processing part of this report. Finally, I would like to extend my gratitude to the environmental team from El Salvador and to all the people that collaborated in carrying out this research study.

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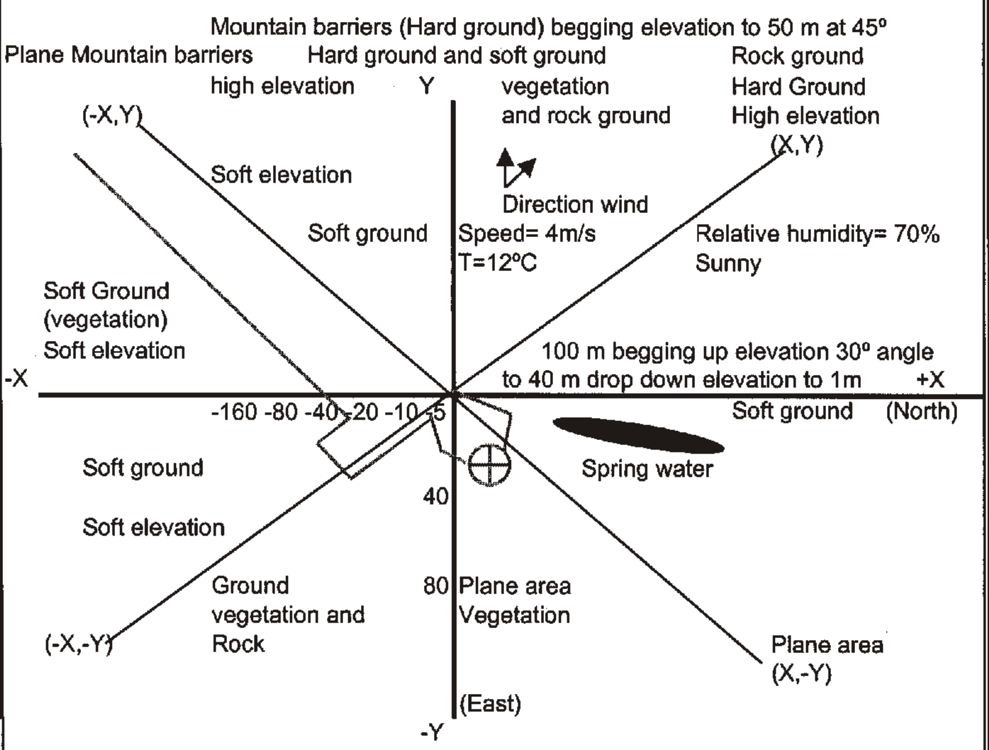
APPENDIX I: Metorological conditions at Nesjavellir 1999-2001

001 REYKJAVIK Meteorological station									
Station	Year	Month	Mean T°C	MmaxT°C	MminT°C	Relat.Hum.	Precipitation	MsurfAirpre	WindSpeed
1	1999	1	0.1	2.4	-2.1	77.8	78.4	992.9	6.2
1	1999	2	-1.3	2	-3.6	77.5	82.5	996.8	6.9
1	1999	3	-1	2.5	-3.6	70.2	20.5	1006.2	4.3
1	1999	4	2.8	6.5	-0.3	71	25.5	1013	5.1
1	1999	5	6.7	9.8	4.1	77.6	86.5	1007.9	6.2
1	1999	6	9	11.9	6.7	78.7	46.6	1008.1	5.9
1	1999	7	10.9	13.9	8.6	82.1	65.6	1009.7	4.4
1	1999	8	11.3	14.2	9.4	83.8	64.5	1013	4.4
1	1999	9	8.4	11.9	5.9	80	71.9	997.1	4.7
1	1999	10	5.6	8.1	3.5	78.4	114.5	1003.2	6
1	1999	11	2	4.9	-0.3	79.7	72.1	1002.8	6.1
1	1999	12	-1	1.9	-3.5	78.3	59	993.2	5.9
1	2000	1	0.7	3.1	-1.7	82.5	74.5	1004.8	5.9
1	2000	2	-1	2	-3.7	79.2	85	987.9	6.7
1	2000	3	0.6	3.5	-2.2	78.2	145.7	1006.8	7.5
1	2000	4	1.5	5	-1.9	65.5	27.6	1017.6	5.6
1	2000	5	6.5	9.6	3.9	74.8	47.8	1008.2	5.3
1	2000	6	9.4	12.7	6.6	73.6	61.6	1013.2	3.9
1	2000	7	11.5	14.5	9.5	84.9	41.1	1013.8	3.8
1	2000	8	10.7	13.9	8.6	84.3	70.7	1009.6	3.1
1	2000	9	8.7	12	6.2	78.1	87.2	1003.4	4.4
1	2000	10	4.8	7.4	2.7	78.6	103.6	992.6	3.8
1	2000	11	0.9	3.5	-1.2	73.2	10.1	1002.6	4
1	2000	12	0.1	2.7	-2	71.5	45.1	1004.3	3.3
1	2001	1	1	3.4	-1.2	77.3	78.2	1000.2	4.9
1	2001	2	-0.2	3.1	-3	74.5	80.8	1009.8	5.7
1	2001	3	0	3.5	-2.8	69.3	24.4	1006.1	3.7
1	2001	4	3.7	7.6	0.9	71.9	32	1008.8	4
1	2001	5	6.6	9.8	4.5	79.2	87.1	1012.9	4.2
1	2001	6	8.8	11.8	6.3	78.8	31.7	1014.2	3.6

APPENDIX II: Noise values collected around borehole NV-16 of Nesjavellir geothermal power plant

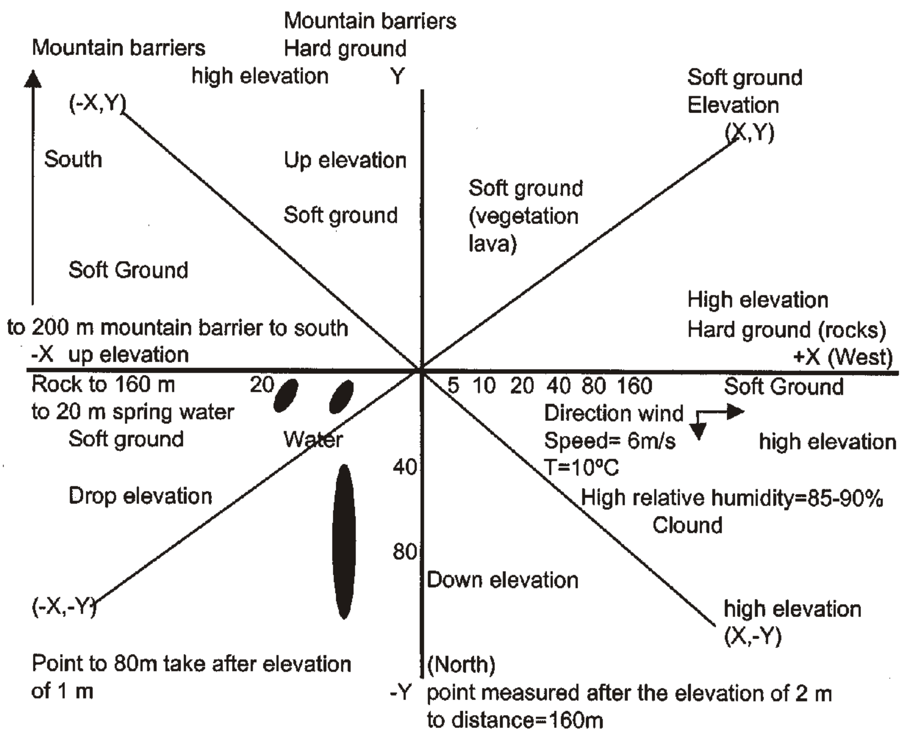
Distance X	Distance Y	Noise dB(A)
5	0	92.5
10	0	87.4
20	0	85.3
40	0	78.3
80	0	67.7
160	0	60.5
5	5	93.6
10	10	87
20	20	83.6
40	40	76
80	80	74.8
160	160	71.1
0	5	91.5
0	10	86.6
0	20	82.6
0	40	76.2
0	80	71.4
0	160	64.5
-5	5	91.4
-10	10	90.3
-20	20	86
-40	40	81
-80	80	70.9
-160	160	59.7
-5	0	93
-10	0	87.6
-20	0	84.1
-40	0	76.4
-80	0	67.4
-160	0	53.8
-5	-5	92
-10	-10	87.5
-20	-20	80.8
-40	-40	77.5
-80	-80	67.1
-160	-160	57.8
0	-5	91.3
0	-10	86.3
0	-20	80.6
0	-40	78.2
0	-80	67.1
0	-160	60.2
5	-5	92.1
10	-10	89.9
20	-20	87.6
40	-40	78
80	-80	70.3
160	-160	62.5



L_{eq} collected for 10 seconds for each direction and different distances, starting at 5 m and doubling the distances upto 160 m

APPENDIX III: Noise values collected around boreholes NV-21/22 of Nesjavellir geothermal power plant

Distance		Noise
X	Y	dB
5	0	104.4
10	0	100.4
20	0	99.2
40	0	87.6
80	0	81
160	0	76.8
5	5	105.5
10	10	103.6
20	20	102.5
40	40	95
80	80	87.8
160	160	78.7
0	5	106.3
0	10	104.5
0	20	101.9
0	40	97.7
0	80	92.6
0	160	93
-5	5	105.2
-10	10	101.8
-20	20	97.2
-40	40	92.2
-80	80	82
-160	160	83
-5	0	106
-10	0	101
-20	0	97.9
-40	0	92.8
-80	0	85.4
-160	0	85.5
-5	-5	110.9
-10	-10	106.8
-20	-20	103.2
-40	-40	98.1
-80	-80	87.2
-160	-160	86.1
0	-5	110.1
0	-10	106
0	-20	101.6
0	-40	96
0	-80	89.5
0	-160	81
5	-5	104
10	-10	99.3
20	-20	96.4
40	-40	91.6
80	-80	86.8
160	-160	78.6



L_{eq} collected for 10 seconds for each direction and different distances, starting at 5 m and doubling the distances upto 160 m

APPENDIX IV: Noise measurements with time

	NV-16		NV-21		NV-22	
	5 m	20 m	5 m	20 m	5 m	20 m
TIME	NOISE	NOISE	NOISE	NOISE	NOISE	NOISE
Minutes	dB (A)	dB (A)	dB (A)	dB (A)	dB (A)	dB (A)
1	92	83.1	105.4	100.2	91.1	86.6
2	91.5	82.8	105.3	98.7	91	86.3
3	91.4	82.8	105.8	98.7	89	87.4
4	91.6	82.8	105.6	98.3	89	87.8
5	91.4	82.9	105.2	98.8	89	86.8
6	91.5	82.9	105.8	96.9	90.8	87.3
7	91.3	83.1	105.7	97.7	91.4	87
8	91.6	82.8	105.9	96.8	90.7	87.4
9	91.4	83.1	105.2	96.9	89	85.8
10	91.4	83	105.6	96.8	89	86.1
11	91.7	83	105.1	96.8	90.9	87.5
12	92	83.2	105.2	96.7	90	87.6
13	92.1	83.5	105.5	96	89	87.9
14	92.6	83.7	105.8	96.7	89.5	88
15	92.4	83.3	105.6	96.6	89.2	87.8
16	92.6	83.4	106	96.2	89.3	87.1
17	91.8	83.4	106.5	96.4	89	87
18	91.8	83.9	107.1	96.6	89.4	87.1
19	92	83.5	107.1	96.9	89.2	86.7
20	92.6	83.2	107.3	96.2	89.9	86.8
21	92.8	83.4	106.8	95.8	89.4	86.2
22	93	84.2	107.1	96.2	89.5	86.4
23	93.3	84.6	107.4	95.6	89.8	86.5
24	92.2	84.7	107.7	97	89.9	86.2
25	91.6	84.8	107.4	98.2	91.1	85.6
26	91.6	85.3	108.5	97.9	91.2	85.7
27	91.8	84.6	108.1	97.8	89	86.2
28	91.6	84.2	109.2	97.2	89.5	87.8
29	91.5	84.3	109.9	97.5	89.7	87
30	91.8	84.5	108.1	97.1	89.4	87.1
31	91.6	84.2	108.1	97	91	86.9
32	91.6	84.6	108.2	97.5	90	86.7
33	91.6	84.4	108	98	90.3	86.8
34	92	84.2	108.1	96.9	90.2	86.2
35	92.1	82.8	110.1	96.9	90.7	86.4
36	91.9	82.9	110	97.2	91.1	87
37	92.3	82.8	110.2	97.8	89.9	87.4
38	92.3	82.7	109.7	97.7	89.6	88
39	92.1	82.9	109.2	98.9	89.7	88.1
40	91.7	83	109.6	96.1	89.4	87.7
41	92.2	83.4	110	96.8	89.6	87.6
42	93.5	83.2	110.1	97	89.6	87.4
43	93.3	83.1	110.1	97.4	89.1	87.6
44	93.5	83.3	110	98.4	89.7	87.4
45	92.3	83.2	110.3	98.9	89.7	86.9
46	92.5	83.1	110.2	99.7	89.5	86.7
47	92.4	82.9	110.3	101.4	89.3	86.7
48	92.4	82.9	110.2	102.6	89.5	86
49	92	83.2	109.8	100.2	89.8	86.1
50	92	83.3	109.4	101.1	89.5	86.1
51	92	82.6	109.1	99.8	89.6	85.7
52	92.2	83	108.4	100.6	90.1	85.9
53	92	83	107.8	102.5	90.6	86.4
54	92.1	83.2	107.9	101.5	91.2	86.3
55	92.1	82.9	107.8	99.6	91.1	86.7
56	91.6	83.1	107.3	99	91.3	87.2
57	91.9	82.9	107.2	98.2	90	87.3
58	92	82.8	106.5	98.6	90.1	87
59	92.1	83.2	106	99	91.2	86.8
60	92	82.8	106	100	91.2	86.7

APPENDIX V: Production conditions of boreholes NV-16, NV-21 and NV-22 with discharge to silencer equipment, discharge at 100ºC

Well No.	Date	P0 (barg)	Qtot (kg/s)	H0 (kJ/kg)	Steam (kg/s)	Water (kg/s)	Well No.	Date	P0 (barg)	Qtot (kg/s)	H0 (kJ/kg)	Steam (kg/s)	Water (kg/s)
NJ-16	1.4.2001	47	16.4	1601	8.6	7.8	NJ-22	3.20.2001	29	47.8	1628	25.6	22.2
NJ-16	1.10.2001	46.5	16.2	1613	8.6	7.6	NJ-22	3.20.2001	28.5	50.2	1544	25	25.1
NJ-16	1.18.2001	47	15.8	1649	8.6	7.2	NJ-22	3.20.2001	28	49.9	1538	24.7	25.1
NJ-16	1.25.2001	47	16.4	1601	8.6	7.8	NJ-22	3.20.2001	26	54	1350	22.3	31.7
NJ-16	2.1.2001	47	16.2	1613	8.6	7.6	NJ-22	3.20.2001		51.9	1371	21.9	30
NJ-16	3.20.2001	21.8	34.5	1787	20.9	13.6	NJ-22	3.20.2001	25	52.2	1379	22.2	30
NJ-16	8.8.2001	58.5	20.5	1155	6.7	13.8	NJ-22	3.20.2001	25	50.4	1408	22.1	28.3
NJ-16	8.23.2001	58.5	21.1	1199	7.3	13.8	NJ-22	3.21.2001	25.1	49.2	1378	20.9	28.3
NJ-21	3.20.2001	23.9	36.2	1830	22.6	13.6	NJ-22	3.21.2001	25.1	46.4	1423	20.6	25.8
NJ-21	3.20.2001	22.5	34.3	1851	21.8	12.5	NJ-22	3.22.2001	25.2	45.5	1415	20.1	25.5
NJ-21	3.20.2001	16.9	21.7	2157	16.7	5	NJ-22	3.22.2001	25	46.4	1453	21.3	25.1
NJ-21	3.21.2001	13.4	24	2172	18.6	5.4	NJ-22	3.22.2001	25.2	50.4	1408	22.1	28.3
NJ-21	3.22.2001	12.5	20.8	2133	15.8	5	NJ-22	3.22.2001	25.2	45.5	1415	20.1	25.5
NJ-21	3.22.2001	12.2	18.1	2150	13.9	4.2	NJ-22	3.22.2001	25.2	50.4	1408	22.1	28.3
NJ-21	3.23.2001	13	16.5	2053	11.9	4.5	NJ-22	3.22.2001	25.2	45.5	1415	20.1	25.5
NJ-21	3.26.2001	10.8	15.9	2274	13.1	2.8	NJ-22	3.23.2001	26	47	1468	21.9	25.1
NJ-21	3.27.2001	10.8	12.6	2153	9.6	2.9	NJ-22	3.27.2001	29.5	42	1764	25	17
NJ-21	3.28.2001	10.8	11.7	2164	9.1	2.7	NJ-22	3.28.2001	29.5	41.5	1781	25.1	16.5
NJ-21	3.29.2001	10.8	12.3	2200	9.7	2.6	NJ-22	3.28.2001	29.5	40.8	1739	23.9	17
NJ-21	3.30.2001	10.8	12.4	2177	9.7	2.7	NJ-22	3.29.2001	29.6	39.4	1798	24	15.3
NJ-21	4.2.2001	10.5	10.3	2435	9.2	1.1	NJ-22	3.29.2001	29.6	40	1772	24	16
NJ-21	4.3.2001	11.2	11.8	2279	9.7	2.1	NJ-22	3.29.2001	29.6	39.4	1798	24	15.3
NJ-21	4.4.2001	10.5	10.2	2462	9.2	1	NJ-22	3.30.2001	29.7	39.2	1806	24.1	15.1
NJ-21	4.5.2001	10.5	10.2	2462	9.2	1	NJ-22	4.2.2001	29.8	37.2	1853	23.7	13.6
NJ-21	4.9.2001	11.6	12.1	2223	9.7	2.4	NJ-22	4.3.2001	30	37.2	1891	24.3	12.9
NJ-21	4.10.2001	11.8	12.7	2244	10.3	2.4	NJ-22	4.3.2001	30	37.4	1920	24.9	12.5
NJ-21	4.11.2001	12	13.2	2165	10.2	3	NJ-22	4.4.2001	30	38.2	1886	24.8	13.4
NJ-21	4.17.2001	11.4	10.6	2506	9.8	0.8	NJ-22	4.5.2001	30	36.9	1945	24.9	11.9
NJ-21	4.18.2001	11.7	11.6	2434	10.4	1.2	NJ-22	4.9.2001	30.2	37.2	1928	24.9	12.3
NJ-21	4.24.2001	12.6	13.1	2177	10.2	2.9	NJ-22	4.10.2001	30.2	36.9	1908	24.3	12.5
NJ-21	4.26.2001	12.2	12.1	2349	10.3	1.7	NJ-22	4.10.2001	30.2	36.3	1896	23.8	12.5
NJ-21	4.27.2001	12.6	12.1	2349	10.3	1.7	NJ-22	4.11.2001	30.4	36.7	1917	24.3	12.3
NJ-21	5.3.2001	11.3	10.1	2627	9.9	0.2	NJ-22	4.11.2001	30.4	36.7	1917	24.3	12.3
NJ-21	5.9.2001	11.8	11	2555	10.4	0.6	NJ-22	4.17.2001	30.8	37.8	1939	25.5	12.3
NJ-21	5.16.2001	12.6	12.4	2402	10.9	1.5	NJ-22	4.18.2001	30.8	37.3	1965	25.5	11.8
NJ-21	5.22.2001	12.3	11.9	2494	11	1	NJ-22	4.24.2001	30.8	37.5	1992	26.1	11.4
NJ-21	5.23.2001	11.4	10.6	2646	10.5	0.1	NJ-22	4.26.2001	30.8	38	1931	25.5	12.5
NJ-21	5.25.2001	12	11.1	2542	10.4	0.7	NJ-22	4.27.2001	30.9	38.6	1942	26	12.5
NJ-21	5.28.2001	12	10.5	2673	10.5	0	NJ-22	5.3.2001	31.2	36.5	1962	25	11.6
NJ-21	5.31.2001	11.9	11.1	2668	11	0	NJ-22	5.22.2001	24.5	39.3	2369	34	5.4
NJ-21	6.5.2001	12.7	13.1	2510	12.1	1	NJ-22	5.23.2001	23.2	25.8	2153	19.8	6
NJ-21	6.8.2001	12.7	15.7	2591	15.1	0.6	NJ-22	5.23.2001	23.2	38.1	2322	32.1	6
NJ-21	6.14.2001	12.5	12.6	2597	12.2	0.4	NJ-22	7.16.2001	40	73.6	2413	65.1	8.6
NJ-21	6.21.2001	12.2	12.5	2619	12.2	0.3	NJ-22	7.16.2001	38	36.8	1559	18.6	18.2
NJ-21	6.28.2001	13.2	15	2311	12.6	2.4	NJ-22	7.17.2001	37	36.8	1559	18.6	18.2
NJ-21	7.12.2001	13.2	15.6	2325	13.2	2.4	NJ-22	7.18.2001	38	36.8	1559	18.6	18.2
NJ-21	7.19.2001	13	14.4	2510	13.3	1.1	NJ-22	7.19.2001	39	36.8	1559	18.6	18.2
NJ-21	7.26.2001	12.5	15.2	2655	15.1	0.1	NJ-22	7.26.2001	41	35.1	1585	18.1	17
NJ-21	8.2.2001	13.3	15	2413	13.3	1.7	NJ-22	8.2.2001	41.5	34.8	1725	20.1	14.7
NJ-21	8.8.2001	13.5	15.6	2325	13.2	2.4	NJ-22	8.8.2001	41.6	34	1630	18.3	15.8
NJ-21	8.16.2001	13.4	13.8	2604	13.4	0.4	NJ-22	8.16.2001	41.2	39.9	1847	25.2	14.7
NJ-21	8.23.2001	13.8	15.9	2381	13.8	2.1	NJ-22	8.23.2001	41.8	34.2	1709	19.5	14.7

APPENDIX VI: Noise measurements

Noise measurements with regards to the frequency type at 5 m distance from boreholes

Frequency	Noise			COMMENT
(Hz)	L dB	LA dB(A)	ΔA	
31.5	105.5	66.1	39.4	Leq data collected during 30 seconds at 5 m distance from borehole NV-21 at different frequencies
63	105.5	79.3	26.2	
125	104.3	88.2	16.1	
250	113.1	104.5	8.6	
500	107.4	104.2	3.2	
1000	108.9	108.9	0	
2000	99.9	101.1	-1.2	
4000	89.9	90.9	-1	
8000	82.8	81.7	1.1	
TOTAL	116.5	111.7		
Frequency	**Noise**			**COMMENT**
(Hz)	**L dB**	**LA dB (A)**	**ΔA**	
31.5	110	70.6	39.4	Leq data collected during 30 seconds at 5 m distance from borehole NV-22 at different frequencies
63	104.6	78.4	26.2	
125	100.4	84.3	16.1	
250	92.8	84.2	8.6	
500	95.7	92.5	3.2	
1000	93	93	0	
2000	89.9	91.1	-1.2	
4000	83.6	84.6	-1	
8000	73.1	72	1.1	
TOTAL	111.7	97.8		
Frequency	**Noise**			**COMMENT**
(Hz)	**L dB**	**LA dB (A)**	**ΔA**	
31.5	109	69.6	39.4	Leq data collected during 30 seconds at 5 m distance from borehole NV-16 at different frequencies
63	97.4	71.2	26.2	
125	97.1	81	16.1	
250	99.1	90.5	8.6	
500	85.3	82.1	3.2	
1000	76.2	76.2	0	
2000	71.8	73	-1.2	
4000	66.3	67.3	-1	
8000	49.4	48.3	1.1	
TOTAL	109.9	91.8		

Noise measurements with regards to the frequency type at 20 m distance from boreholes

Frequency (Hz)	Noise L dB	Noise LA dB(A)	ΔA	COMMENT
31.5	96.6	57.2	39.4	Leq data collected during 30 seconds at 20 m distance from borehole NV-21 at different frequencies
63	97.6	71.4	26.2	
125	97.5	81.4	16.1	
250	95.9	87.3	8.6	
500	97.8	94.6	3.2	
1000	90.3	90.3	0	
2000	80.5	81.7	-1.2	
4000	70.1	71.1	-1	
8000	57	55.9	1.1	
TOTAL	104.3	96.8		

Frequency (Hz)	Noise L dB	Noise LA dB (A)	ΔA	COMMENT
31.5	98	58.6	39.4	Leq data collected during 30 seconds at 20 m distance from borehole NV-22 at different frequencies
63	92.6	66.4	26.2	
125	88.4	72.3	16.1	
250	80.8	72.2	8.6	
500	83.7	80.5	3.2	
1000	81	81	0	
2000	77.9	79.1	-1.2	
4000	71.6	72.6	-1	
8000	61.1	60	1.1	
TOTAL	99.7	85.8		

Frequency (Hz)	Noise L dB	Noise LA dB (A)	ΔA	COMMENT
31.5	100.8	61.4	39.4	Leq data collected during 30 seconds at 20 m distance from borehole NV-16 at different frequencies
63	94.6	68.4	26.2	
125	91.4	75.3	16.1	
250	84	75.4	8.6	
500	75.7	72.5	3.2	
1000	68.9	68.9	0	
2000	68.7	69.9	-1.2	
4000	66.9	67.9	-1	
8000	51.5	50.4	1.1	
TOTAL	102.2	80.7		

Noise measurements with regards to the frequency and distances

NV-21								
Frequency (Hz)	Noise (dB)	S-PowerLevel (dB)	Noise (dB)					Distance (m)
	Distance 5 m		63 Hz	250 Hz	500Hz	2000 Hz	4000 Hz	
31.5	105.5	130.5	105.5	113.1	107.4	99.9	89.8	5
63	105.5	130.5	99.5	107.1	101.4	93.9	83.8	10
125	104.3	129.3	93.5	101.1	95.4	87.9	77.8	20
250	113.1	138.1	87.4	95.0	89.3	81.8	71.7	40
500	107.4	132.4	81.4	89.0	83.3	75.8	65.7	80
1000	108.9	133.9	75.4	83.0	77.3	69.8	59.7	160
2000	99.9	124.9	69.4	77.0	71.3	63.8	53.7	320
4000	89.8	114.8						
8000	82.8	107.8						

NV-22								
Frequency (Hz)	Noise (dB)	S-PowerLevel (dB)	Noise (dB)					Distance (m)
	Distance 5 m		63 Hz	250 Hz	500Hz	2000 Hz	4000 Hz	
31.5	110	135.0	104.6	92.8	95.7	89.9	83.6	5
63	104.6	129.6	98.6	86.8	89.7	83.9	77.6	10
125	100.4	125.4	92.6	80.8	83.7	77.9	71.6	20
250	92.8	117.8	86.5	74.7	77.6	71.8	65.5	40
500	95.7	120.7	80.5	68.7	71.6	65.8	59.5	80
1000	93	118.0	74.5	62.7	65.6	59.8	53.5	160
2000	89.9	114.9	68.5	56.7	59.6	53.8	47.5	320
4000	83.6	108.6						
8000	73.14	98.1						

NV-16								
Frequency (Hz)	Noise (dB)	S-PowerLevel (dB)	Noise (dB)					Distance (m)
	Distance 5 m		63 Hz	250 Hz	500Hz	2000 Hz	4000 Hz	
31.5	109	134.0	97.4	99.1	85.3	71.8	66.3	5
63	97.4	122.4	91.4	93.1	79.3	65.8	60.3	10
125	97.1	122.1	85.4	87.1	73.3	59.8	54.3	20
250	99.1	124.1	79.3	81.0	67.2	53.7	48.2	40
500	85.3	110.3	73.3	75.0	61.2	47.7	42.2	80
1000	76.2	101.2	67.3	69.0	55.2	41.7	36.2	160
2000	71.8	96.8	61.3	63.0	49.2	35.7	30.2	320
4000	66.3	91.3						
8000	49.4	74.4						