EVALUATION OF NOISE POLLUTION FROM OIL DRILLING AND TESTING ACTIVITIES IN A MAJOR METROPOLITAN CITY IN NORTHERN ITALY

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2019

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DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF TECHNOLOGY (ENVIRONMENTAL MANAGEMENT)

INSTITUTE OF BIOLOGICAL SCIENCES
FACULTY OF SCIENCE
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

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Matric No: **SGH 130013**

Name of Degree: **MASTER OF TECHNOLOGY (ENVIRONMENTAL MANAGEMENT)**

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"): **EVALUATION OF NOISE POLLUTION FROM OIL DRILLING AND TESTING ACTIVITIES IN A MAJOR METROPOLITAN CITY IN NORTHERN ITALY**

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EVALUATION OF NOISE POLLUTION FROM OIL DRILLING AND TESTING ACTIVITIES IN A MAJOR METROPOLITAN CITY IN NORTHERN ITALY

ABSTRACT

Noise has an adverse impact on the quality of human life. According to the World Health Organization (WHO) and the European Union's task force meeting in Geneva in 1995, excessive noise seriously harms human health and interferes with people's daily activities at school, work, home and during leisure time. Limited availability of noise pollution data and high variability during oil well drilling and testing activity make it necessary to monitor its consequential noise pollution via research. The objectives of this study are to measure and present the noise generated during these activities in the selected areas, to analyse these results against the local authority's permissible noise levels (60 dB_A for day and 50 dB_A at night) and finally to statistically analyse the variables that most impact the measured noise. The research area in Northern Italy was selected since it is an urban community area, with defined oil and gas activity in the vicinity. Continuous noise monitoring stations were installed in front of houses closest to the drilling rigs (distance of 144 m – 328 m) and sound levels were sampled over seven months in two different drilling locations – 'Location 1' and 'Location 2'. A total of 8,954 data points were measured with 52% data coming from Location 1 and 48% from Location 2. The study also analyzed rig types, wells, high level well activity and weather via a strength of factors analysis.The monitoring indicated that both locations produced higher sound levels (decibels, dB_A) during day time as compared to night time. The noise measured was between 31.3 dB_A to 83.1 dB_A in both locations. Location 1 showed a mean noise value of 53.0 dB_A in the day and 50.6 dB_A at night compared to Location 2 that showed overall lower values with a mean noise level of 49.1 dB_A in the day and 44.4 dB_A at night. The study showed that the noise generated fell within the specified governmental limits, hence protecting the wellbeing of nearby residents from excessive noise. The efficiency of the flaring enclosure was proven successful in reducing the flaring noise from 50.9 dB_A to 46.9 dB_A. It was found that variables such as Relative Humidity (%), Global Radiation (W/m^2), Drilling the 8.5" section, Completions, Persons on Board Rig (POB) and Drilling of the 12.25" section caused an increase in noise by varying degrees. However, installing the flaring burner enclosure, using rig type 2 and having a higher degree of wind direction decreased sound levels. To summarize, the results of this study supports other limited research in understanding the noise generated during oil and gas activities. . By restricting noise limits, oil and gas drilling activities can take place to generate a much needed energy source with minimal environmental noise pollution impact towards surrounding communities.

Keywords: Noise, urbanization, drilling, flaring

PENILAIAN PENCEMARAN BUNYI DARIPADA AKTIVITI CARIGALI DAN PENGUJIAN PETROLEUM DI KOTA METROPOLITAN ITALI UTARA

ABSTRAK

Bunyi bising berlebihan mempunyai kesan buruk terhadap kualiti hidup manusia. Menurut Pertubuhan Kesihatan Sedunia (WHO) dan pasukan petugas Kesatuan Eropah di Geneva pada tahun 1995, bunyi berlebihan boleh membahayakan kesihatan manusia dan mengganggu aktiviti harian di sekolah, di tempat kerja, di rumah dan semasa waktu lapang. Sumber data pencemaran bunyi yang terhad dan tidak konsisten semasa aktiviti-aktiviti carigali dan pengujian petroleum adalah justifikasi untuk projek penyelidikan ini. Objektif-objektif projek ini adalah untuk mengukur dan melaporkan tahap bunyi yang dijanakan oleh aktiviti-aktiviti carigali di kawasan terpilih, dan membandingkannya dengan tahap bunyi yang dibenarkan (60 dB_A di waktu siang dan 50 dB_A di waktu malam), dan akhirnya manjalankan analisis statistik untuk mengenalpasti faktor yang paling mempengaruhi tahap bunyi yang dihasilkan. Kawasan penyelidikan di Utara Itali dipilih kerana ia adalah kawasan komuniti metropolitan, dengan aktiviti-aktiviti petroleum di persekitarannya. Stesen pemantauan bunyi yang berterusan telah dipasang di hadapan kediaman yang paling dekat dengan pelantar penggerudian (jarak 144 m – 328 m) dan bunyi bising diukur sepanjang durasi tujuh bulan di kedua-dua lokasi penggerudian – 'Lokasi 1' dan 'Lokasi 2'. Sejumlah 8,954 bacaan bunyi diukur dengan 52% data diperolehi di Lokasi 1 dan 48% di Lokasi 2. Kajian ini juga menganalisiskan jenis telaga penggerudian, telaga, aktivi tahap tinggi, aktiviti terperinci dan cuaca melalui analisis faktor kekuatan. Keputusan dari pemantauan menunjukkan bahawa kedua-dua lokasi menghasilkan tahap bunyi yang lebih tinggi (dB_{Av}) pada waktu siang dibandingkan dengan waktu malam. Bunyi yang diukur adalah di antara 31.3 dB_A ke 83.1 dB_A di kedua-dua lokasi. Lokasi 1 menunjukkan nilai bunyi min 53.0 dB_A pada siang hari dan 50.6 dB_A

pada waktu malam berbanding dengan Lokasi 2 yang menunjukkan nilai lebih rendah dengan tahap bunyi min 49.1 dB_A pada siang hari dan 44.4 dB_A pada waktu malam. Kajian ini menunjukkan bahawa bunyi bising yang dihasilkan adalah dalam julat yang ditetapkan oleh kerajaan, yang mana berjaya melindungi kesejahteraan penduduk berdekatan daripada bunyi berlebihan. Kecekapan benteng pembakaran terbukti berjaya mengurangkan bunyi pembakaran dari 50.9 dB_A kepada 46.9 dB_A. Didapati juga bahawa faktor seperti Kelembapan Relatif (%,) Radiasi Global (W/m^2), Penggerudian 8.5", Completions, bilangan pekerja di telaga preggerudian (POB), dan Penggerudian bahagian 12.25" menyebabkan peningkatan bunyi di pelbagai peringkat. Walau bagaimanapun, pemasang benteng pembakaran, menggunakan pelantar jenis 2 dan tahap arah angin berjaya mengurangkan tahap bunyi. Sebagai rumusan, hasil kajian ini menyokong penyelidikan lain yang terhad dalam memahami tahap-tahap bunyi yang dihasilkan semasa aktiviti carigali minyak dan gas. Dengan menghadkan tahap bunyi, aktiviti carigaji petroleum boleh diteruskan menghasilkan sumber tenaga yang sangat diperlukan dengan kesan pencemaran alam sekitar yang minimum terhadap masyarakat yang berdekatan.

Kata kunci: Bunyi bising, aktiviti antropogenik, carigali petroleum, pembakaran

ACKNOWLEDGEMENTS

I express profound gratitude to my parents, my family and friends throughout the duration of my studies. I thank all my lecturers in the Science Faculty especially my supervisor, Dr Fauziah Binti Shahul Hamid and my lecturer Professor Agamuthu A/L Pariatamby for their mentorship and guidance that has allowed me to complete my dissertation, and for encouraging my interest in the field of environmental management.

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LIST OF SYMBOLS AND ABBREVIATIONS

Φ	:	Porosity
k	:	Matrix permeability
S_w	:	Water saturation
ACGIH	:	American Conference of Governmental Industrial Hygienists
ANOVA	:	Analysis of Variance
Bbl	:	Barrels
bcm	:	Billion cubic metres of natural gas
BHA	:	Bottom Hole Assembly
Boe/bboe	:	Billion of oil equivalent / billion barrel of oil equivalent
CFC	:	Chlorofluorocarbon gas
dB	:	Decibel
DNL	:	Day-Night Noise Level (L_{dn})
EIA	:	Environmental Impact Assessment
EPA	:	Environmental Protection Agency
FDP	:	Field Development Plan
IEC	:	International Electrotechnical Commission
ISO	:	International Organization for Standardization
L_{eq}	:	Equivalent Sound Level
L_{eq} (8)	:	Equivalent A- weighted sound level for an eight hour work day
Mdarcy	:	Mili darcy
MSHA	:	Mine Safety and Health Administration
Mtep	:	Million tonnes equivalent of petroleum
NIOSH	:	National Institute for Occupational Safety and Health
OSHA	:	Occupational Safety and Health Administration
P&A	:	Plug and Abandonment

POOH	:	Pull out of Hole
PSL		Permissible Sound Level
RIH	:	Run in Hole
RMS	:	Root mean square value
SPE	:	Society of Petroleum Engineers
UN	:	United Nations
UNI EN	:	Italian National Unification (Italian edition of European standards)
US	:	United States of America
WHO	:	World Health Organization

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background

The world's population is expected to reach 9.9 billion by 2050, up 2.3 billion or 29% from an estimated 7.6 billion current population (Population Reference Bureau, 2018). Today, 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050. Projections show that another 2.5 billion people could be added to urban areas by 2050, with close to 90% of this increase taking place in Asia and Africa (United Nations, 2018).

Even with this expected increase in the world's population, the earth can only sustain a limited number of people. This is due to resources limitations such as water, food, housing and sanitation, all of which are crucial for growth and comfort; i.e. quality of life (McLeod, 2018). There is a link between the decline in quality of life with an increase in population growth with many demands being affected, namely air quality, transportation needs (air, land and marine), environment (green spaces), housing demands, food insecurities, fresh water supplies along with waste disposal resources which are increasing (Herrmann et al., 2012). Sustainable development is the key to successfully managing this urban growth, especially in low-income and lower-middle-income countries where the most rapid urbanization is expected between now and 2050 (United Nations, 2018). The United Nations (UN) also states that urban growth is closely related to three dimensions of sustainable development: economic, social and environmental.

Figure 1.1 displays the expected increase in the diverse types of manufacturing industries from 2012 to 2040 (in trillion dollars) to cater for the increase in expected population growth. This demonstrates a rise in industrialization expansion which helps to explain changes in the industrial sector energy consumption (Conti et al., 2016).

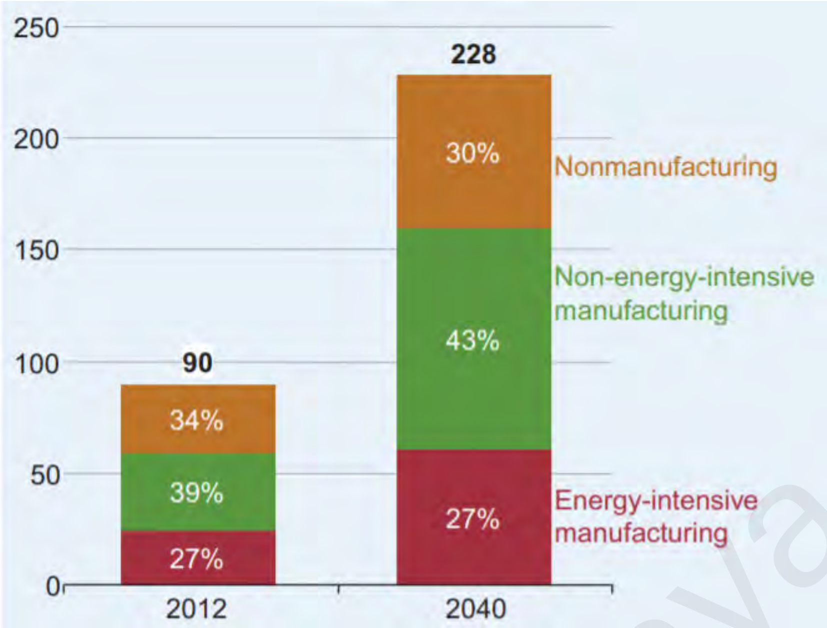


Figure 1.1: Global gross output by industrial subsector. Image reproduced from Conti et al. (2016).

To cater to the demands of industrialization, the world's energy consumption must increase accordingly. This is used in industries such as process and assembly, steam and cogeneration, process heating and cooling, lighting and air conditioning for buildings. The industrial sector energy consumption also includes basic chemical feedstocks such as natural gas, used to produce agricultural chemicals. Natural gas liquids (NGL) and petroleum products (such as naphtha) are both used for the manufacture of organic chemicals and plastics, among other uses (Conti et al., 2016). Figure 1.2 shows the estimated upward trend in fuel requirements in billions of oil equivalent (boe) and its source (renewable and non-renewable), based on a report by British Petroleum (British Petroleum, 2013).

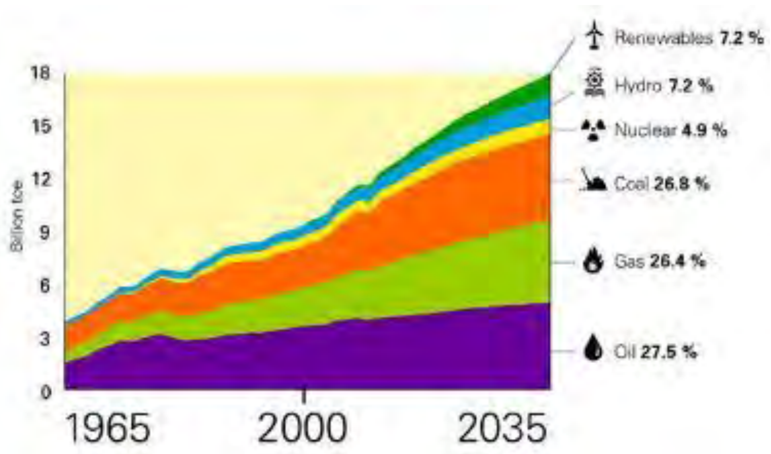


Figure 1.2: Fuel consumption trending. Image reproduced from British Petroleum (2013).

Figure 1.3 shows the current and projected trend of world population growth against the corresponding expected increase in energy consumption (Bradley & Fulmer, 2004).

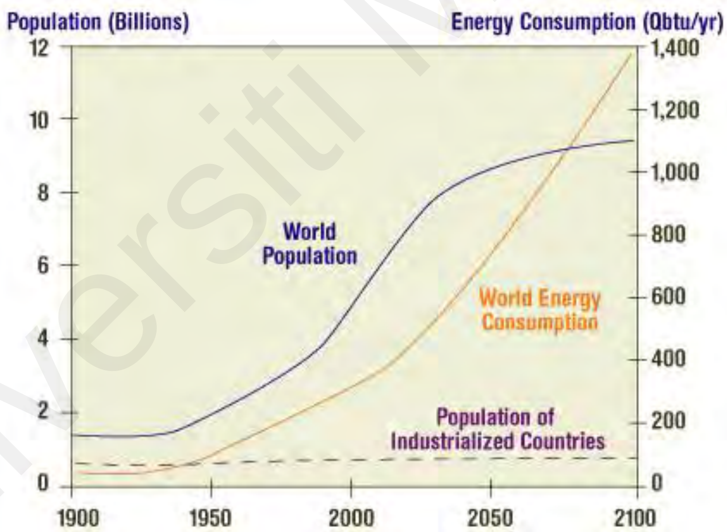


Figure 1.3: World population and energy demand. Image reproduced from Bradley & Fulmer (2004).

To meet the increase in fuel demand, oil and gas production will need to increase proportionately via drilling rig activity to explore, find, store and produce more oil and gas as energy source (Williams, 2018). This forecasted increase is shown in Figure 1.4. Underground gas storage is a common way to sustain between a constant gas supply and the seasonal and daily variability of gas consumption (Verga, 2018).

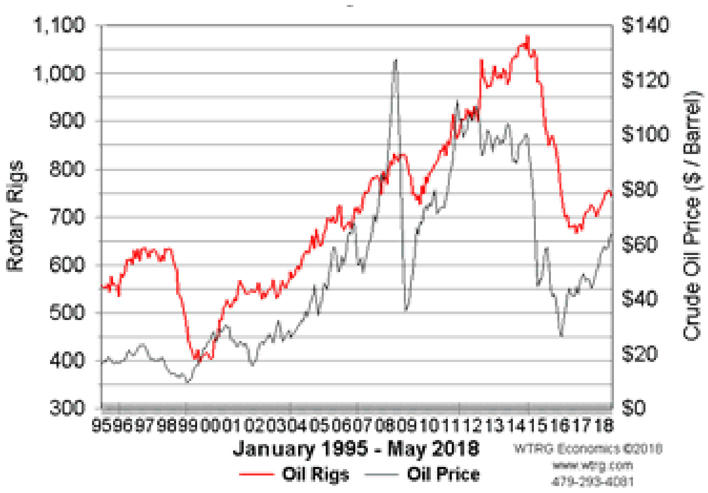


Figure 1.4: International rig count and oil price trend, 1995 to 2018. Adapted from: Williams (2018).

Table 1.1. describes the petroleum cycle, from the exploration phase up to the production phase of oil and gas. Drilling wells (either for producing oil and gas including underground gas storage) is a way to access the targetted reservoir at depths beneath the surface.

Table 1.1: Oil and gas field life cycle phases. Adapted from Jahn et al. (2003).

Phase	**Description**
Exploration	High risk investment activity related to finding oil/gas reserves.
Appraisal	Program conducted with aim of accurately assessing the potential reserves and producible volumes.
Development Planning	A Field Development Plan (FDP) is formulated to define the development activities of a new field, or extension to an existing development encompassing drilling, testing, subsurface and surface facilities requirements and operational and maintenance philosophy.
Production	Wells are drilled using drilling rigs (onshore or offshore) and put on production via a flow and metering system.
Plug & Abandonment	When production is no longer economical, wells and platforms are removed from production by being plugged and abandoned. This stage involves cutting of steel platforms, floating concrete structures, reutilization of shallow water platforms and jackets as artificial reefs.

The process of finding oil and gas (including underground storage areas) begins with an estimation of reserves, to the drilling then production stage, the processing phase to turn it into useable domestic and industrial by-products and finally to the decommissioning of production platforms (Jahn et al., 2003; Yergin, 2012). To extract oil and gas from underground, a drilling rig is used on surface to provide sufficient power to create a conduit downhole which is also known as a 'well'. The design and size of the downhole equipment and materials to be used is performed by the well engineer supported by the geoscience and petroleum engineering teams (Jahn et al., 2003). Drilling and testing processes used for exploring oil and gas wells are the same used to store gas underground for heating and other industrial uses, as is the case in Italy. In terms of constructing a well, the following steps generally take place:

1. The location is prepared, in roads and the drilling pads are constructed

2. The rig moves to the location, placing different equipment, camp and accommodation trailers and workshops around the location

3. Conductor pipes are driven, or a large hole is drilled using the drilling rig to then run the pipes, and a cement fluid is pumped in the outer annular area to seal it in place. This provides a basis for installing the well control equipment and wellhead, used to also stabilize the drilling rig.

4. Subsequent holes and tubulars (also known as casings) are drilled, run in hole and cemented to reach the targeted reservoirs at the total depth of the well.

5. Completions operations are when the well has tubing and downhole artificial lifting equipment installed to bring the oil or gas to surface. The equipment is usually run, the communication with the wellbore takes place by perforating the final production casing and create a pathway for the hydrocarbons to enter the wellbore and flowed to surface.

Nitrogen pumped via smaller size coiled tubing is the usual method to ´lift´ the well, which creates a lighter density that can reach the surface.

6. Flaring is an operation that is part of certain exploration or appraisal wells in which gas is brought to surface and burnt to test the extent of the formation and characteristics of the oil/gas found in that well.

7. Depending on the well objective (production or evaluation), how the well is closed in is decided. If being produced, it is hooked up to the production lines and oil or gas is flowed to the collection or refining centres. If the well was only meant to be evaluated, it now must be plugged (by pumping cement plugs at various intervals down the borehole and tested) and then abandoned in order to ensure that no fluid can reach surface, and that as much of the area is clear of all traces of drilling activity.

Further details about the drilling process is described in Appendix A. The rig is equipped with various pieces of machinery that create five rig systems that work together to drill to the targeted depth (anywhere from 500 m to approximately 5000 m below the surface). The five land rig systems are the hoisting, rotating, circulating, power and well control systems that include pumps, engines, generators and other moving pieces (Bourgoyne Jr. et al., 1986).

Since Roman times, excessive sound has been considered a hindrance to peaceful rest of the city's population, so rules were put in place to ban transportation during the night hours to prevent excessive noise pollution in Rome (Goines & Hagler, 2007). This was one of the earliest cases of man-made noise or annoyance recorded. Drilling equipment can generate high sound levels; diesel engine power generators (106-109 dB_A) and cranes (103-111 dB_A in the crane driver cabin) (Melling et al., 1975). This increase in drilling activity also brings the oil and gas operators closer to numerous communities which previously have had little to no contact with the industry (Weston & Macfarlan, 2015) and with that, additional environmental pollution exposure.

In its peak in 1994, Italy produced a cumulative 6.4 Bboe of which 77% was gas and 23% oil (Cazzini, 2017) but in the recent economic downturn of 2006, hydrocarbon production accounted for only 8% (14.9 Mtep) of the Italian energy demand (Bertello et al., 2008). One way to overturn the increase in energy prices (due to reduced supply and increased demand) is to find creative alternatives such as to convert areas of natural gas production to underground gas storage wells where the techniques are similar to drilling an oil well. Doing this allows gas prices to reduce, making it easier for citizens to afford energy and sustain a good living standard. Italy is expected to add around 249 billion cubic feet (bcf) of underground gas storage capacity between 2019 and 2023, from 14 planned and announced underground gas storage sites (GlobalData Plc, 2019).

Italy's gross domestic product (GDP) figure in 2018 was $2,071,413 million, leaving it ranked 8th in the ranking of 196 countries GDP (Country Economy, 2019). Italy's has increased by about 0.8%, and the demand for electricity and gas has followed the same trend. In 2018, Italy's energy source was mainly 79% provided for by fossil fuels at about 79%, with oil for 34%, gas for 37% and coal for 8% of total energy consumption (Fischer et al., 2018). This is why the drilling industry is still active today in Italy, namely for drilling of natural gas and gas storage wells.

1.2 Problem Statement

In the case of the drilling locations in Northern Italy, the two sites were located at distances between 144 m and 328 m to the nearest residential home. The sounds generated could have a negative impact on the quality of life, depending on the levels produced.

Measuring and analysing the actual sounds from the well drilling and testing activity and contributing factors against the council set limits is the objective for conducting this vital project, to protect the inhabitants in terms of impact towards health and wellbeing.

Analysing the noise generated from industrial activities against its apparent adverse effects is a critical aspect towards sustainable development and management of anthropological activities. Noise can harm human health and interfere with people's daily activities at school, work, home and during leisure time (WHO Europe, 2009). Adverse noise effects could include hearing impairment, interference with speech, disturbance of rest and sleep, psychophysiological, mental-health and performance effects, annoyance, as well as interference with intended activities (U. S. EPA, 1974). Several other studies report that noise, being an unwanted sound creates annoyance in humans (Berglund et al., 1999; Goines & Hagler, 2007). According to a European Union (EU) publication, about 40% of EU countries population is exposed to road traffic noise at levels exceeding 55 dB_A, while 20% is exposed to levels exceeding 65 dB_A during the day time and more than 30% is exposed to levels exceeding 55 dB_A at night (WHO Europe, 2009). The number of complaints from citizens pertaining to noise is constantly increasing. A study by Hong Kong’s Environmental Protection Department (2002) showed that the number of noise complaints are substantial in a developing country. These results are shown in Figure 1.5, showing that there is a growing concern from anthropological activities in developing countries.

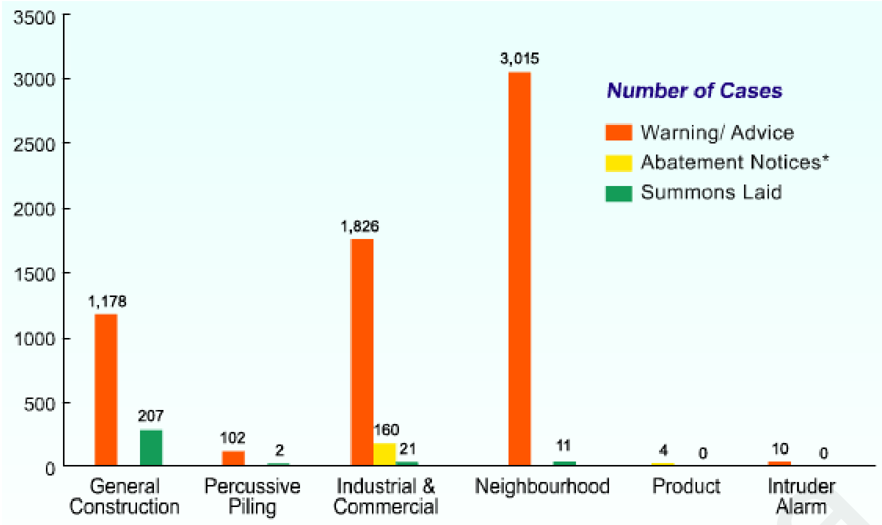


Figure 1.5: Noise complaints by type. Image reproduced from Government of Hong Kong SAR (2002).

Noise also generates adverse effects on animals (disrupting habitats, defining territories, attracting mates, deterring predators, navigation, finding food, changing their breeding, migration and survival methods, migration and ecosystems). During the oil and gas refining process, noise can exceed 90 dB_A which can be detrimental to overall health (Blickley & Patricelli, 2012; Blumstein et al., 2011). In the marine environment, oil and gas activity increases underwater noise that can potentially kill, injure and temporarily deafen various marine mammals; requiring a long-term global strategy to control anthropogenic noise pollution (Tyagi, 2008). Several other studies refer to noise pollution within the context of occupational hazards (Foo, 2014; Hammer et al., 2014; Sarok & Susil, 2012).

Quantifying the problem using noise measurements or analytical means is the first step in addressing and potentially solving this anthropological noise issue. The subsequent step refers to determining an applicable noise limit to cap the noise exposure (Cavanaugh & Tocci, 1998; Manea et al., 2017).

There is reported inconsistency across data collection methodologies by the many private and public entities and types of drilling operations, thus making the results difficult to compare (Guy, 2016).

Based on available published literature, it can be observed that while there is multitude analysis related to air, water and land pollution caused by the drilling industry (and separate studies related to urban noise), there are very few studies that link both. This is a reason for conducting this research to jointly analyse both these factors: noise pollution from well drilling activity in the urban Italian environment with the aim of narrowing the existing knowledge gap in these fields. The question to be answered is: can noise data during specific drilling and testing activities exceed government noise regulations that are put in place to protect citizens, and what factors influence these sound levels?

1.3 Research Objectives

To expand research pertaining to noise generated by the well drilling industry activities in urban areas, the corresponding research objectives of this study are:

1. To assess the noise pollution imposed on the local community from drilling and well testing activity during the 7-month operation campaign

2. To analyse the levels of noise pollution generated by drilling and well testing activities against the limits set by the local authority by measuring levels of exceedance on both sample locations (Location 1 and 2)

3. To evaluate the noise measurements by day mode, high level rig activity, weather, enclosure and impact from selected key variables (efficiency of flare burner enclosure installation, rig type, number of persons on board and weather) on the measured sound levels via a strength of factors analysis.

CHAPTER 2: LITERATURE REVIEW

2.1 Basic Sound and Noise Concepts

This section will provide information on sound and how it can become noise. Understanding the physics of noise will also provide a background to this research and its results. Goines and Hagler (2007) state that there is growing evidence that noise pollution is not merely an annoyance, like other forms of pollution, but has a wide range of adverse health, social and economic effects. A textbook definition of sound is "a rapid variation of atmospheric pressure caused by some disturbance of the air" (Berger, 2003). Sound propagates as a wave of positive pressure disturbances (compressions) and negative pressure disturbances. The ear receives a sound wave and directs it to the ear drum as a variation in air pressure. This pressure is then converted and amplified as an acoustic wave which is then transmitted into the inner ear (the cochlea) and further transmitted into the brain as nerve impulses. This signal is processed by the brain and impairment to any of these stages can affect hearing.

Sound is generally described in terms of three variables: amplitude (perceived loudness), frequency (pitch) and time pattern (Weston & Macfarlan, 2015). The Occupational Safety and Health Administration (OSHA) provides further description of the key terminologies used in standard noise measurement and reporting guidelines (Occupational Safety and Health Administration, 2013):

- Decibels: Dimensionless unit used to measure the intensity of sound (dB), based on a logarithmic scale. This notation is implied anytime a "sound level" or "sound pressure level" is mentioned.
- Sound pressure level: The vibrations associated with sound are detected as slight variations in pressure, measured in decibels. The reference sound

pressure is the standardized threshold of hearing and is defined as 20 micropascals (0.0002 microbars) at 1,000 Hz.

- dB_A= A-weighted decibel, a frequency dependent correction that is applied to a measured or calculated sound of moderate intensity to mimic the varying sensitivity of the ear to sound for different frequencies, could be measured as C-weighted, depending on varying frequencies (dB_C).
- dB_A, L_{eq}= average of continuous noise level, where noisy events have a considerable influence. Describes the concept of fluctuating level with time, related to a continuous steady level

The A-weighted scale is most likened to the noise able to be detected by the human ear, hence is used in most noise studies (DeGagne & Burke, 2008; Melling et al., 1975; Radtke, 2016). A report by the U.S. EPA (1974) reported that the A-weighted sound level correlates well with the complex human response, as derived from a spectral analysis. Noise is to be measured and reported in reference to time, example L_{eq} ($_8$) denotes the equivalent A-weighted sound level for an eight-hour work day to evaluate the environmental noise affecting people for extended periods of time (U. S. EPA, 1974).

Sudden, intense acoustic or noise events, such as an explosion could also be known as instantaneous Peak Noise Limit and cause hearing damage if the exposure is for a prolonged amount of time. Some country and industry regulations stipulate necessary actions to be taken by the employer and employee, including audiometric testing and the reduction of noise exposure at the work place, and should be in line with international norms and latest recommendations of the ISO standards (International Organisation for Standardisation, 1999). OSHA describes the range of typical sound levels in which a level of 140 dB_A can begin to cause pain as shown in Figure 2.1 (Occupational Safety and Health Administration, 2013).

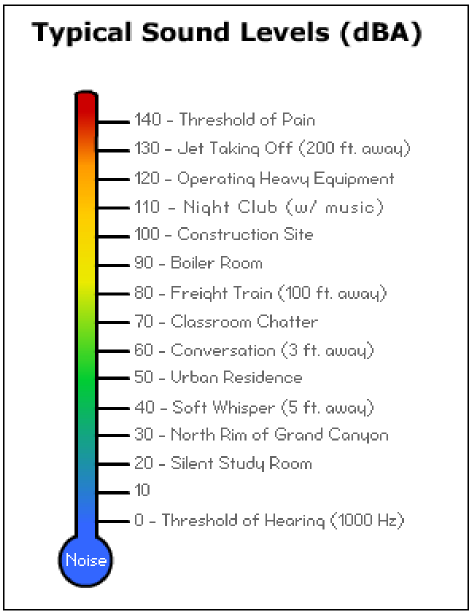


Figure 2.1: Decibel scale of typical sound levels (dB_A). Image reproduced from Occupational Safety and Health Administration (2013).

2.2 Effects of Noise Exposure

Numerous noise studies have been undertaken for different target areas such as aviation/aircraft noise, land transportation noise, domestic noise, industrial noise, etc. Depending on the objective of the study partaken by university researchers, governments, health and safety organizations or global foundations for human wellbeing, the reporting of the health effects is tied towards their target audience. For example, a study on noise in residential areas would most likely focus on the impact of noise towards night time activities such as sleep of those residents.

2.2.1 Occupational Hazards

Research by the U.S. EPA (1974) has shown that continuous noise levels above 90 dB_A appear to have potentially detrimental effects on human performance, mainly on long hours monitoring (vigilance) tasks, information gathering and analytical processes. OSHA (2013) provides extensive information and statistical analysis pertaining to the effects that a person exposed to excessive occupational noise could experience. Noisy environments can affect the human body in many ways namely(Occupational Safety and Health Administration, 2013):

1. Auditory Effects - noise-induced temporary and permanent threshold shift, acoustic trauma, and tinnitus. These effects can be worsened if workers have extended shifts (eight hours or more). Another drastic cause of sudden hearing impairment is acoustic trauma which refers to a temporary or permanent hearing loss due to a sudden, intense acoustic or noise event, such as an explosion. This is known as instantaneous or impulse sounds.

2. Worker Illness and Injury Reports - Hearing loss represented 12% of all 2010 occupational illnesses, shown in Figure 2.2 (Occupational Safety and Health Administration, 2013). This represents more than 18,000 workers who experienced significant loss of hearing due to workplace noise exposure.

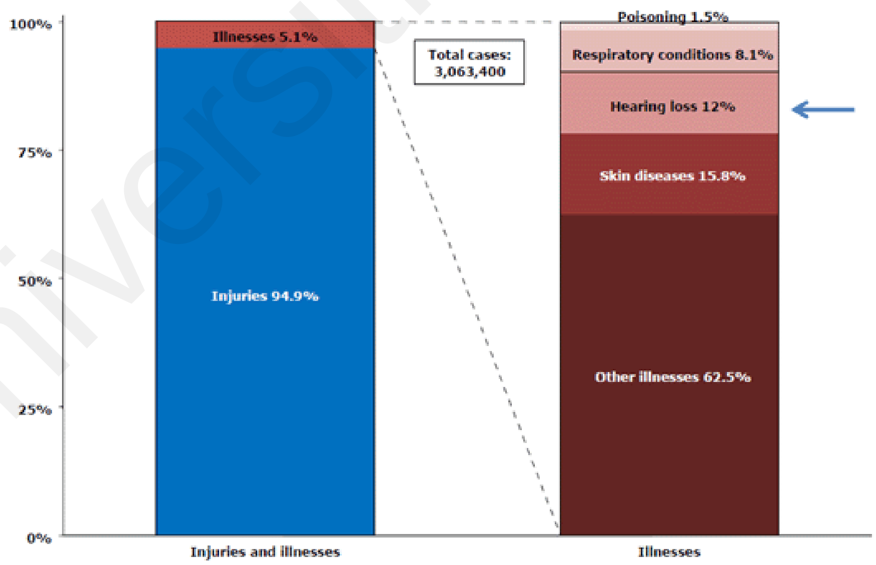


Figure 2.2: Distribution of nonfatal occupational injury and illness cases in 2010. Adapted from Occupational Safety and Health Administration (2013).

The Malaysian Factories and Machinery (Noise Exposure) Regulations (1989) were legislated for occupational safety and health relating to noise. It stipulates the maximum permissible noise levels and exposure limits that can be allowed at the work place. For example, for a continuous eight hour working day exposure is 90.0 dB_A that corresponds to a maximum allowable 100% noise exposure (Malaysian Ministry of Labour, 1989). A summary of these results is shown in Table 2.1.

Table 2.1: Summary of allowable time exposure for occupational noise limits. Adapted from Malaysian Ministry of Labor (1989)**.**

Noise Levels, Leq	**100% Exposure**	**50% Exposure**
85.0 dB_A	16 hrs	8 hrs
90.0 dB_A	8 hrs	16 hrs
95.0 dB_A	4 hrs	8 hrs
100.0 dB_A	2 hrs	4 hrs
105.0 dB_A	1 hr	2 hrs
110.0 dB_A	30 minutes	1 hr

Between years 2003 to 2008, Witter et al. (2008) noted that there were limited studies pertaining to research on noise and health effects on oil and gas workers, and even less that addressed the health effects of noise on communities surrounding oil and gas operations. They analysed 24 relevant studies within this time frame (Witter et al., 2008).

Zhang et al. (2016) discuss the potential safety risks associated with drilling facilities and workers, along with suggestions on how to combine risk management guidelines with information technology. A web and mobile version of an intelligent safety risk management software for drilling operations was developed that could be used to anticipate risks of each drilling activity. Insufficient control of operational drilling risks can potentially lead to catastrophic results, loss of equipment or assets, cause irreversible damage to the environment and worst of all, loss of human life. Some of the prevailing reasons to why incidents still occur in such a mature industry could be due to poor awareness or implementation of adequate safety risk management tools, safety risks, safety risk information sharing and incomplete safety risk management systems (Zhang et al., 2016).

2.2.2 Sleep Disturbance and Health Effects

The World Health Organization commissioned a noise study in Europe to investigate the relationship between noise and health effects. For any noise level less than 30 dB_A $L_{night, outside}$, no effects on sleep were observed except for a slight increase in the frequency of body movements during sleep (WHO Europe, 2009). There is no sufficient evidence that the biological effects observed at levels below 40 dB_A $L_{night,outside}$ are harmful to health. However, adverse health effects are observed above 40 dB_A $L_{night,outside}$ such as self-reported sleep disturbance, environmental insomnia and increased use of omnificent drugs and sedatives to promote sleep which hereby confirms 40 dB_A as equivalent to the lowest observed adverse effect level (LOAEL) for night noise (WHO Europe, 2009).

Figures 2.3 and 2.4 show the average motility and infarcts that is expressed as a percentage increase (compared to a baseline number); the number of highly sleep disturbed people is expressed as percent of the population; complainers are expressed as a percent of the neighbourhood population; awakenings that are expressed in number of additional awakenings per year (Babisch, 2002). Both study areas respectively represent road traffic and aircraft noises during night time, when people are sleeping and resting, showing an increase in the number of awakenings above an exposure of 50 dB.

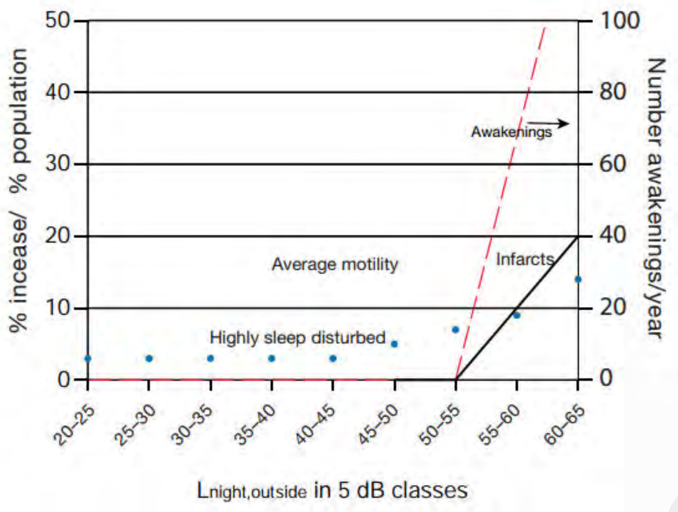


Figure 2.3: Effects of road traffic noise at night. Image reproduced from Babisch (2002).

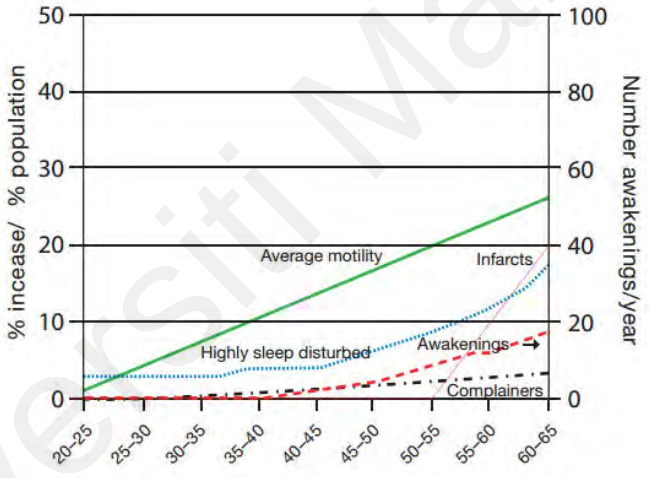


Figure 2.4: Effects of aircraft noise at night. Image reproduced from Babisch (2002).

The Environmental Protection Agency recommends environmental noise levels lower than a threshold of 30.0 dB_A to minimise sleep disturbances (U. S. EPA, 1974). The sleep disturbances and effects seem to be linked to the consequence of reduced sleep quantity, and the effect that has on resulting reduced total sleep quality (Matsumoto et al., 2017). Figure 2.5 shows the relationship between noise exposure and the potential health related issues it could create; with irreversible damages if not managed adequately (Babisch, 2002).

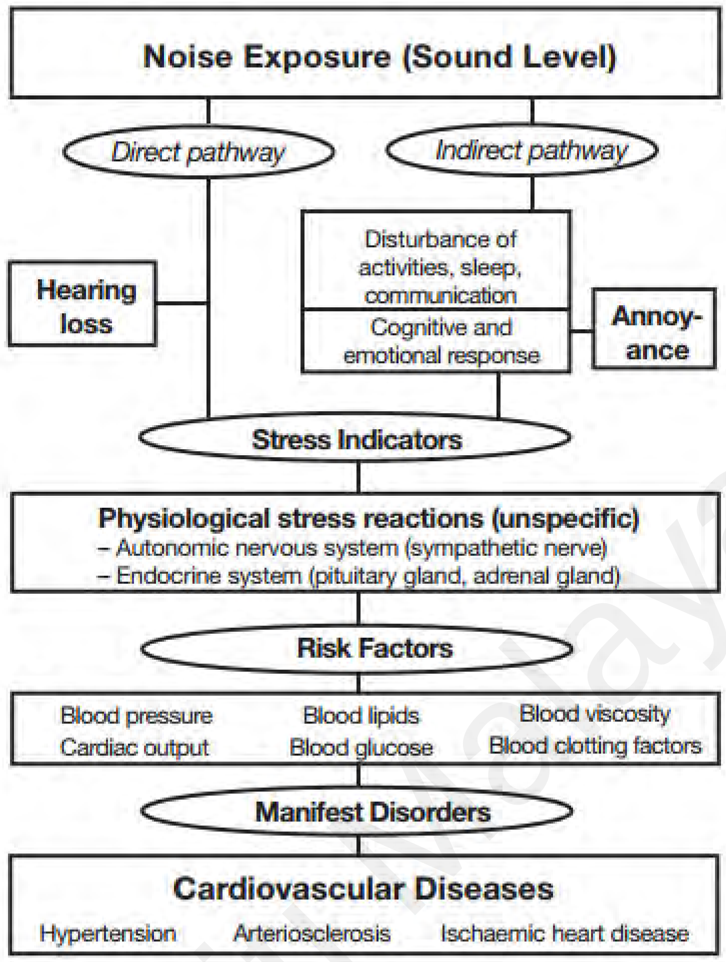


Figure 2.5: Noise effects reaction scheme. Image reproduced from Babisch (2002).

Other results of excessive noise include hearing impairment, speech intelligibility, physiological functions (hypertension and ischaemic heart disease, increased blood pressure and an increased risk for hypertension, cardiovascular effects), mental illness, performance, social and behavioural impact, annoyance, interference with speech perception (Berglund et al., 1999). Cardiovascular disease could appear when there is long term exposure to noise above 65.0 dB or acute exposures above 80.0 to 85.0 dB (Goines & Hagler, 2007). Other research conducted on the effects of noise pollution on cardiovascular diseases suggests positive association between the two due to reduced quality sleep that can cause multiple biological impacts towards noise-induced hypertension (Tsaloglidou et al., 2015).

2.3 Current and Historical Assessment of Noise Pollution

Today, oil and gas activities have a reputation for being an immediate and long-term threat to global, national and regional public health and climate due to a noted lack of education when it comes to public knowledge about fracking (which involves drilling wells and then hydraulically fracturing shale rock with large quantities of water and additives at high pressure) with the aim of extracting as much oil as possible (Epstein & Selber, 2002; Hammer et al., 2014; Kolk, 2001; Weston & Macfarlan, 2015; Witter et al., 2008). Fourteen reports, governmental studies and policies were analysed by Watterson and Dinan (2018) to conclude that there is no clear consensus as to the quantifiable damage of (unconventional wells) oil and gas extraction processes towards public health. The report hence suggested additional longer-term research be conducted (Watterson & Dinan, 2018).

In terms of urban noise surveys, Brown and Lam (1987) suggested that there were four different survey types in terms of their primary spatial-sampling orientation; random sampling, sampling by land use categories, receptor-oriented and source-oriented sampling. The type of environment would dictate which survey type was adequate for analysis of the resultant sound levels measured.

In recent years, there has been an increased number of studies conducted to understand the extent of environmental pollution from oil and gas activity. One such study by Ward and Nicol (2016) provided a comprehensive analysis of public health concerns caused by Canadian shale gas production (including the pre-production stages of drilling, hydraulic fracturing, and well completion, as well as abandonment) which showed a big gap in information gathering related to the impacts of noise pollution (Ward & Nicol, 2016). This is common in for the oil and gas activity, with little or no mention of noise impacts. Noise generated by oil and gas/petrochemical processing installations is generally an issue within the plant itself as well as its impact towards the community locations within the surrounding environment (Addiscombe Environmental Consultants Limited, 2018). This section will review various literature pertaining to noise generated by urban transportation, oil and gas studies as well as industrial noise.

2.3.1 Urban Transportation Noise Studies

Urban noise studies exist for noise generated by humans (schools, businesses, marketplaces and construction) as well as from transportation studies (ground traffic and aviation). In India, motor vehicles are reported to be the main source of noise, contributing 55% to the overall urban noise (Banerjee et al., 2008) yet while in Europe, road traffic noise accounted more than 90% of unacceptable noise levels (daytime LA_{eq} > 65.0 dB_A) (Manea et al., 2017).

Garg et al. (2017) conducted a detailed road noise study across seven major cities in India with continuous noise monitoring throughout the year. The average L_{day} (06–22 h) and L_{night} (22–06 h) values observed in the year 2011–2014 for the 35 locations studied in which 14 locations were in a commercial zone, five industrial, seven residential and nine silence zones were described. The long-term noise monitoring shows that ambient noise levels marginally increased since the past four years in 29 out of 35 sites (82.9%) studied. The L_{day} and L_{night} levels observed for 35 sites for the year 2014 reveals that only four industrial sites (11.4%) meet the ambient noise standards (Garg et al., 2017).

Various noise management strategies should be undertaken to reduce the ambient noise levels to below the specified standards. These include enforcing bans on pressure horns of vehicles, installation of noise barriers around hospitals and schools, extensive plantation of trees, vegetation and earth beams, noise monitoring and control of loudspeakers, generator sets, roadways and civil planning, use of porous elastic road surfaces, timing traffic lights and restricting entry of heavy vehicles in residential areas and silence zones especially during night time (Garg et al., 2017).

Bouzir et al. (2017) identified 47 measurement points and A-weighted L_{eq}(1-min) were recorded by a Landtek SL5868P sound level meter in the city of Biskra, Algeria. Results showed that the urban noise level varied from 55.3 dB_A to 75.8 dB_A on weekdays and from 51.7 dB_A to 74.3 dB_A during the weekends (Bouzir et al., 2017). Figure 2.6 shows that 70.2% of the results of the weekday measurements and 55.30% of the results of the weekend measurements have sound levels that exceeded the 70.0 dB_A noise limit designated by the Algerian law and the World Health Organization recommendations (Bouzir et al., 2017; WHO Europe, 2009).

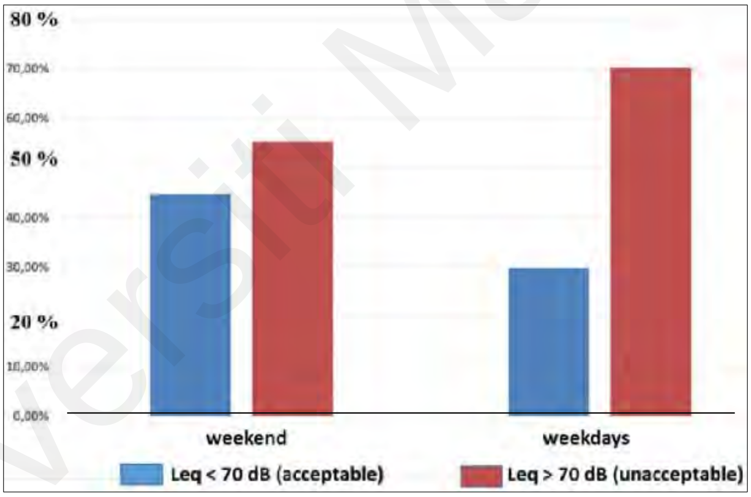


Figure 2.6: Excess of noise level compared permissible levels by Algerian law. Image reproduced with permission from Bouzir et al. (2017).

Weather conditions was also captured and considered during data gathering, namely temperature (°C), humidity (%) and wind (weak/heavy speeds). Weekday values were higher in some areas yet higher during the weekend in others. Bouzir et al. (2017) explained that the potential reason for this trend was due to the increase in the speed of the vehicles during the weekends due to the low traffic flow and, on the weekend unique events like markets that are in several locations in the city which increased the sound levels as more people spend time outside the home running errands or spending time with family and friends (Bouzir et al., 2017).

2.3.2 Oil and Gas Noise Studies

As early as 1975, noise studies on drilling offshore platforms had been undertaken. In more recent years, studies indicate that "oil and gas activities produce noise at levels that may increase the risk of adverse health outcomes, including annoyance, sleep disturbance, and cardiovascular disease" (Hays et al., 2016). At the same time, the public usually complains about noise generated from drilling rigs (Weston & Macfarlan, 2015). Fulton and Kuo (2013) found that in marine underwater environments, pressure measurements in the air and water differ by 26 dB. By understanding where the excessive sound comes from, the right risk management steps can be implemented to limit the resulting noise to within acceptable levels.

2.3.2.1 Drilling and Completion Studies

Noise from oil and gas development comes from several sources: truck traffic, rig equipment, machinery such as cranes, engines, well pumps and compressors and others. Upstream or downstream activities utilize different equipment and daily operating procedures, which generate various levels of sound (Stollery, 2014).

According to one of the earlier studies on noise generated by drilling activities on offshore platforms, the principal areas of concern of high noise levels are those that come from the drilling platform itself – the engine room, mud mixing and cement pump areas and living quarters (Melling et al., 1975). The study defined various guidelines for conducive work and living conditions, as workers could spend up to 28 days living on the rig site during their shifts; 60.0 dB_A for good speech communication in loud areas and

40.0 dB_A in living quarters for good rest (Melling et al., 1975). The major noise sources from drilling activity came from brake drum squealing (93.0 – 96.0 dB_A which dropped to 78.0 dB_A when not operating), drawworks direct current motors (92.0 – 95.0 dB_A), mud pump rooms (93.0 – 97.0 dB_A), diesel engine power generators (106.0 – 109.0 dB_A) and cranes (103.0 – 111.0 dB_A in the crane drivers cabin close to the engines) (Melling et al., 1975). All measurements were compared against the limit of L_{eq} of 90.0 dB_A for continuous exposures of eight hours.

Redman (1986) studied the process of drilling environmentally sensitive wells in Southern England. Due to pressure from residents and workers close to the drilling site, the local (Southampton) university was commissioned to provide advice on appropriate acoustic control measures. The result was the Wolfson Unit Report No. 2963 (1984) that specified the following noise limits (when measured outside the nearest dwelling):

i) 35.0 dB_A at L_{90} level (2200 hrs to 0700 hrs)

ii) 40.0 dB_A at L_{10} level (0700 hrs to 2200 hrs)

The L_{90} level was the best measure of steady noise radiated by major rig noise sources e.g. generators, mud pumps, solids control equipment and rotary systems and should be reliably monitored during the night. The L_{10} level was a measure of the noise associated with the intermittent noise sources e.g. material handling, site vehicles and other activities most of which take place during the day (Redman, 1986).

In 2004, a gas well was drilled on the Charleston University campus to reduce utility bills (by using gas as an energy/heat source). In researching the requirements for drilling a well in an urban setting, it was found that the well distance had to be more than 500 ft to the nearest residence, to ensure minimal imposition to the community (Spady & Poole, 2005). Residents were concerned about noise, safety during operations, inconvenience from traffic, road closures and safety after well was completed (vandalism, terrorism, children or animals could be hurt by exposure to the machinery and equipment). Noise studies were performed to forecast potential noise impacts. The findings showed that the ambient noise levels were between 48.0 and 85.0 dB_A (comparable to a quiet office or inside a moving car on a highway), and any noise from drilling rig components or construction was less than 70.0 dB_A (below ambient levels outside of a sports field) when measured from 200 - 500 ft from the source (Spady & Poole, 2005).

At the source however, noise levels of major rig equipment were high (89.0 dB_A for power generators, 98.0 dB_A for a backhoe/digger, 98.0 dB_A for drilling rigs and 101.0 dB_A for air compressors) (Spady & Poole, 2005). The study presented some key points for noise measurements on drilling sites which include distance to residential areas, communicating progress to communities for their agreements as part of obtaining drilling permits, measurement of sound at specific distances from the source (200 ft, 300 ft and 500 ft) and weather and temperature data collected and reported during noise surveys (Spady & Poole, 2005). Weston and Macfarlan (2015) provided a comprehensive summary of typical noise levels generated from major drilling rig and production equipment sources. Table 2.2 summarizes the results from that study.

Table 2.2: Noise measurements of rig and production activity in La Plata. Adapted from Weston & Macfarlan (2015).

Location within drilling site	Noise Level (dB_A)	Measured Distance
Typical compressor station	50.0	375 ft from property boundary
Pumping units	50.0	325 ft from well pad
Fuel and water trucks	68.0	500 ft from source
Crane for hoisting rigs	68.0	500 ft from source
Concrete pump used during drilling	62.0	500 ft from source
Average well construction site	65.0	500 ft from source

A study by the Southwest Pennsylvania Environmental Health project (Environmental Health Project, 2017) provides a summary of current research findings of noise levels from unconventional oil and gas activities. It shows that the noise measured from various sample drilling sites did exceed the allowed limit. All measurements were made and presented from a distance because barriers, topography and other factors between the sensor and noise source can affect noise measurements (Noise Pollution Clearinghouse Organization, 2017). Examples of the noise levels measured near selected oil and gas sites are as follows (Environmental Health Project, 2017):

- Fort Worth (2006): 71.0 – 79.0 dB_A drilling noise at 200 ft from well
- Fort Worth (2006): 102.0 dB_A rig generator at 10 ft
- New York (2011): 44.0 to 68.0 dB_A during drilling at 250-2000 ft
- New York (2011): 72.0 to 90.0 dB_A during fracking at 250-2000 ft
- New York (2011): up to 102.0 dB_A during fracking at 50-500 ft
- West Virginia (2013): one-hour noise measurements at several of 7 well pads exceeded 55.0 dB_A annual 24-hour average

These results were further consolidated by Radtke (2016) in collaboration with the Colorado Oil and Gas Conservation Commission (COGCC) and researchers at Colorado State University (CSU). This study is elemental in providing industry relevant information related to noise generated during drilling, completion, testing and production activities, as well as studying the effectiveness of sound walls installed around drilling and flaring sites. The sound meters used for recording noise levels were four Larson Davis noise dosimeters (Spark model 706RC) and one Larson Davis model 824 handheld sound-level meter with 23 oil and gas sites selected for sampling between November 2014 and March 2015. Sampling locations were not differentiated by the various company operators yet focused on the four oil and gas activity categories. A and C weighted sound averages were taken, with octave band analysis performed to identify the major frequencies at each location because the study identified distance as one of the variables that impacts the noise measured (Radtke, 2016). Distance was measured using a Nikon 550 Rangefinder made in Tokyo, Japan (measurements were collected at approximately 107 m, 53 m, 27 m, 13 m and as close as safely possible from the most significant noise source in each main direction). Five second and 15 min L_{eq} measurements were taken when oil and gas machinery and equipment were operating and reported according to the COGCC regulations of day and night (day 7 am to 7 pm; and night as 7 pm to 7 am). The study showed that hydraulic fracturing sites had the highest sound levels while sites in the production phase had the lowest levels. Even so, as the distance from the noise source increased, the average sound levels for hydraulic fracturing sites became very similar to the average sound levels of drill sites. The C-weighted sound level measurements were significantly higher than the A-weighted sound measurements at every oil and gas site (Radtke, 2016). This indicates low frequency noise at the targeted sites. The study included noise contour maps highlighting the areas with the highest to lowest noise readings based on geographic location identifiers. The results of this study can be summarized as follows (Radtke, 2016):

1. Noise characterization without walls –
    a. Sound (dB_A) levels measured (without walls installed) showed a similar tendency of reducing levels with increasing distance to noise source. The average differentials were 14 dB_C and 23 dB_A. The highest noise levels were found at fracking sites, followed by completion sites, yet both showing the lowest noise measurements at production sites.
    b. Sound (dB_C) levels measured showed a reduction in noise with increasing distance between sound level meter and noise source. The highest sound measured was 94.0 dB_C just 14 m from fracture sites, and the lowest was 62.0 dB_C at 107 m from the production site. The highest trend of noise was generated by fracking sites, followed by drill site, completion sites and finally production sites. All areas showed a reducing tendency with increasing distance to the source.
2. Effectiveness of sound wall installations - It was shown that both A and C weighted sound levels reduced when sound walls were installed at drilling and fracturing sites. With the installation of sound walls, sound levels at drilling sites were reduced from 65.0 dB_A to 59.0 dB_A (6 dB_A reduction) and 79.0 dB_C to 73.0 dB_C (6 dB_A) at 107 m from the noise source. Sound levels at fracturing sites were reduced from 70.0 dB_A to 59.0 dB_A (11 dB_A reduction) and 80.0 dB_C to 74.0 dB_C (6 dB_A reduction) at 107 m from the noise source. These levels exceed the local regulations of 65.0 dB_C and 55.0 dB_A.

Even while being quite comprehensive in the field of oil and gas noise characterization, the researchers encountered certain limitations such as (Radtke, 2016):

- limited oil and gas sites for sampling that meet the inclusion criteria that limited consistency especially in measuring noise from fracturing sites with barriers/enclosures and completion activities
- limited access to noise source due to safety factors (unsafe operating conditions such as high thermal radiation during flaring operations)
- potentially skewed data caused by acoustic shadow trial measurements of sound measurements collected within 91 m outside of the sound wall
- variability of day and night could not be accurately determined due to lack of 24 hr sampling data set (even with 5-second and 15-minute interval) measurements during ¨worst-case¨ scenarios or expected loudest noise generating activity taking place

2.3.2.2 Testing and Flaring Studies

Ghadyanlou and Vatani (2015) defined flaring as ”A safe and effective method for the disposal of hydrocarbons in situations where there is an equipment failure or in emergencies, such as instrument failure, power failure or a fire in the plant”. Flaring is a significant source of greenhouse gases emissions, contributing about 400 Mt-CO_2 emissions worldwide (Emam, 2016). Many of the resultant vapours are corrosive, explosive or flammable and cannot simply be released into the atmosphere, so burning them is essential (Ghadyanlou & Vatani, 2015). Besides heat, noise from flaring can cause discomfort and annoyance to those working or living nearby. Bussman and Knott (2000) conducted flaring experiments that showed flaring noise could be reduced (from initial values of 100.0 dB_A) by injecting water at various angles into the flare stream. The experiment was successfully able to reduce noise significantly for all flaring rates and exceeded a 15 dB_A reduction from an initial value of 115.0 dB_A. A 75% reduction on heat radiation was also observed. Hantschk and Schorer (2008) corroborated that noise from flaring in that it could go up to 103.0 dB_A. Noise measurements are to be accurately reported as a function of distance (Bouzir et al., 2017; Radtke, 2016; Redman, 1986; Weston & Macfarlan, 2015). Table 2.3 presents the noise and thermal radiation that was measured by Ghadyanlou and Vatani (2015) in their experiment.

Table 2.3: Thermal and noise emissions from flaring. Adapted from Ghadyanlou & Vatani (2015).

Distance, m	Thermal Radiation, kW/m^2	Noise level, dB
70	6.04	84.8
80	5.88	84.5
90	5.67	84.1
100	5.42	83.7

Other researchers studied the various parameters that defined flaring noise, namely flare type and geometry, smoke suppression equipment, flare load, properties of the flare gas, flame volume and length, control valve parameters, noise characteristics (spectrum, directivity, tonality and impulsiveness), noise control features (mufflers, absorptive linings, noise screens, insulation) and conditions of sound propagation (Bussman & Knott, 2000; Hantschk & Schorer, 2008). Hantschk and Schorer (2008) also suggested to use VDI guideline 3732 to mathematically predict sound emissions from flares. Smith et al. (2016) conducted noise measurements at varying distances of 100’-0” and 200’-0” to the East of the flare tip using two Norsonics NOR140 Type I noise meters at night. They shut off all non-essential equipment (compressors, forklifts, etc.) to minimize the background noise and avoid contamination of the noise results (Smith et al., 2016).

2.3.2.3 Oil and Gas Processing Studies

After drilling, completion and testing activities, a well is either put on production or abandoned (if not economically viable). The wells are hooked up to production lines and pumped to oil and gas processing/collection stations some distance away. According to an article by Boyle et al. (2017), compressor stations not only have compressor units, but other equipment such as scrubbers, strainers/filter separators, turbines, electric motors, reciprocating motors, gas cooling systems and mufflers.

A noise study was conducted in Maryland, USA that found residents living near a natural gas compressor station were exposed to high noise levels. 24-hour sound measurements from a total of 11 homes in Doddridge County were taken close to the two compressor stations (Boyle et al., 2017). Indoor sound level monitors where installed in the bedrooms of the residents because that is where people spend most of their time when at home, and outdoor monitors were placed in the yard facing the natural gas compressor station (Boyle, et al., 2017). To ensure a representative sound level, inhabitants were asked not to play loud music or use the television for 24 hours in the room where the indoor monitor was placed. The study measured sound according to distance to the compressor station; located <300 m (n = three homes); between 300 and 600 m (n = three homes), between >600 and 750 m (n = two homes), or more than 1000 m (n = three homes) (Boyle et al., 2017). For a control set, homes that were located >1000 m from the nearest compressor station were selected. The study also analysed the sound measured during day time and night time which was important for understanding the potential impact to rest and sleep. A total of 29, 612 one-minute measurements was collected from the selected 11 homes on 22 total sites (11 indoors and 11 outdoors). The control (or baseline) sound levels were 51.6 dB_A for the outdoor, and 42.2 dB_A for indoors. The outdoor sound levels ($L_{eq,\ 24hr,\ outdoor}$) recorded did indicate that homes located <300 m from a compressor station had the highest sound levels, regardless of when the sound levels were monitored. There is no clear correlation of sound reducing with increasing distance from the compressor station. This could be explained by further analysing the numerous uncontrolled environmental factors that exists during sounds collection. The summary sound levels with various distances to the nearest compressor station is shown in Figures 2.7 and 2.8 (Boyle et al., 2017).

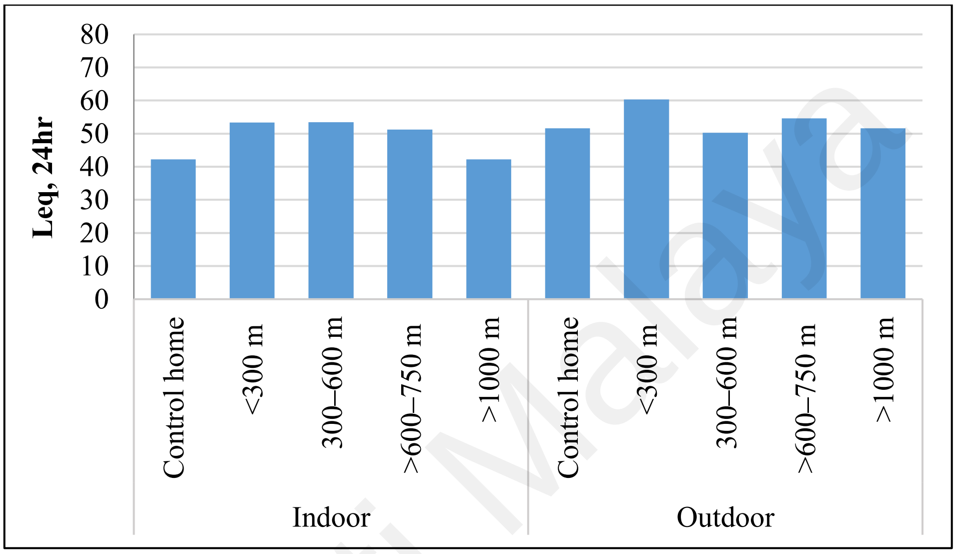


Figure 2.7: Leq, 24hr sound levels (dB$_A$) by proximity and location (indoors vs. outdoors). Adapted from Boyle et al. (2017).

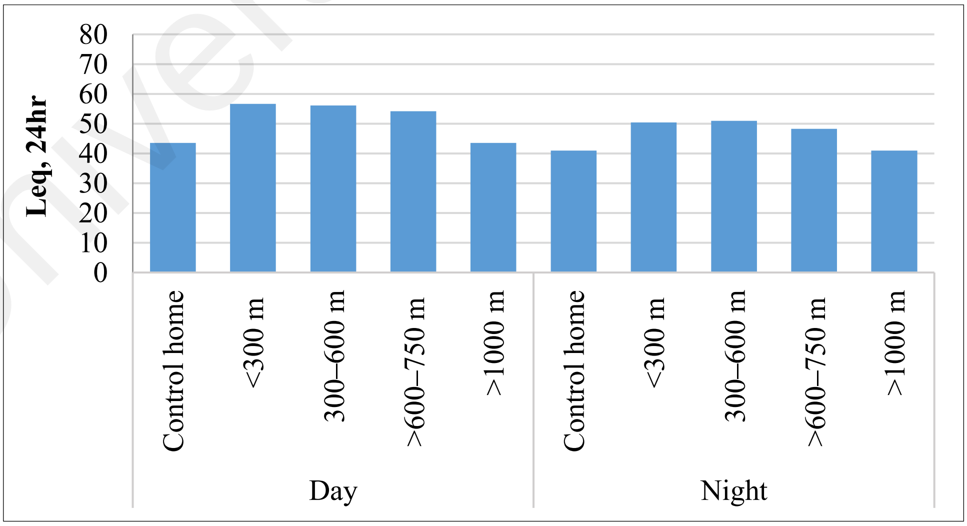


Figure 2.8: Leq, 24hr sound levels (dB$_A$) by distance and time of day. Adapted from Boyle et al. (2017).

2.3.3 Industrial Noise Studies

They are numerous studies conducted for monitoring, recording and analysis of sound generated by the construction industry and its impact towards workers and residents near the activity. One such study conducted by researchers in Xinjiang University (China) describes the noise levels caused by construction equipment at work sites, the impact of these noises and what was done to manage this pollution risk (Yin et al., 2017). It showed that on average, the noise generated by all types of construction equipment such as air drills, carpentry, compactors and electric drills all exceed 90.0 dB_A which exceeds the guidelines recommended (WHO Europe, 2009; Yin et al., 2017). The results of the study are shown in the bar chart in Figure 2.9.

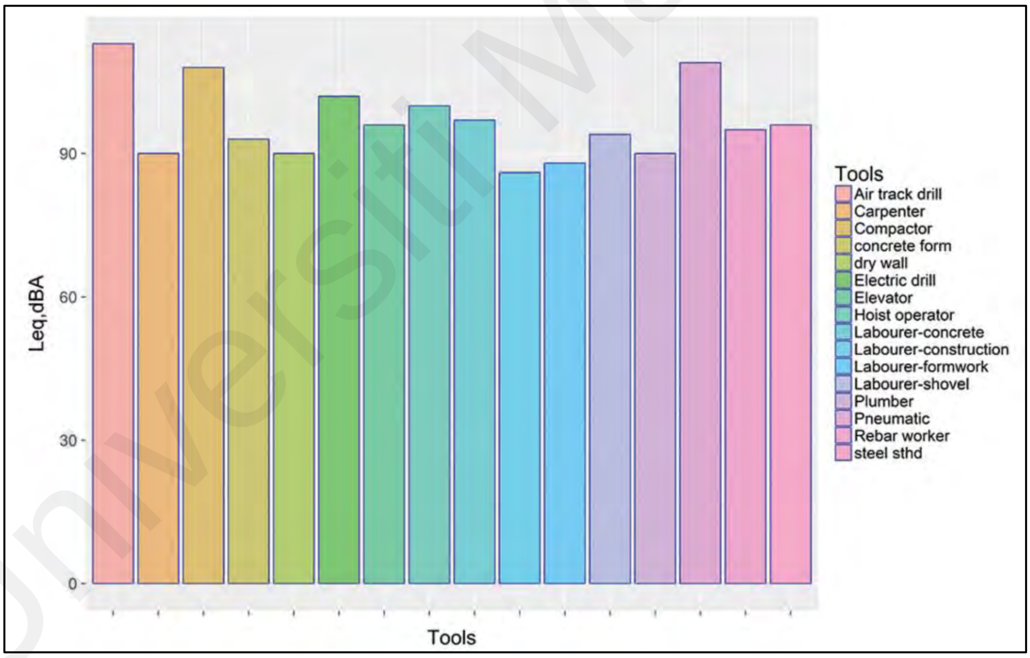


Figure 2.9: Leq from construction activity in China. Image reproduced from Yin et al. (2017).

In a study related to occupational health and safety systems at selected sewage treatment plants, it was found that excessive sounds (L_{Aeq} 94.2 dB_A) were produced by wastewater flow pumps and air blowers that created an on-site health risk which could cause auditory effects, including hearing loss, speech interference and psychological/sociological impacts such as annoyance (Malakahmad et al., 2012). Ismail et al. (2008) studied the environmental noise impact from four different industrial projects in Malaysia, namely a Petronas refinery extension project MG-3, Janamanjung power station in Perak, a concrete plant in Semenyih and a co-generation plant in Melaka which showed that L_{Aeq} noise levels at the selected monitoring stations were between 45.2 to 76.2 dB_A during the day-time and 42.8 to 56.0 dB_A during night time (Ismail et al., 2008). These results were similar to typical noise impacts from other industrial development projects in Malaysia. Zolfagharian et al. (2012) conducted an interview of 15 construction professionals to investigate the frequency and severity of environmental impacts across construction of residential buildings in Malaysia. It showed that construction activities were the second highest source of noise pollution, where transportation resources were the first. This strengthens the need for a more effective awareness campaign and the implementation of noise control strategies such as barriers and application of noise protective tools (Zolfagharian et al., 2012).

Another study was conducted to determine the occupational hazards in 30 selected wooden furniture factories located in Malaysia, Thailand, Indonesia and Vietnam, focusing on impacts from dust, noise and chemical solvents exposure (Ratnasingam et al., 2010). The study aimed to identify the extent of hearing damage among the wooden furniture industry workers over nine months period between March and November of 2009. A calibrated portable sound level meter (standard BS6504) was used to measure the occupational noise, with the possible noise-induced hearing problems quantified by audiometric tests, using audio chambers in the range of 500-8000 Hz, with 500 Hz intervals. Results revealed that 43% of the factory workers were exposed to a noise level higher than the recommended permissible limit, with 25.8% of them having a slight handicap with permanent threshold shift between 30.0 and 40.0 dB_A, while 8.9% of the workers showing a significant handicap with a permanent threshold >40.0 dB_A

(Ratnasingam et al., 2010). The research also revealed that the rough milling department, which involves heavy-duty operations was discovered as the major noise contributor, generating a maximum sound level of 130 dB_A which was worsened by the limited supply and enforcement of hearing protective devices utilization (Ratnasingam et al., 2010).

2.4 Factors Affecting Noise

Understanding the factors that impact the level of noise is critical in identifying the most suitable abatement techniques. This is valid for all environments, be it residential, industrial, natural habitats and ecosystems, transportation, or a mixture of any of these. Analysing noise can be complicated, due to the extensive variability in its source (WHO Europe, 2009). Some of the factors that must be considered include measuring exposure or calculating/predicting exposure, choice of noise indicators, population distribution, time-activity patterns of the exposed population and combined exposures to multiple sources of noise generators (WHO Europe, 2009).

According to a booklet by the Noise Pollution Clearinghouse Organization (2017), noise monitoring is common in noisy industries (which is achieved via installation of a noise monitoring system) but there are challenges to successfully controlling noise in drilling environments. These challenges include issues related to noise generation (causes of the noise such as activity, equipment, population, etc), noise measurement (sensor type, noise contamination from external factors such as other urban noise, weather, etc) and the noise measurement complexities itself (Stollery, 2014). The American National Standards Institute has defined various factors that affect the sound level meters sensitivity, namely atmospheric pressure, intense sound fields, vibration, air temperature and humidity (American National Standards Institute, 1983).

Some of the factors that impact noise measurement at the receiver area include absorption and transmission, having open/closed windows (generates up to 20-30 dB_A difference), placement of microphone stations (sensors usually installed away from facades and obstacles, downwind, in dry conditions, wind speed of less than 5 m/s, and with the microphone 1.2 - 1.5 m above ground level) and validity of the sensor functionality via calibration (Boyle et al., 2017; NIOSH, 1998; Noise Pollution Clearinghouse Organization, 2017; OSHA, 2013; Wang et al., 2005; WHO Europe, 2009).

Atmospheric attenuation and meteorological conditions such as wind and temperature are some of the factors affecting noise propagation. Atmospheric attenuation refers to the reduction of noise as it passes through air and is dependent on factors such as distance from source (being the most influential), frequency of the noise (high or low), ambient temperature, relative humidity and ambient pressure. Wind speed increases with altitude whereas temperature gradients create effects such as wind gradients, except that they are uniform in all directions from the source (Noise Pollution Clearinghouse Organization, 2017).

WHO Europe (2009) also reported that the link between a barrier and noise is not always easily obtained. By controlling one factor, another could be compromised. Residents with closed windows reported a reduction of sleep disturbances due to noise, but also reported an increase in sleep disturbances due to poor ventilation. This could imply that noise levels are lower (with closed windows), yet adverse health effects increased which could skew research results on noise impact towards human health (WHO Europe, 2009). Schreckenberg (2012) reports a much steeper increase in the incidence of closed windows when road traffic noise reaches elevated levels, than in the case of railway noise. Even when night-time noise levels reach 55.0 dB_A, only 35% of the residents exposed to railway noise reported that they closed their windows at night.

Most levels mentioned in this report do not take background levels into account. Where long-term L_{Aeq} levels are related to effects like hypertension and self-reported sleep disturbance, background levels are ignored, but could obscure the effect at the lower end of the scale (Schreckenberg, 2012). Physically constructed barriers have been reported to have sound-insulating and sound absorbing properties which reduce overall sound levels (Witter et al., 2008).

2.5 Noise Pollution Management

Risk management requires understanding of an issue to identify and implement adequate prevention and mitigation steps to provide a safe working and living environment. Weston and Macfarlan (2015) state that noise control is most often addressed via a combination of common law, nuisance law and/or local codes and ordinances. The U.S. Environment Protection Agency (1974) recommends an indoor day and night noise level (L_{dn}) of 45.0 dB, which translates to a night time average sound level of 35.0 dB as necessary to protect against sleep interference (U. S. EPA, 1974). The Occupational Safety and Health Administration (OSHA) mandates the criterion level at 90.0 dB_A for 8h for safe hearing levels (Occupational Safety and Health Administration, 2013). To ensure that the noise does not exceed unsafe levels, it is mandatory for organizations to engineer their operations to firstly prevent, and secondly mitigate excessive noise (Bies & Hansen, 2003; Occupational Safety and Health Administration, 2013). Some countries enforce strict noise limits during the night time by adding 5 - 10 dB as a substitute for the increased irritation of inhabitants to night sounds (Weston & Macfarlan, 2015). Table 2.4 below shows the permissible sound levels from various countries around the world (both developed and developing) as well as reference values from the WHO and European Commission. The values in Table 2.4 aim to provide a safe working limit for human hearing to potentially prevent injury caused by excessive or prolonged noise pollution.

Table 2.4: A-weighted noise level standards in selected countries of the world. Adapted from Chauhan et al. (2010).

Country	Industrial Area Day/Night Limit	Commercial Area Day/Night Limit	Residential Area Day/Night Limit	Silence Zone Day/Night Limit
Australian Capital Territory	65/55	55/45	45/35	45/35
India	75/70	65/55	55/45	50/40
Japan	60/50	60/50	50/40	45/35
U.S. (E.P.A)	70/60	60/50	55/45	45/35
W.H.O & European Commission	65	55	55/45	45/35

There exist various control measures for governments and corporations to control noise generated by oil and gas operations. There are three principal areas for defining a noise management plan that fully covers the industry approved and best practices for recommended noise management measures (WHO Europe, 2009). These areas are legal, engineering and education and information methods.

Garg et al. (2017) suggested noise mapping and zoning around roads, airports and industrial areas. OSHA (2013) defined four methods for treating noise sources which are modification, retrofit, substitution and relocation. Shubham et al. (2016) explained how noise muffling by increasing distance between the noise source and receiver could mitigate results. The National Institute for Occupational Safety and Health (NIOSH), the body providing occupational safety management guidance for all industrial workers, explains various ways that organizations can retrofit equipment and reducing exposure as a way of protecting employees from excessive noise (National Institute for Occupational Safety and Health, 1998).

Examples of potential risk measurement steps below is obtained from multiple reference sources (Berglund et al., 1999; Department of Environment Malaysia, 2016; European Environment Agency, 2017; Goines & Hagler, 2007; Qui et al., 2014; Shubham et al., 2016; Smith & Gloeckler, 1991; Stollery, 2014; U. S. EPA, 1974; Weston & Macfarlan, 2015).

Legally, governments and counties can enforce noise abatement via control of noise emissions, control of noise transmission, noise mapping and areas zoning (roads, airports, residences and industries), enforcing speed limits, restricting the hours of operation for noise-intensive activities, creating minimum requirements for acoustical properties of buildings as well as suggest orientation of buildings and traffic management. Some of the engineering solutions suggested include emission reduction by source modification (change of road surfaces, engine mufflers), new engine technology (electric motors), transmission reduction via enclosures around machinery (noise screens, barriers), noise muffling (increase distance of activity to road/residences), and passive protection (ear plugs; ear muffs; insulation of dwellings). In underwater marine environments, various noise reduction methods could include bubble curtains, pile caps, physical barriers and dewatered cofferdams (Fulton & Kuo, 2013). Another way to deal with the noise is via the biological method, i.e. sleeping pills, alcohol, or other medications. Education and information dissipation can be achieved by raising public awareness, monitoring and modelling of soundscapes to encourage research and development in further understanding noise and how best to manage its effects (National Institute for Occupational Safety and Health, 1998).

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

The research location was selected with approval from the oil and gas service company contracted to conduct and manage the drilling, completion and testing activities of the 14 wells drilled in Lodi county in Northern Italy from two drilling locations. The collected sound data provides valuable insight of noise generated by the drilling industry. While limited studies are available, public perception of drilling is bad based on the perceived detrimental impact of drilling on the environment (Adebayo & Tawabini, 2012). The names of the oil and gas operator, drilling contractors and service providers involved in these activities have been omitted from publication as they are not critical to the objectives of this research.

The project site is where drilling, completion and flaring activity is conducted near residential/industrial areas, making it an area where the local council and government have the prerogative to manage noise limits from drilling activities. Since drilling and well testing (flaring) activity will now take place in this urban area in Lodi county (Northern Italy), the sound levels should not exceed the permissible noise limits defined by the local council. This is the basis for this research. The site map in Figure 3.1 shows the aerial view of the metropolitan town and the current urban activities that take place in the area, shown as Locations 1 and 2.

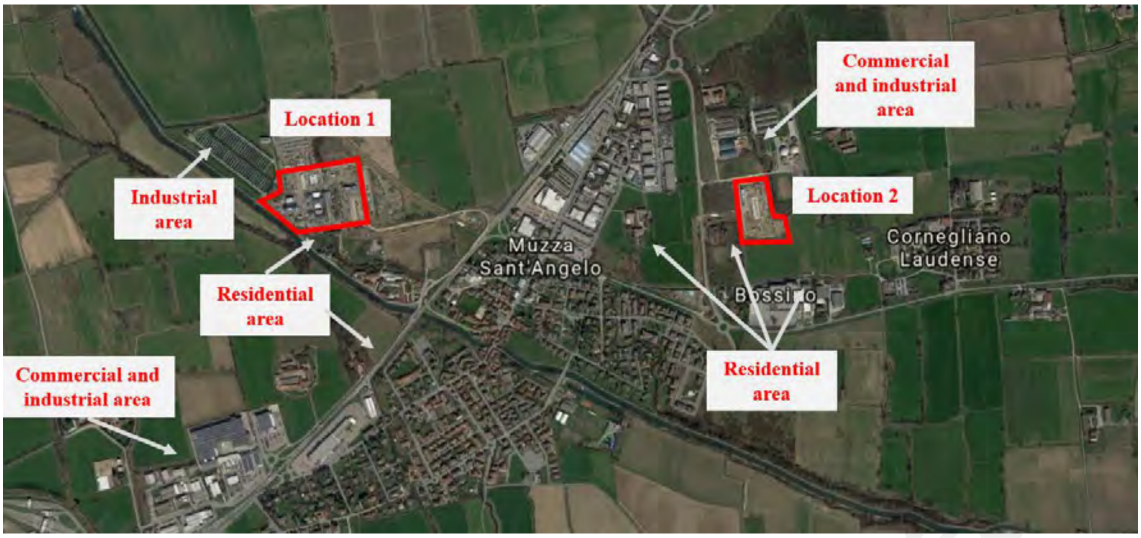


Figure 3.1: Residential, commercial and industrial areas surrounding Locations 1 and 2. Reproduced from Google Earth. Retrieved 2 June 2019 from https://earth.google.com/web/@45.28624945,9.4898132,77.61108483a,716.93044583d,35y,0h,45t,0r/data=ChMaEQoJL20vMGdyNWhqGAIgASgCKAI.

Sound was then measured daily from the beginning of the drilling campaign (after the drilling location was constructed and rigs were mobilized to location) until the end of the project. This entire drilling, completion and testing process took 1.2 years with 7 months of active sound measuring to collect as many data points as possible, making the analysis more substantial and to mitigate potential variability in the measurement scenarios. The onsite operations were performed in real time which means that it could not be controlled or repeated should portions of data collection fail.

The sound levels were measured using a Svan971 Level sound meter from Svantek (2018). This sensor is suitable for measuring sound in accordance to standards such as ISO 9612, OSHA, MSHA and ACGIH as well as being a Class 1 Sound Level Meter, compliant to IEC 61672 (Svantek, 2018). The meter is approved in most countries around the globe for sound measuring. In addition to being technically suitable, the sound meter was selected for its flexibility, light weight attributes, easy and powerful processing, auto-calibration and power efficiency which are important factors when taking field measurements.

3.2 Research Data

The type of data used in this research project is observational data, as an installed sensor/monitoring station was used to monitor and record the sound data. Since the data was measured instantaneously in real time (could be re-created), the variables of the sampling are clearly set to measure as effectively the most reliable information.

3.3 Research Design

The sections that follow will provide more information as to the reasoning behind each variable, its selection strategy and description of how and why it would impact noise. Table 3.1 shows the variables involved in this research design, both independent and dependent.

Table 3.1: Research variables.

	Data	**Variable Type**	**Description**
1	Location 1 & 2	Independent	Data collected in each location, 1 and 2
2	Wells (name)	Independent	The number of wells drilled in both locations, 1 and 2
3	Rig	Dependent	Each location had 2 different rigs operating, rig 1 and 2 with different equipment and machinery
4	Time of data - Day/night	Independent	Separate data taken during the day (6 am to 10 pm) and night (10 pm to 6 am)
5	High level activity	Independent	Description of high-level drilling / completion / rig move / testing activity
6	Noise barrier installation	Dependent	Describe if the noise barrier was installed around the rig
7	Flare burner enclosure installation	Dependent	Describe if a flare burner enclosure was installed during testing
8	Meteorological / weather conditions	Dependent	Hourly report of Temperature, Relative Humidity (%), Global Radiation (W/m^2), Precipitation (mm), Wind speed (m/s), Wind direction (°)

3.3.1 Research Area - Site Selection

The area of study is a city located in the north of Italy, approximately 25 kilometres southeast of Milan and about 8 kilometres west of Lodi. The location was selected because it is a metropolitan area with identified oil and gas activity that would take place in the urban area. Northern Italy has goals to store from 100 million cubic meter to more than 1 bcm in the coming years to invest in the gas storage business that aligns with Italy's aim of having a total of 13 storage facilities with a combined capacity of approximately 17 bcm (Savcenko & Elliott, 2019). The two drilling areas are in an urban metropolitan area, where people live and work and has a population of 2,917 (510/km^2 population density) (iStat Italy, 2018). Approximately 150 persons (from residences and businesses) and 60 rig workers a day are exposed to noise generated by the drilling and testing activities in varying degrees. Figure 3.2 shows the location map of the two drilling areas (Location 1 and Location 2) which is distanced 1.37 km between one location to the other.

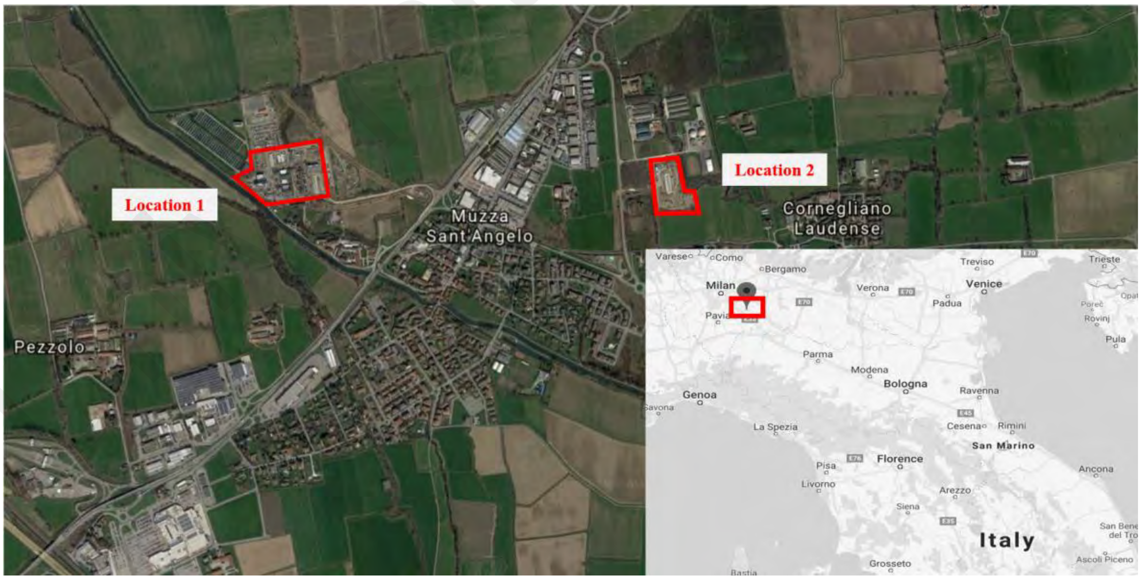
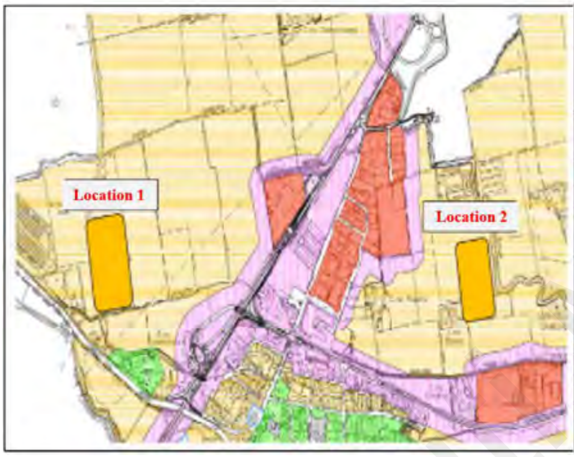


Figure 3.2: Location 1 and 2 of research site. Reproduced from Google Earth. Retrieved 2 June 2019 from https://earth.google.com/web/@45.28624945,9.4898132,77.61108483a,716.93044583d,35y,0h,45t,0r/data=ChMaEQoJL20vMGdyNWhqGAIgASgCKAI.

Due to the potential exposure from this anthropological activity, the local city council has already conducted a noise map study of the area which is published in the project EIA report. Figure 3.3 below shows the results of the noise map for the drilling and well testing areas (Location 1 and Location 2) and the corresponding day and night sound limits for each corresponding area. The two drilling and well testing locations are considered as Class 3 or mixed area which includes residential and industrial applications meaning that a daytime limit is set at 60 dB_A, and a night time limit of 50 dB_A.



Area	Day Sound Limit (06:00-22:00) dBA	Night Sound Limit (22:00-06:00) dBA
I- particularly protected area	50	40
II- Prevalently residential area	55	45
III-Mixed type area	60	50
IV-Prevalently industrial area	65	55
V-area of intense human activity	70	60
VI-Exclusively industrial area	70	70
Temporary Activity Area	-	-

Figure 3.3: Area Permissible Noise Levels (for day and night) by local council. Adapted from Centro Elettrotecnico Sperimentale Italiano Giacinto Motta SpA (2007).

For an area to be suitable for underground gas storage, the reservoir underneath the surface location needs to be able to hold natural gas for future use and have a good rate at which that gas can be withdrawn (Verga, 2018). Verga (2018) also noted that depleted oil and gas reservoirs, deep saline formations, salt caverns and un-minable coal beds are favourable conditions for safe geological storage of natural gas. To reach the reservoir underground, a conduit needs to be built; i.e. drilling a well. These wells use the same oil drilling and testing processes to reach the targeted reservoirs.

Teatini et al. (2011) reported that Northern Italy is conducive for gas storage because most of the hydrocarbons detected in the area are Pliocene and Pleistocene biogenetic/diagenetic gas. The Pliocene and Quaternary reservoirs are in thrusted anticlines, simple drape structures, and stratigraphic traps. A typical feature of this basin is that gas accumulation occurs in multipay zone reservoirs which is suitable for gas storage. The reservoir has the following conducive properties; an average reservoir porosity Φ of 25%–30%, matrix permeability k of 5-1000 mdarcy and water saturation S_w range from 35% – 75% respectively. Reservoirs are sealed on top by deep marine shales and impermeable sandstone (Teatini et al., 2011). All these factors improve the feasibility of the well and success of the project.

3.3.2 Measurement Scope

This section will explain the scope of the data measurement or sampling stage in terms of duration (timeline) and rig activity scope. This project measures sound at the closest residence or business to the centre of the drilling and testing site for a defined time frame, in which the activities performed by the rig differs throughout the day and night. The well design of a standard oil and gas well is explained in Appendix A to provide understanding and context to the activities measured.

3.3.2.1 Sampling Duration

The data collection phase was conducted from October 2016 to December 2017. There were 2 separate campaigns, Campaign 1 and 2. The gap between campaigns were to allow for the results of the first drilling campaign to be consolidated and analysed to update the scope and objectives of the second campaign. Examples of noise studies in both downstream and upstream oil and gas industry activities are explained in Section 2.3.2. There are limited monitoring studies and publications which indicates that sampling should be done in as many sites as possible, for the longest duration possible (Guy, 2016;

Radtke, 2016). For this reason, the sampling scope was conducted for as long as possible to take advantage of the drilling, completion and testing activities conducted on the drilling and flare sites. The dates of each campaign are presented in Table 3.2.

Table 3.2: Sampling measurement dates.

	Campaign 1		**Campaign 2**	
Location	**Measurement began**	**Measurement ended**	**Measurement began**	**Measurement ended**
1	08-Oct-16	22-Dec-16	11-Sep-17	31-Dec-17
2	08-Oct-16	22-Dec-16	11-Sep-17	30-Nov-17

3.3.2.2 Rig Activity Monitoring

The activity conducted at the rig site (oil and gas operations) are divided into rig move, drilling, completion, testing and plug and abandonment. In terms of data set, the monitoring was done in two drilling locations, known as 1 and 2 each with Rigs 1 and 2 operating separately on the corresponding drilling locations. Rigless activities are described as activities that take place without any rig present and occurred in both drilling locations. These include well intervention activities such as minor completions, coiled tubing work and testing. It is important to classify this to be able to then evaluate if the wells with a rig have higher sound levels compared to without a rig. Table 3.3 shows the number of wells and the well names that were drilled from each rig (1, 2 and rigless) and corresponding location. The average duration for each well was 41.31 days to drill, complete and test. The information below is critical to presenting the analysis results in Chapter 4 by means of location, rig and well number to be able to showcase which of these variables produce higher sound levels and for what reason.

Table 3.3: Wells drilled per rig/rigless.

Location	Rig Type	Number of wells drilled	Well Number/Classification
1	1	8	1, 2, 3, 4, 5, 6, 7, 7-ST
2	2	6	8, 9, 10, 11, 12, 13
1 and 2	Rigless	6	1, 2, 3, 5, 6, 7-ST

Figure 3.4 shows the duration of drilling, completion and testing activity reported on rigs 1, 2 and rigless, where the most data was recorded on rigs 1 and 2, which also shows how many La_{eq}(hr) sound points were measured during the sampling duration (since data was measured every 1 hour). It can be seen here that most of the activity was performed by Rig Type 1 (4144 hrs), followed by Rig Type 2 (3710 hrs) and then rigless (498 hrs) activities. The similar duration between Rigs Type 1 and Type 2 shows that there is a good mix of data for analysis.

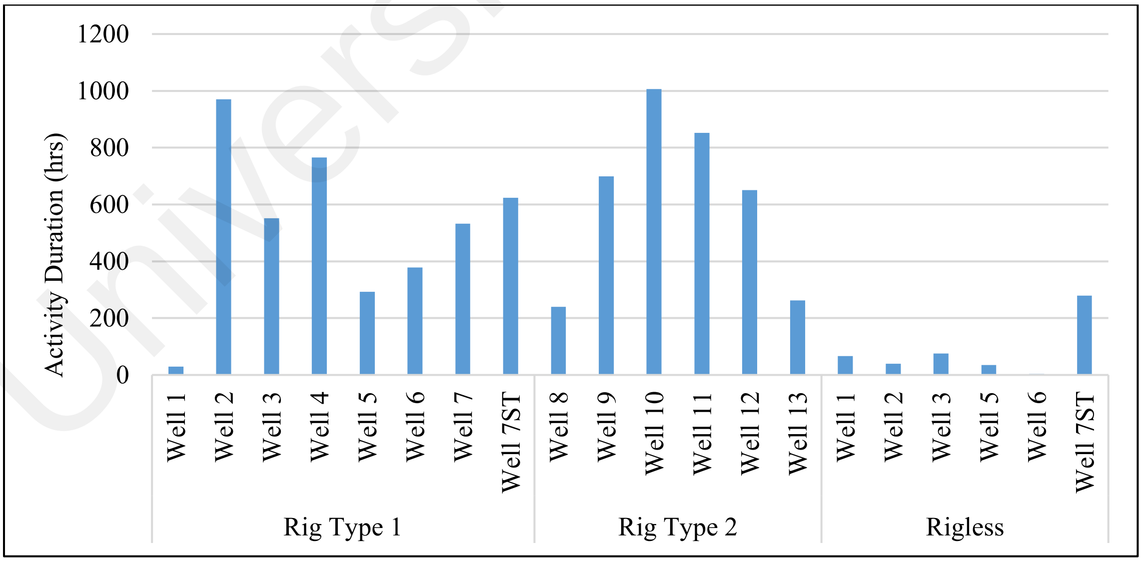


Figure 3.4: Rig and Rigless activity duration.

As per the activity breakdown shown in Figure 3.5, the well activities are reported in various categories by the different sections and activities to later be used for statistical analysis, to showcase which activities generated higher (or lower) noise levels. This information is critical for future drilling projects, where depending on the higher noise contributing factor, the drilling operator can implement corresponding noise reduction measures as explained in Section 2.5. Further explanation about the description of each activity performed by the drilling rig for a well (during the sampling duration) is specified in Section 1.1 and Appendix A.

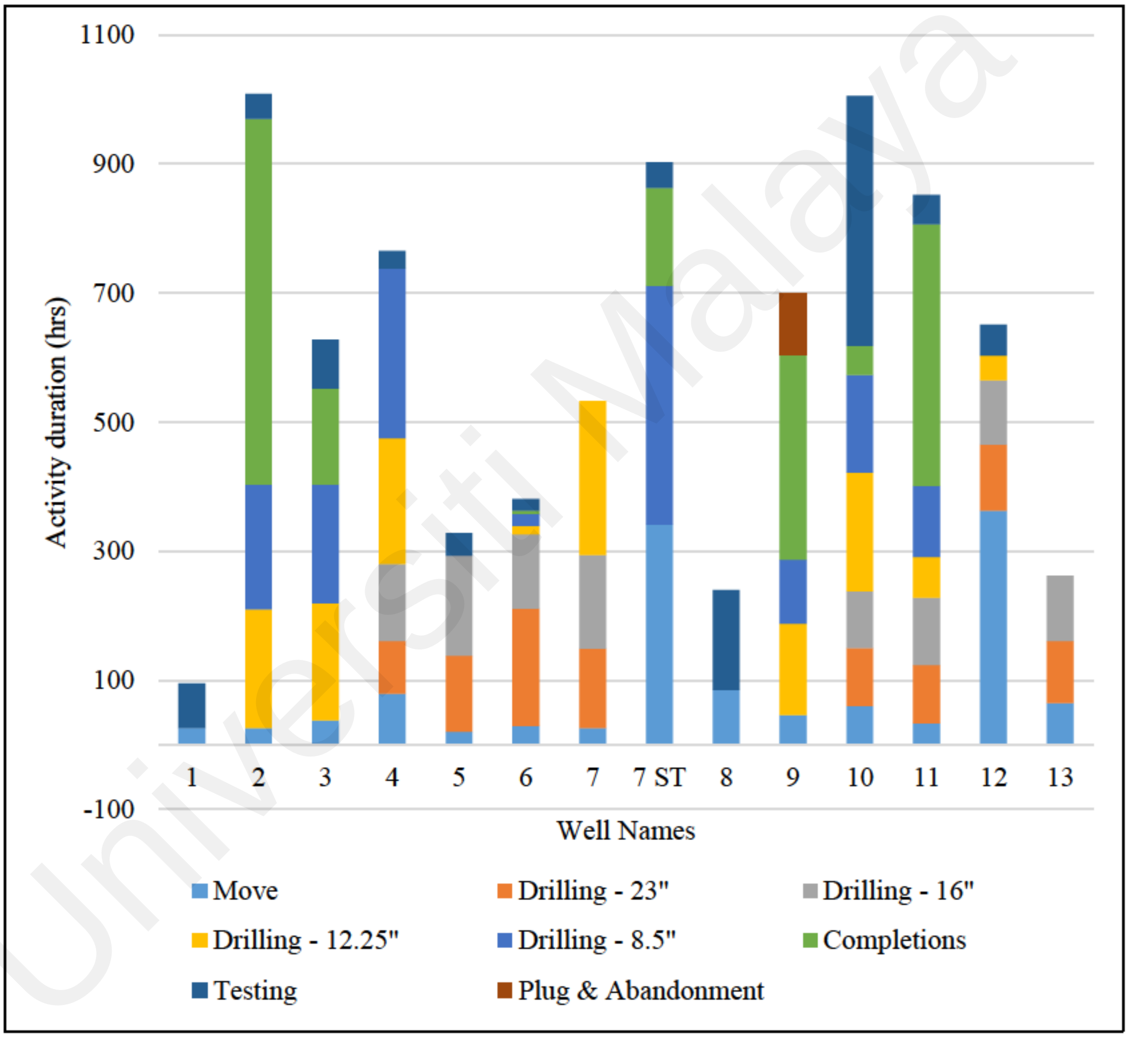


Figure 3.5: Activity duration per activity type on each well.

In terms of highest to least, Table 3.4 shows the total duration for each activity throughout the sampling phase.

Table 3.4: Total duration of high level well operations activities.

Activity	**Total Operation Duration (hrs.)**
Completions	1641
Drilling - 8.5"	1389
Drilling - 12.25"	1239
Move	1237
Testing	940
Drilling - 16"	927
Drilling - 23"	884
Plug and abandonment	95

During the different activities, various rig components are utilized at different rates. These different motors, engines, tools and systems generate different levels of sound. Service companies might transport additional equipment such as trucks, pumps and mixers to the location for specific activities and remove them after the job is completed (Guy, 2016). This in turn could further increase the noise levels, which is why understanding the type of activity could help explain why certain activities produce a certain sound level. Individual equipment specification details of rigs 1 and 2 can be found in Appendix B. Figure 3.6 shows a picture of Rig 1 used in this study.

Figure 3.6: Drilling Rig 1 used in Location 1. Photograph by the author (2017).

3.3.2.3 Sampling Frequency

Sound measurements were collected 24 hours a day during the drilling, completion and well testing activities on two drilling rigs (Rigs 1 and 2) on the two locations (Locations 1 and 2). Day time noise data was collected from 6:00 am to 10:00 pm, and night time data from 10:00 pm to 6:00 am. Day time and night time hours were defined by the county´s noise regulations, the same council that defined a noise limit of 60 dB_A for day time and 50 dB_A for night time. Various activities that fall under ´standby´ activities include waiting classifications such as planned wait times, waiting on contractor/waiting on service providers, waiting on operator decisions/orders, people or equipment and waiting on weather conditions to improve. This information provides a good reference of the environment with only residential and urban traffic noise. Daily data audits were conducted to ensure that the sensor was functioning well. However, there were instances where the sound was not captured by the sensors due to several reasons (as described in Section 2.4):

1. Impact of meteorological events – wind, rain
2. Failure of sensor to detect noise – potentially due to lack of charge, wiring connection issues, sensor failure, etc.
3. Sensor disconnected due to rig moving activity, power shut down on the rig (generator failure) etc.

A sample of the daily noise monitoring results is shown in Figure 3.7 where the LAeq is taken every 1 hour, with day and night limits presented to provide a visual representation of the sound levels- if it falls within or exceeds the county limits (60 dB_A and 50 dB_A respectively).

Location 1: Noise Report 11 October 2016

Date	Limit Assoluto Giorno	Limit Assoluto Notte	Period	Unit	Start Date	Null	End Date	Null	Laeq	Unit
October 11, 2016		50	Night	Leq	0 00 00	-	12 59 AM	=>	51 6	dBA
October 11, 2016		50	Night	Leq	1 00 00	-	1 59 AM	=>	52 7	dBA
October 11, 2016		50	Night	Leq	2 00 00	-	2 59 AM	=>	52 2	dBA
October 11, 2016		50	Night	Leq	3 00 00	-	3 59 AM	=>	50 6	dBA
October 11, 2016		50	Night	Leq	4 00 00	-	4 59 AM	=>	51 2	dBA
October 11, 2016		50	Night	Leq	5 00 00	-	5 59 AM	=>	51 1	dBA
October 11, 2016	60		Day	Leq	6 00 00	-	6 59 AM	=>	52	dBA
October 11, 2016	60		Day	Leq	7 00 00	-	7 59 AM	=>	54 8	dBA
October 11, 2016	60		Day	Leq	8 00 00	-	8 59 AM	=>	53 6	dBA
October 11, 2016	60		Day	Leq	9 00 00	-	9 59 AM	=>	53	dBA
October 11, 2016	60		Day	Leq	10 00 00	-	10 59 AM	=>	52 7	dBA
October 11, 2016	60		Day	Leq	11 00 00	-	11 59 AM	=>	52 7	dBA
October 11, 2016	60		Day	Leq	12 00 00	-	12 59 PM	=>	51 9	dBA
October 11, 2016	60		Day	Leq	13 00 00	-	1 59 PM	=>	52 1	dBA
October 11, 2016	60		Day	Leq	14 00 00	-	2 59 PM	=>	53 4	dBA
October 11, 2016	60		Day	Leq	15 00 00	-	3 59 PM	=>	52 2	dBA
October 11, 2016	60		Day	Leq	16 00 00	-	4 59 PM	=>	52 3	dBA
October 11, 2016	60		Day	Leq	17 00 00	-	5 59 PM	=>	51 7	dBA
October 11, 2016	60		Day	Leq	18 00 00	-	6 59 PM	=>	50 5	dBA
October 11, 2016	60		Day	Leq	19 00 00	-	7 59 PM	=>	52 1	dBA
October 11, 2016	60		Day	Leq	20 00 00	-	8 59 PM	=>	51 8	dBA
October 11, 2016	60		Day	Leq	21 00 00	-	9 59 PM	=>	50 1	dBA
October 11, 2016		50	Night	Leq	22 00 00	-	10 59 PM	=>	48 7	dBA
October 11, 2016		50	Night	Leq	23 00 00	-	11 59 PM	=>	49 7	dBA

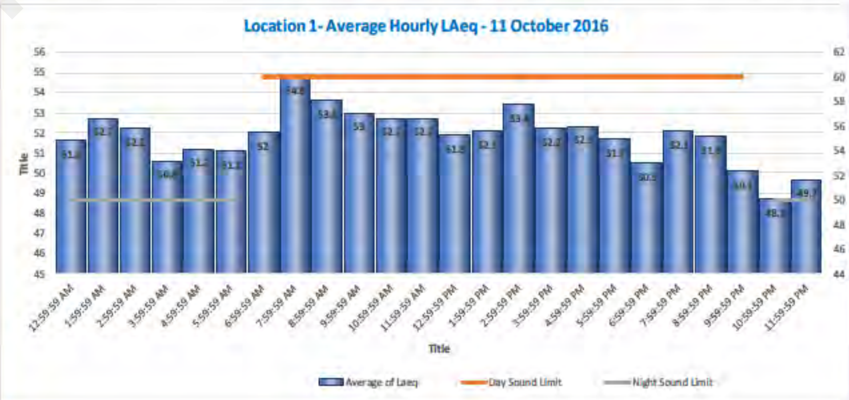


Figure 3.7: Sample of a daily noise monitoring report.

3.3.2.4 Noise Barriers

To achieve compliance with the noise limits set by the local council, one of the measures undertaken at the beginning of operations were the installation of noise/acoustic barriers close to the edge of the rig sites and at the walls between the rig and the closest residents to dampen the noise. The installation of the barriers (sound-absorbing) complied with the following parameters (Stollery, 2014):

- Height – 5 meters from ground level
- Positioning - South Side and West Side
- Coefficient of Absorption – 0.5
- Class - Sound insulation / Category B3 (UNI EN 1793-2) - DLα> 24 dB
- Acoustic Power / Category A3 / A4 (UNI EN 1793-1) - DLα> 8-9 dB
- Support: Metal frames

In this study, the noise barriers were installed throughout the study, hence the effectiveness of its ability to reduce noise levels will not be analysed. Such barriers have been reported to have sound-insulating and sound absorbing properties (Witter et al., 2008). The barriers installed on Locations 1 and 2 are shown in Figure 3.8.

Figure 3.8: Noise barriers installed on Locations 1 and 2. Photographs by the author (2017).

3.3.2.5 Flare Burner Enclosures

Flaring can be one of the highest frequency noises generating activities in the oil and gas industry (101-116 dB_A) (Bussman & Knott, 2000; Hanstschk & Schorer, 2008). To mitigate the impact of this noise, certain drilling operators invest in flare burner enclosures to ensure a safe working area for their employees, for protection from heat, flame and noise (Hays et al., 2016). This study will analyse the potential impact of the flare burner enclosures (the burners were only installed in 2017, none in 2016) in reducing flaring noise levels. Figure 3.9 shows the position of the burners on Location 1.

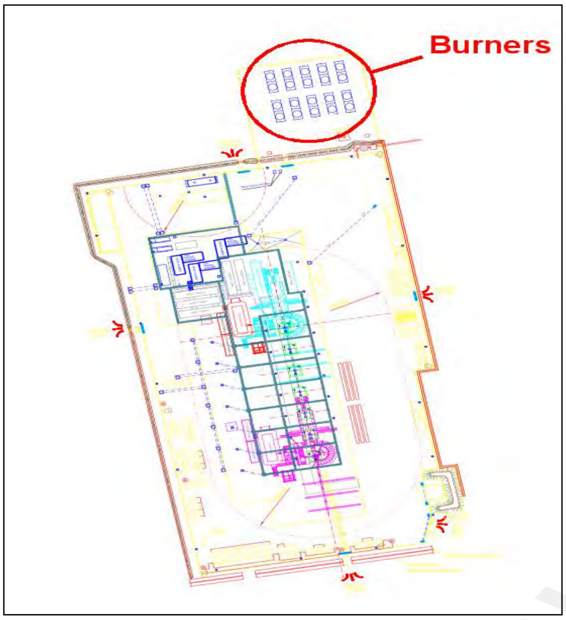


Figure 3.9: Flare burners position on Location 1.

Figure 3.10 shows pictures of flaring operations that took place on Location 1 and 2 respectively in 2016 without any burner enclosures installed. Figure 3.11 shows the burner enclosures installed on Location 2 in 2017.

Figure 3.10: Flaring operations on Locations 1 and 2 without enclosures. Photographs by the author (2016).

Figure 3.11: Flare burner enclosures on Location 2. Photograph by the author (2016).

3.3.3 Sampling Method – Sensor Installation and Location Layout

Two monitoring stations were installed at the residence in closest proximity to the rig sites, in both locations (Locations 1 and 2) to measure the sound levels generated (each station has 1 sound level meter as part of the station). The below information specifies the distance between each location's monitoring stations to the main noise sources at both the drilling and flaring locations;

Location 1: Fixed sensor (at nearest residential home) to centre of rig ……….144 m

Location 1: Fixed sensor (at nearest residential home) to centre of flare site….251 m

Location 2: Fixed sensor (at nearest residential home) to centre of rig ……......282 m

Location 2: Fixed sensor (at nearest residential home) to centre of flare site….328 m

Based on the local authority noise map and placement of the drilling location (Figure 3.4), a continuous noise monitoring station was located southward at nearest sensitive receptor as shown in Figures 3.12 and 3.13 below (station marked in red circle) at the nearest house from the drilling site.

Figure 3.12: Image of Location 1 sensor position. Reproduced from Google Earth. Retrieved 2 June, 2019 from - https://earth.google.com/web/@45.28740978,9.46426367,78.79113279a,142.90989073d,35y,0h,44.99635005t,-0r/data=ChMaEQoJL20vMGdyNWhqGAEgASgC.

Figure 3.13: Fixed noise monitoring station at closest residence to Location 1. Photographs by the author (2017).

On location 2, a separate, different yet similar arrangement for another continuous noise monitoring station was located at the nearest sensitive receptor in front of the closest residence (Figures 3.14 and 3.15).

Figure 3.14: Image of Location 2 sensor position. Reproduced from Google Earth. Retrieved 2 June, 2019 from https://earth.google.com/web/@45.28778652,9.48092817,77.1260307a,379.43962155d,35y,-0h,44.99785404t,-0r/data=ChMaEQoJL20vMGdyNWhqGAEgASgC.

Figure 3.15: Fixed noise monitoring station at closest residence to Location 2. Photographs by the author (2017).

3.3.4 Research Instruments

The noise monitoring stations consisted of the following equipment:

- Svantek SC91 Microphone Extension Cable
- Svantek SA271 Microphone Outdoor Protection Kit
- Svantek SV36 Class 1 Acoustic Calibrator 94 dB / 114 dB at 1 kHz
- Svantek SA420B Tripod

To ensure the quality of the measurement, the system was calibrated at installation time then every 30 days with a Type 1 sound calibrator. The deviations were between ±0.2 dB. In compliance to Italian Legislation, the calibration certificate of the monitoring station and of the calibrator were not to be older than two years.

Data accuracy and reliability is a critical factor in the statistical modelling of noise levels. Equipment calibration was performed according to the suppliers recommended procedures (Yusoff & Ishak, 2000). Appendix C shows the calibration certificates for both the sensors used for monitoring. Some of the main specifications of this sound level meter are (Svantek, 2018):

- Sensor information: SVANTEK 971 Sound Level Meter
- Standards: Class 1: IEC 61672-1:2013, Class 1: IEC 61260-1:2014 (Type Approved)
- Microphone: ACO SV 7052E, 35 mV/Pa, repolarised 1/2” condenser microphone
- Meets international standards: ISO 9612, OSHA, MSHA and ACGIH
- Linear Operating Range: 25 dBA RMS ÷ 140 dB_A Peak (in accordance to IEC 61672)

- Dynamic Measurement Range: 15 dBA RMS ÷ 140 dB_A Peak (typical from noise floor to the maximum level)
- Internal Noise Level Less than 15 dB_A RMS
- Dynamic Range >110 dB
- Frequency Range 10 Hz ÷ 20 kHz

In terms of strengths, the noise measurement equipment was compliant with International Electro Technical Commission standards (IEC651/IEC804). Each sensor was set to collect slow response, A-weighted sound levels (dB_A) to filter out much of the low-frequency noise (i.e., considered the "normal" limit of human hearing).

Limitations of the open installation method include factors that could impact the data points and quality of data obtained, including malfunction of the sensor, strong climate conditions (wind/rain/snow) and other equipment hardware failure. The sensor could not be enclosed as this would dilute the sound quality being measured. Both noise monitoring stations were equipped with a Type 1 sound level analyser interfaced with outdoor microphone and data transmission system, able to transmit 1/3 octave spectrum per second to a secured web page.

The following actions were taken during installation of the measurement equipment to ensure the values were correctly measured:

1. Weather monitoring to identify excessive weather conditions such as rain, wind speed and direction.
2. Sensor height, direction and distance installed in the right position to ensure representative monitoring conditions. To avoid interference with the ground, the sound measuring station was placed approximately five feet above the ground surface (International Organisation for Standardisation, 1999).

3. Free from significant ambient noise sources such as high-volume roadways or other unwanted noise sources.

3.4 Research Procedure

To systematically conduct this research, the process steps defined to conduct this study is mapped out as a flowchart in Figure 3.16.

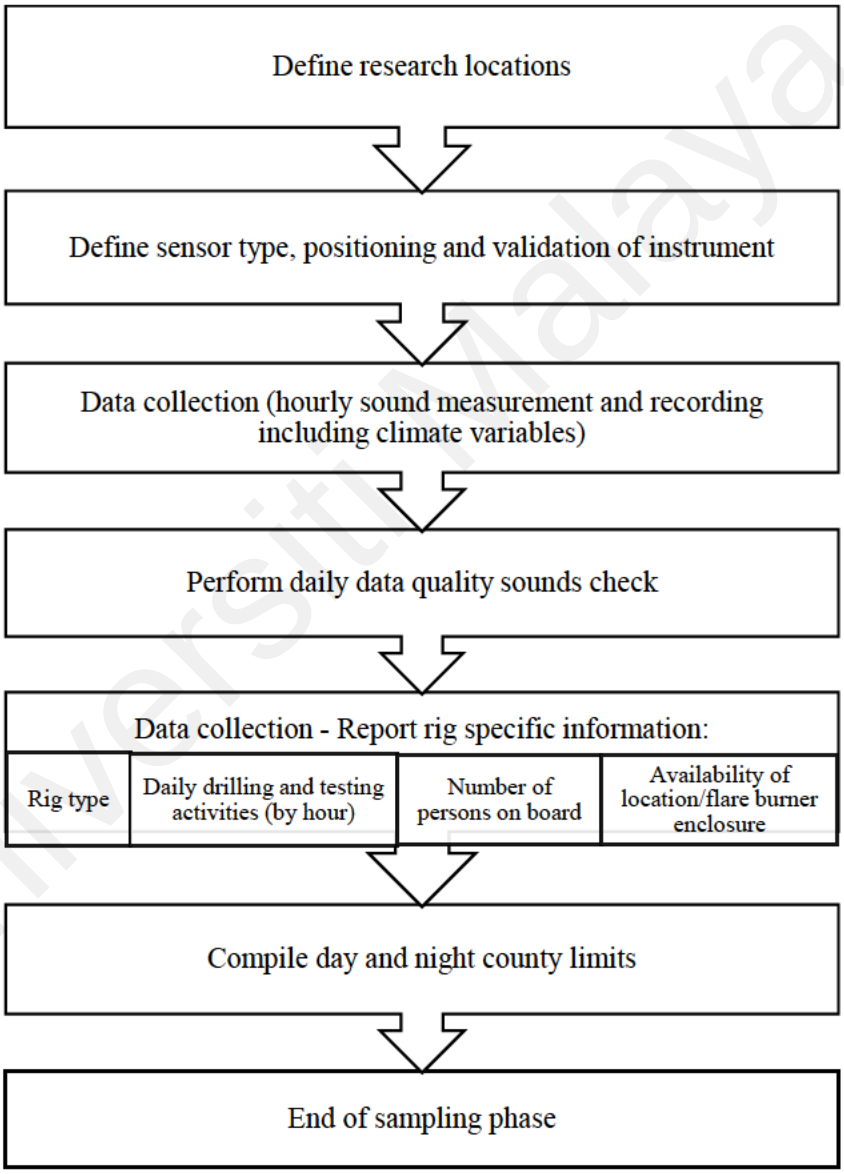


Figure 3.16: Research procedure.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Descriptive Analysis

This section describes the sound data collected during the study using basic statistics such as frequency, percentage, mean and median. La_{eq} data (measured in decibel) gathering was conducted during the drilling and well testing activity on both locations 1 and 2 via sensor measurements. Baseline data was obtained from historical data reported in 2006 and aims to provide a reference or control study with only traffic noise occurring (since there was no other drilling or well testing activity that took place during that time at both locations). For analysis purposes, although the Svantek 971 sound level meter measures data every one second, the data that was provided as output from the measurement system was hourly L_{eq} data. All subsequent study was made using one-hour L_{eq} data due to the large and low frequency sound data.

Descriptive analysis is a well-accepted method for presenting and analysing noise levels. Some noted studies that presented results of their studies similarly include (Morillas & Carmona, 2002; Morillas & Gozalo, 2016). As part of the descriptive analysis, it is critical to highlight some basic information of where and when the data was obtained. During the seven months data gathering phase of this study, a total of 8954 data points was measured (La_{eq} every 1 hr). Sound data was measured in dB_A (A-weighted decibel) as it is the frequency closest to human hearing (DeGagne & Burke, 2008; OSHA, 2013; Radtke, 2016). To understand noise trends, L_{eq} or equivalent sound is used (Occupational Safety and Health Administration, 2013). Table 4.1 shows the descriptive analysis of the sound data presented by year, location and well name. All statistical analysis was conducted using IBM® SPSS Statistics version 23.

Table 4.1: Descriptive statistics by year, location and well name.

Category	Factor/ Group	n (Total = 8954)	%
Year	2006 (baseline)	28	0.3
	2016	3504	39.1
	2017	5422	60.6
Location	1	4654	52.0
	2	4300	48.0
Well Name (Loc. = 1)	1	95	1.1
	2	1009	12
	3	626	7.5
	4	765	9.1
	5	328	3.9
	6	381	4.5
	7	533	6.4
	7 ST	903	10.8
Well Name (Loc. = 2)	8	240	2.9
	9	699	8.3
	10	1006	12
	11	852	10.2
	12	651	7.8
	13	262	3.1
n = number of samples in a group; % = percentage of sample from total sample			

Based on year of collection, 39.1% of the total data collected were measured in 2016, while 60.6% of the data obtained was measured in 2017. The difference comes from the actual well duration in which some wells took longer than others. The baseline traffic data of 2006 was obtained from a secondary source and was not measured during this study. In terms of location, there was a slightly higher percentage of data coming from activities in Location 1 (52.0%) compared to Location 2 (48.0%). This is due to more drilling and testing activities held on Location 1 compared to Location 2. Each location drilled and tested a specific number of wells with varying activities and duration, hence providing a different split of data available for each well. The three highest quantity of sound data was collected on wells 2, 7 ST and 11 as the sensors were functional for a higher duration due to conducive weather conditions and those being the wells with higher durations. Wells 1, 2, 3, 4, 5, 6, 7 and 7 ST were drilled from Location 1; while Wells 8, 9, 10, 11, 12 and 13 were drilled from Location 2 (as described in Table 3.3).

To perform statistical analysis, it is required to conduct a preliminary data source analysis to understand the quantity and quality of valid data points available from each location. If the data points are too low (N< 10), these results should be omitted from the study. For Location 1, it has eight wells data (drilled) on location (including a Baseline 1), while Location 2 has six wells and Baseline 2. Figure 4.1 illustrates the data obtained per well on Location 1, with the highest amount of data measured on Well 2 (22%) and Well 7 ST (20%).

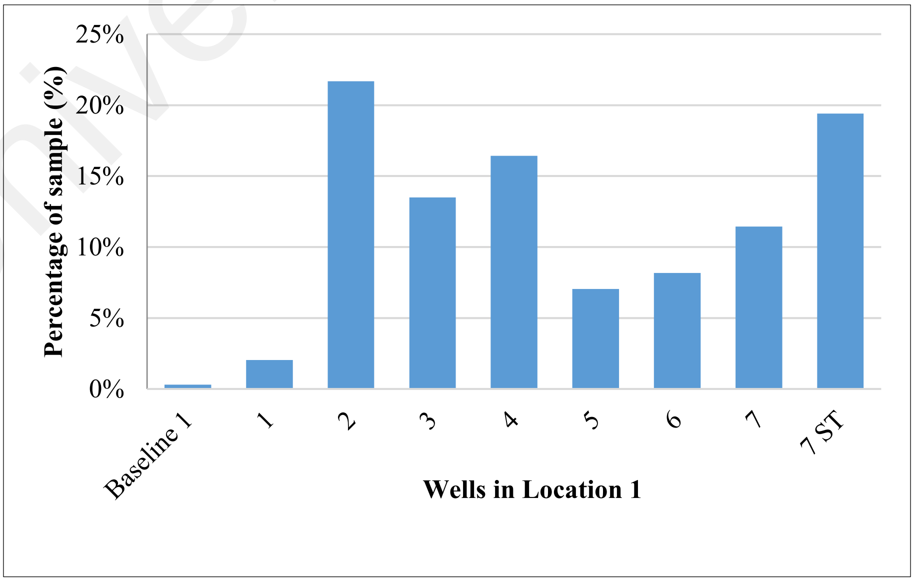


Figure 4.1: Distribution of available sound data by well (Location 1).

Table 4.2 shows the statistical description for rig type, high level activity category and if the flare burner enclosure was installed during flaring operations.

Table 4.2: Descriptive statistics by rig type, well activity and flare burner enclosure installation.

Category	Well Activity	n	%
Rig	Type 1	4142	49.4
Rig	Type 2	3710	44.3
Rig	Rigless	526	6.3
High level activity	Completions	1641	19.6
High level activity	Drilling - 12.25"	1237	14.8
High level activity	Drilling - 16"	927	11.1
High level activity	Drilling - 23"	884	10.5
High level activity	Drilling - 8.5"	1389	16.6
High level activity	Rig Move	1237	14.8
High level activity	Plug and abandonment	95	1.1
High level activity	Testing	940	11.2
Flaring Burner Enclosure Installation	No	7931	88.6
Flaring Burner Enclosure Installation	Yes	1025	11.4
n = number of samples in a group; % = percentage of sample from total sample			

For rig type categorization, most data recorded are from wells drilled using rig type 1 (49.4%) followed by rig type 2 (44.3%) while only 6.3% of the measured sound level data were from rigless wells (no drilling rig was used but all activity was conducted directly on the well itself). Rig 1 was mainly operational on Location 1, and Rig 2 was assigned to drill wells on Location 2. Some of the activities that are conducted without a rig include rig move operations and testing operations (specifically coiled tubing activity where coiled pipe is run downhole for well cleaning, lifting and testing operations), road traffic (baseline) and plug and abandonment activities are the least occurring high level activities in Location 1 and 2, both with 1.1% and 0.3%, respectively. On the contrary, the highest frequency of data was collected during Completions (19.6%), Drilling - 8.5" (16.6%) and Drilling - 12.25" (14.8%) and Rig Move (14.8%) activities. Furthermore, 11.4% of the data recorded are from wells installed with a flaring burner enclosure, equivalent to 994 data points (allowing for statistical tests to be applied) versus 88.6% data set from flaring operations without an enclosure being installed. The enclosure was installed on November 2016 onwards after the first batch of flaring activities were conducted, to reduce the sound levels generated to ensure it was below the government limits. This allows for a comparison study to be made for noise generated with and without an enclosure present.

Figure 4.2 shows that most of measured sensor data in Location 2 comes from Wells 9, 10 and 11 with percentages of data availability of 20%, 28%, and 24% respectively. Similarly, all other wells in Location 2 contributed a significant number of data points except for Baseline 2 which further justifies omitting it from statistical analysis.

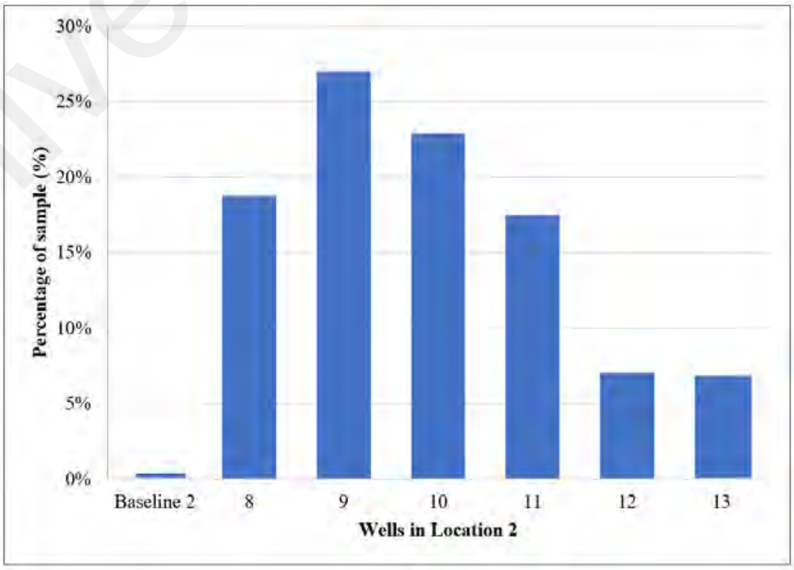


Figure 4.2: Distribution of available sound data by well (Location 2).

The lowest sound level recorded is 31.3 dB_A while the highest sound level recorded is 83.1 dB_A during the entire measurement phase on both locations. Based on OSHA (2013), this lowest recorded value is a relatively low sound level, almost silent, whereas the highest could be likened to a freight train passing. The min and max values are instantaneous sound points and only occurred at sudden instances, not comparable to constantly occurring noise, for which the mean and median are better descriptive methods. These values are obtained after the data set was cleansed. Table 4.3 shows the temperature, relative humidity, global radiation, precipitation, wind speed, wind direction, and sound level (dB_A) data set by mean, median, min and max values.

Table 4.3: Descriptive statistics for complete data set.

Variable	Mean	Median	Min	Max
Ambient Temperature (°C)	7.2	7.8	-3.0	21.0
Relative Humidity %	84.1	100.0	0.0	100.0
Global Radiation (W/m^2)	56.7	0.0	0.0	657.0
Precipitation (mm)	0.0	0.0	0.0	0.0
Wind speed (m/s)	1.5	1.4	0.0	5.0
Wind direction (°)	169.8	192.0	0.0	360.0
Sound level (dB_A)	50.1	50.0	31.3	83.1

4.2 Data Cleansing

Prior to conducting a normality assessment and other statistical tests, the study was analysed to exclude any data recorded when it was raining or with wind speeds of more than 5 m/s due to the potential to skew the statistical analysis from adverse meteorological conditions (Stollery, 2014). In addition, there were 302 data points with no recorded sound data which could be attributed to failure of the sensor (non-functional/not connected). Both these data sets are removed from the total data set prior to conducting further statistical analysis. Baseline data from 2006 (on both locations) was also removed due to lack of data points and uncertainty of measurement procedure integrity. DeGagne and Burke (2008) enforced proper procedures via the importance of using noise meters approved by international standards, ensuring that instruments were suitably calibrated prior to use and the consideration of wind speed, direction of microphone positioning and distance from dwellings. Table 4.4 shows the average sound level and descriptive data differentiating results with and without rain and/or wind speed (higher than 5 m/s).

Table 4.4: Sound level (dB_A) by rain and wind.

Raining or Windy (>5m/s)	n	Mean	S. D.	p value
No	7194	50.0	4.93	<0.001
Yes	608	50.6	4.22	
n = number of samples in a group, S. D. = standard deviation of sound level in a group				

An independent t-test shows that there is a significant difference in sound levels between the two groups (with and without rain or wind speed higher than 5 m/s). Rain or wind which blows stronger than 5 m/s speeds does significantly increase the sound level, L_{eq} by 0.6 dB_A, thus these records will be omitted from further analysis to isolate non-related activities and retain the study to focus on drilling and testing related activities only.

4.3 Sound Level (dB_A) Normality Assessment

To conduct a normality assessment, a histogram curve is developed along with a Q-Q plot and Kolmogorov-Smirnov normality tests. These are generated with the sound level, L_{eq} (dB_A) as the dependent variable. Figure 4.3 shows the histogram of the cleaned-up data set, which shows the data exhibiting a normal distribution (bell shape).

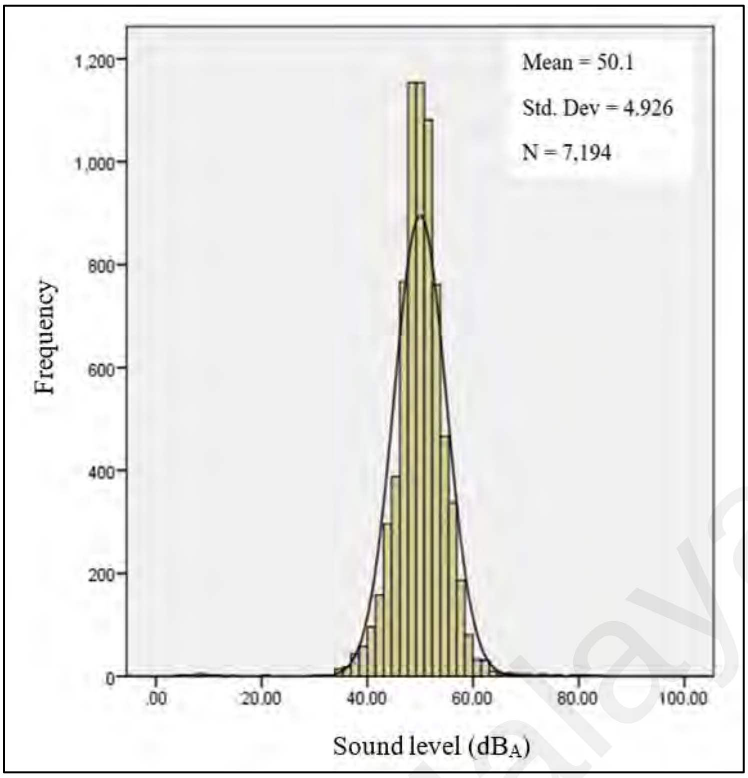


Figure 4.3: Sound level (dB_A) of total data set.

The value of Kolmogorov-Smirnov normality test was lower than 0.05 (Table 4.5), and the Q-Q plot (Figure 4.4) showed that the data does not scatter along the diagonal, hence concluding that the data does reflect a normal distribution.

Table 4.5: Kolmogorov-Smirnov normality test of total data set.

Variable	**Statistic**	**df**	**Sig.**
Sound level (dB_A)	0.073	7194	<0.001

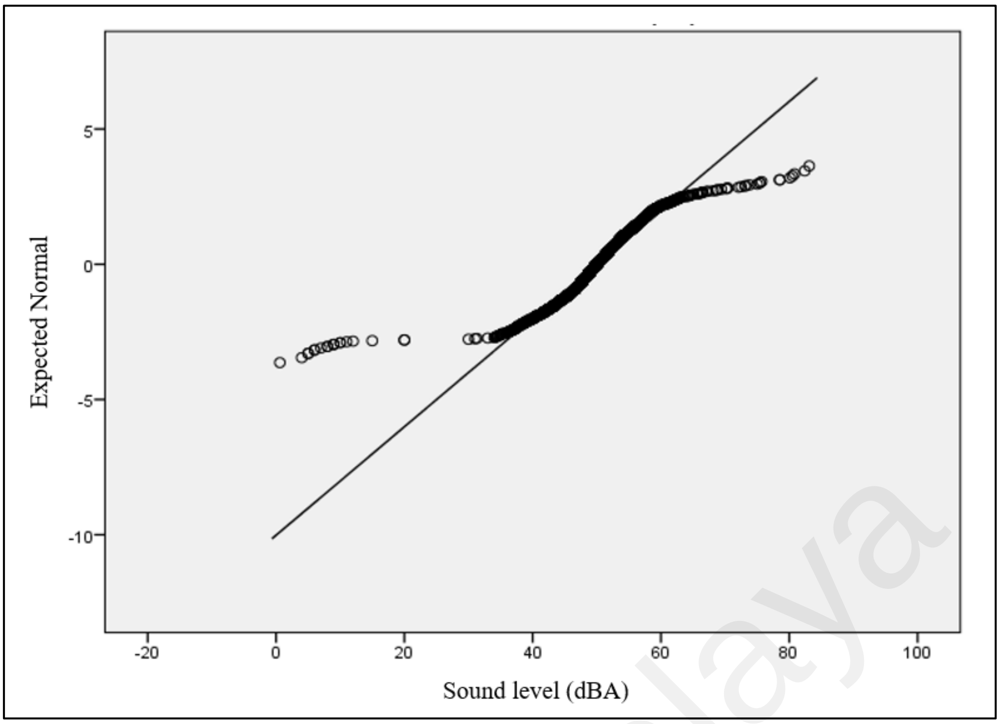


Figure 4.4: Q-Q plot for sound level (dB_A) of total data set.

These results are validated by the central limit theorem that says that when data approaches or is more than 30 points, the data distribution will approximate a normal distribution (Hays, 1994). The median and mean value of sound level (dB_A) were 55.3 and 50.1, respectively, thus concluding that the data is normally distributed and parametric statistical tests can be used for this study. In addition, non-normal data will likely cause a biased estimation of mean values, causing the mean value estimated to be far different from the median value. Understanding the degree of skewness of noise data could help narrow noise survey target areas (Brown & Lam, 1987; Garcia & Faus, 1991). Apart from that, the dependent variable (sound level) was analysed using different percentile levels as shown in Table 4.6.

Table 4.6: Sound level (dB_A) at different percentile of total data set.

Percentiles	Sound level (dB_A)
L_{99}	37.6
L_{95}	44.7
L_{90}	50.0
L_{50} (Median)	55.3
L_{10}	57.1
L_1	61.8
Mean L_{Aeq}	50.0

Equivalent values are critical analysis factors in noise studies such as mean, L_1, L_{10}, L_{50}, L_{90}, L_{95} and L_{99}. These $L_{(n)}$ indices describe the noise levels exceeded for n% of the measurement time (where n is 1, 10, 50, 90, 95 and 99) (Gracey & Associates, 2016; Nelson, 1982) and can provide high level understanding of an environment's noise overview. L_1 value of 61.8 dB_A shows that for only 1% of the time, data was above 61.8 dB_A while L_{99} value of 37.6 dB_A indicates that 99% of data recorded had sound levels above 37.6 dB_A. 10% of the data recorded had sound levels above 57.1 dB_A. This aims to show that during this study, the sound levels most likely experienced by the nearby population are sounds below 55.3 dB_A which are acceptable levels as frequently generated in an urban residence and likened to a conversation heard 3 ft away (Berglund et al., 1999; OSHA, 2013).

In various oil and gas noise studies, it was shown that the L_{90} level was the best measure of steady noise radiated by the major noise sources on the rig (generators, mud pumps, solids control and rotary system) which could be reliably monitored at night, whereas the L_{10} level was a measure of the noise associated with the intermittent/impulse noise sources e.g. material handling, random machine startups, site vehicles and other activities most of which take place during the day (Redman, 1986). In this study, the same conclusions can be made where L_{1-10} shows events that are not frequent, or only take place at certain times during certain activities/instantaneous, and L_{50-90} are events that take place throughout the duration of measurement. Nelson (1982) described L_{90} as the background/residual noise (the level in dB_A that is exceeded 90% of the time), L_{50} as the median or average noise level (exceeded 50% of the time) and L_{10} as the peak noise level (exceeded 10% of the time).

One sample reference study conducted ANOVA testing by setting the fixed factor as land use with four categories; residential, educational, transportation, and commercial, while noise was the dependent variable to understand its relationship (Baloye & Palamuleni, 2015). Similarly, in this study, noise is also defined as the dependant variable and measured again critical actors such as location, day mode, noise limits and well activities.

4.3.1 Noise Level (dB_A) by Location

This section analyses the differences between sound levels in Location 1 and 2 to identify whether it is Location 1 or 2 that has significantly higher noise levels. Understanding this can provide insight towards which variable contributed the most towards the high (or low) noise levels. Table 4.7 presents the summary result of the 2-way ANOVA test used for this section.

Table 4.7: Statistic test for sound level (dB_A) by location.

Location	n	Mean	S. D.
1	3911	52.2	3.40
2	3255	47.5	4.33
F = 2626.7, p < 0.001 n = number of samples in a group, S. D. = standard deviation of sound level in a group			

It shows that there is significant difference in sound levels between Locations 1 and 2 ($F = 2626.7$, $p < 0.01$) with a 0.05 significance level. Based on the same table, Location 1 demonstrates an overall higher mean sound level of 52.2 dB_A compared to Location 2 with mean sound level at 47.5 dB_A. The subsequent sections shall explain the reason for this. These noise levels are not excessive and would not cause significant hearing problems to the urban populations at these specified distances but might affect sleep quality of the residents nearby (WHO Europe, 2009).

Figures 4.5 and 4.6 shows all data points measured in Location 1 and 2 during the measurement phase which is a mixture of background noise and points of intense impulse/instantaneous sounds, as can be seen by the various high and low data points. Both these noise types can cause temporary and permanent damage if excessive and subjected for long exposure periods (Blumstein et al., 2011).

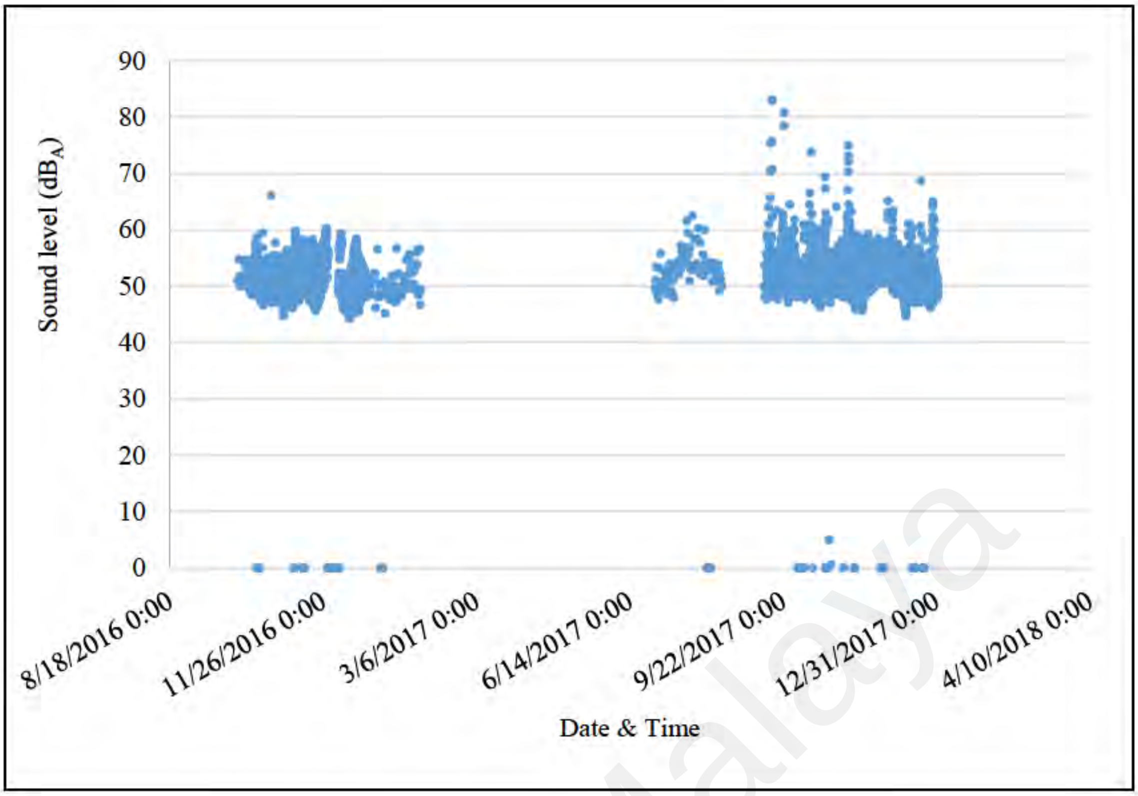


Figure 4.5: Sound levels (dB$_A$) measured in Location 1.

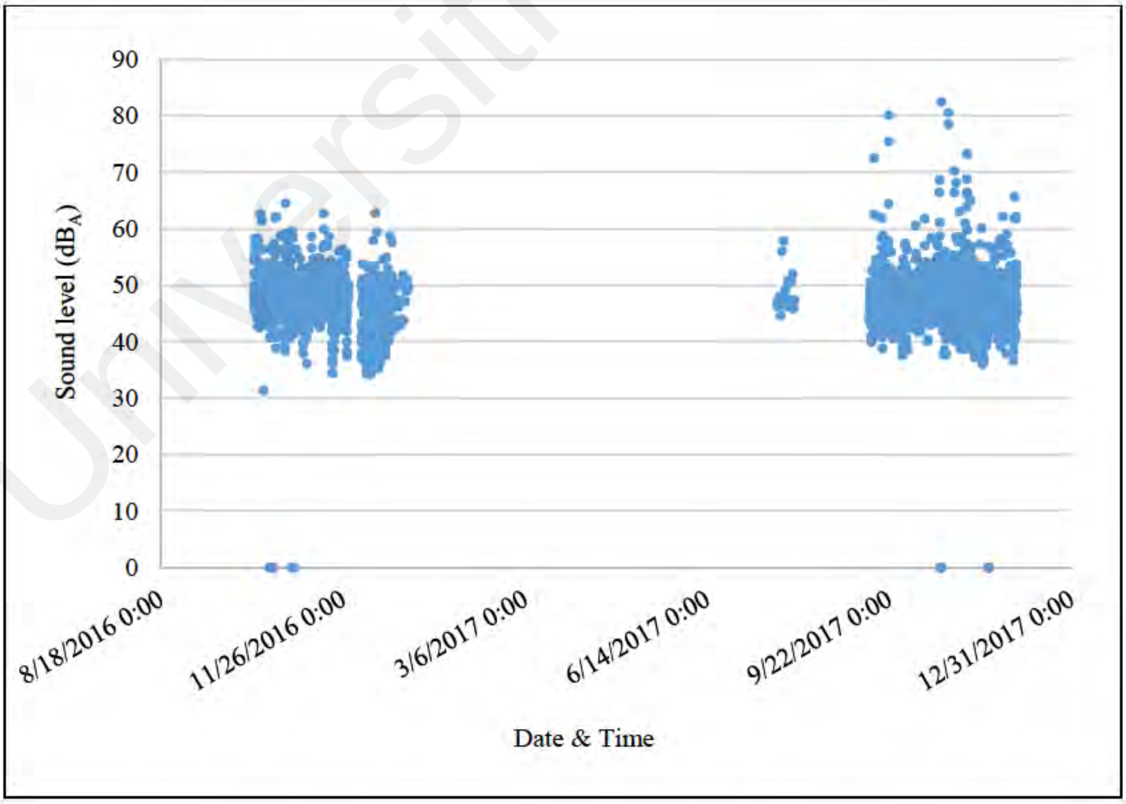


Figure 4.6: Sound levels (dB$_A$) measured in Location 2.

Figure 4.7 presents the mean sound levels of both Locations 1 and 2 at 95% confidence level. It shows that significantly higher sound levels were produced on Location 1 compared to Location 2 (overall sound data for both day and night condition).

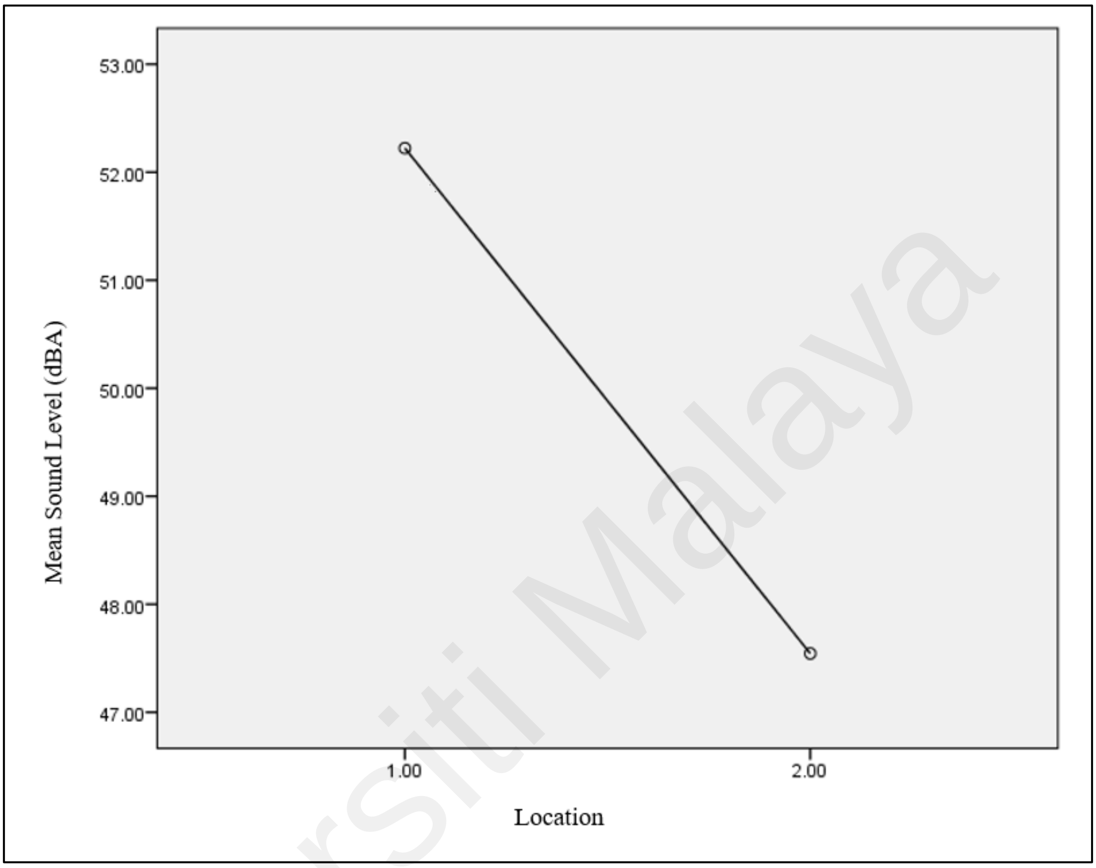


Figure 4.7: Mean plot (95% CI) for sound level by location.

The box plot generated (Figure 4.8) shows the shape of the distribution, its central value, and its variability of sound data collected in both Locations. The limits of the boxes are the quartiles; the heavy black vertical line represents the median, and the vertical fine black lines are the maximum and minimum values, as similarly presented in various urban noise studies, one of which was conducted in Caceres, Spain (Morillas & Carmona, 2002).

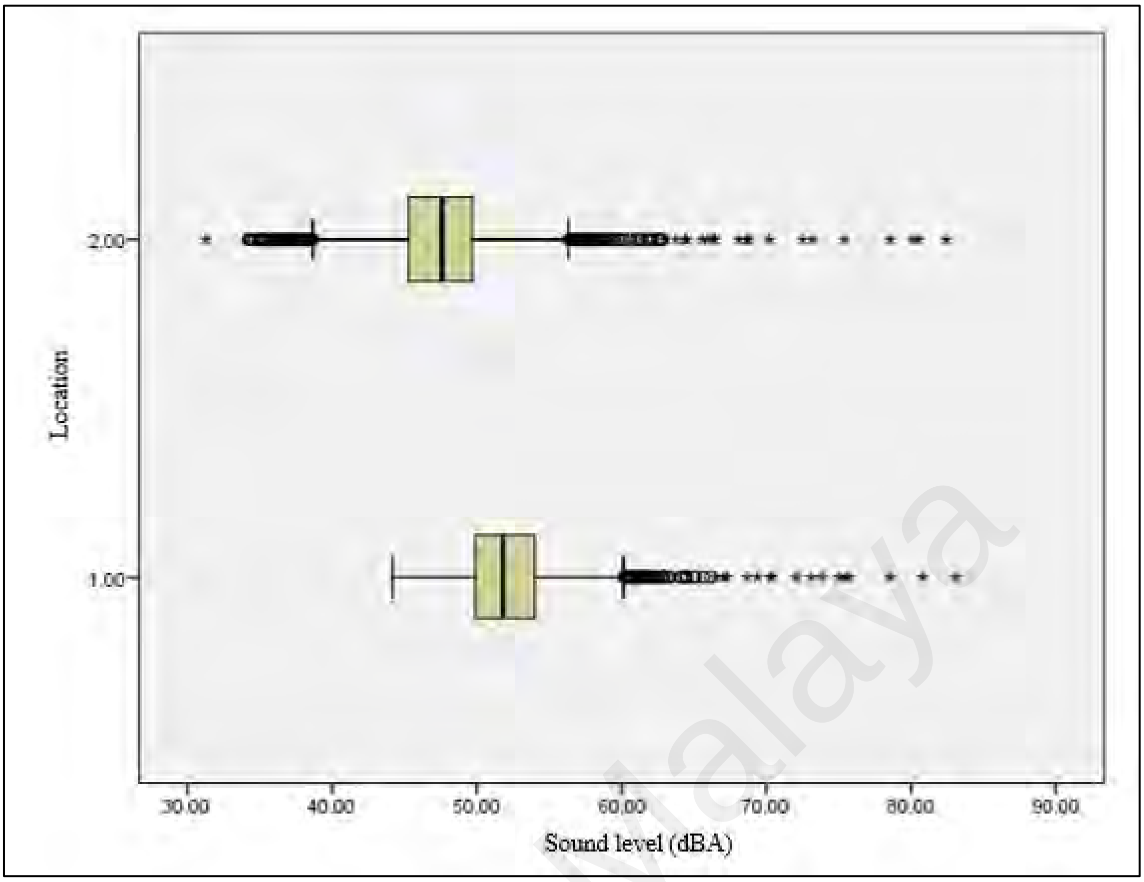


Figure 4.8: Box plot for sound level (dB_A) by location.

Further analysis was conducted to identify the cause of the variance on each location. An analysis of the wells on each location was made via a one-way ANOVA, to identify the significant differences in sound levels (dB_A) between wells followed by a Tukey HSD test to identify the homogeneous grouping. Tukey HSD test classified the mean sound level of wells into two subgroups, i.e. Group 1 (lower mean sound level) and Group 2 (higher mean sound level). The results are presented in Table 4.8.

Table 4.8: Statistic test for sound level (dB_A) by wells in Location 1.

Well Name	n	Mean	
		Group 1	Group 2
1	95	51.2	
2	872		52.8
3	511		52.6
4	650	51.2	
5	297	51.4	
6	341	51.4	
7	354		52.8
7 ST	793		52.7
Tukey HSD test, F = 25.4, p < 0.001 n = number of samples in a group			

There are significant differences in sound levels (dB_A) between wells in Location 1 ($F = 25.4$, $p < 0.001$) at a 0.05 significance level. Results of the Tukey HSD test further showed that the level of sound can be classified into two groups based on the resultant sound levels, as shown in the table for ease of analysis, to identify the wells which had higher sound levels. All data is based on cleansed data.

Based on Figure 4.9, wells number 1, 4, 5 and 6 (blue bars) are in the same group 1 with relatively lower mean sound levels (dB_A) compared to wells numbered 2, 3, 7 and 7-ST (red bars) in group 2.

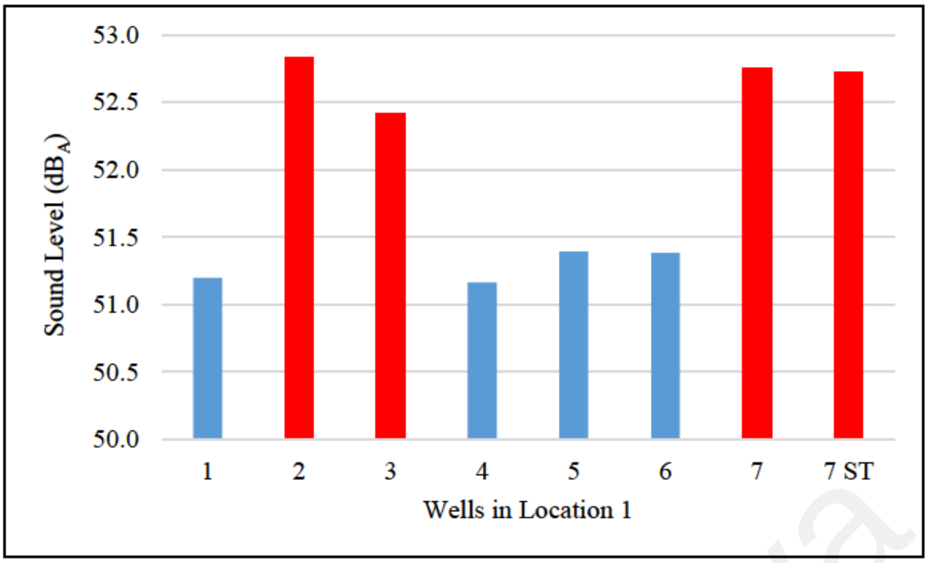


Figure 4.9: Sound level (dB_A) by wells in Location 1.

Therefore, this study concludes that wells 2, 3, 7 and 7 ST significantly contributes to the high sound levels measured in Location 1. Weather, rig type and differences in terrain would explain some of the differences found on each location, as these are some of the distinguishing factors between the two.

Next, the study analyses the differences in sound levels between the wells in Location 2 to identify the significant contributor of the high sound levels in Location 2. A one-way ANOVA test was conducted to test whether there is significant difference in sound levels between the wells in Location 1, while Tukey HSD test was conducted to classify the well into groups based on their sound level similar to other noise studies (Baloye & Palamuleni, 2015). Table 4.9 shows F value of 13.7 with p value less than 0.001, indicating that there is a significant difference in sound levels between the wells at a 0.05 significance level. Tukey HSD post hoc test were conducted and managed to classify the sound level of wells into two subgroups, i.e. Group 1 (lower mean sound level) and Group 2 (higher mean sound level) as shown in Table 4.9. The table shows that wells numbered 8 and 10 are in group 1 with relatively significant lower sound level compared to wells in group 2 with that were found to have higher sound level.

Table 4.9: Statistic test for sound level (dB_A) by wells in Location 2.

Well Name	n	Mean	
		Group 1	Group 2
8	221	46.9	
9	635		48.3
10	930	46.7	
11	785		47.8
12	454		47.9
13	230		47.9
Tukey HSD test, $F = 13.7$, $p < 0.001$ n = number of samples in a group			

It can be concluded that except for wells 8 and 10, all other wells are significant contributors to the high sound level in location 2. Figure 4.10 graphically shows a bar chart of wells 8 and 10 with the lowest sound levels (in blue) and wells 9, 11, 12, 13 with the highest sound levels (in red).

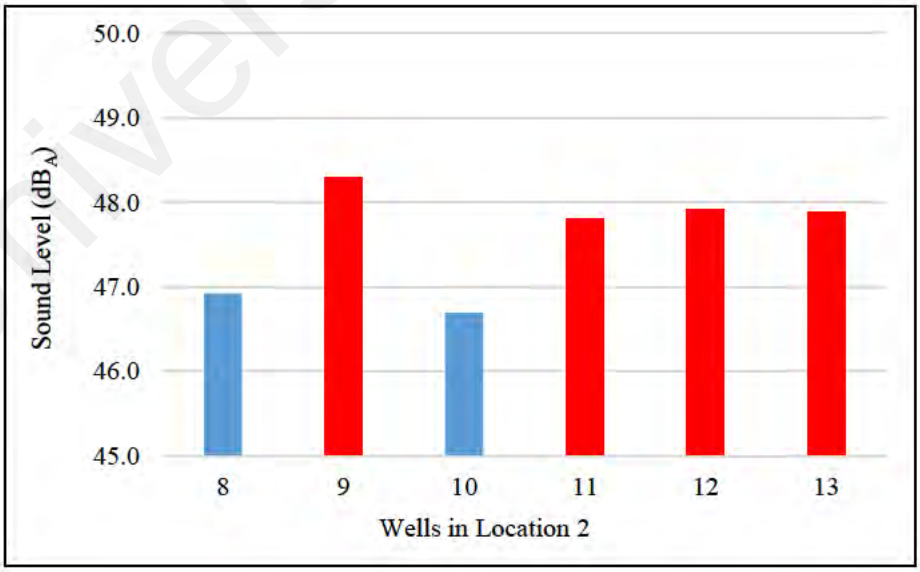


Figure 4.10: Sound level (dB_A) by wells in Location 2.

Even though the wells identified as the higher noise contributors are not necessarily the wells of longer duration wells of the project, one of the reasons for this lower tendency on Location 2 is the additional distance (282 m) from the activity site to the sensor location compared to Location 1 (144 m). Noise Pollution Clearinghouse Organization (2017) state that atmospheric attenuation (reduction of noise as it passes through air) can be dependent on factors such as distance. This study on focused on fixed monitoring stations to record the noise heard by the residents, hence only presenting the data at one fixed distance.

4.3.2 Noise Level (dB_A) by Day Mode

In this section, the study examines the differences in sound levels between day and night. According to WHO Europe (2009), it is critical to measure day and night sound levels to be able to research its social and health impact towards residents near an urban or industrial activity. Based on these results of the analysis, there are significant differences in sound levels between day and night modes ($F = 1051.5$, $p < 0.05$) at a 0.05 significance level. Sound levels are different during day and night, firstly depending on the type of well activity, and secondly by people movement and vehicular traffic which is lesser at night (delivery of equipment and tools, materials and food). This is also due to the strict noise regulations enforced for night time activities to safeguard a quieter environment for residents to rest. The regulations were 50 dB_A for night time and 60 dB_A for day time, which also created a culture of lowering noise at night time to not exceed the government night time limit which could lead to fines and penalties. The different types of rig equipment could also affect the overall noise, and how fast rig components could be shut down that could impact sound levels. Rig 2 which is a newer generation rig (more modern) would have the ability to reduce noise levels by installing more efficient equipment. Table 4.10 shows that during day time, the sites in general produced significantly higher sound levels with a mean value of 51.25 dB_A as compared to night time of 47.85 dB_A.

Table 4.10: Statistic test for sound level (dB_A) by day mode.

Day mode	n	Mean	S. D.
Day	4731	51.25	5.09
Night	2435	47.85	4.40
$F = 1051.5$, $p < 0.001$ n = number of samples in a group, S. D. = standard deviation of sound level in a group			

From all the data gathered, there was a reported 129 hours of suspended night time activity, where no rig site activity was allowed until day time arrived to mitigate the night time noise levels. This would explain some of the lower night time values found in this study. According to WHO Europe (2009) and Matsumoto et al. (2017), noise levels above 40 dB_A at night can potentially lead to adverse health effects including sleep deprivation which can lead to other health problems.

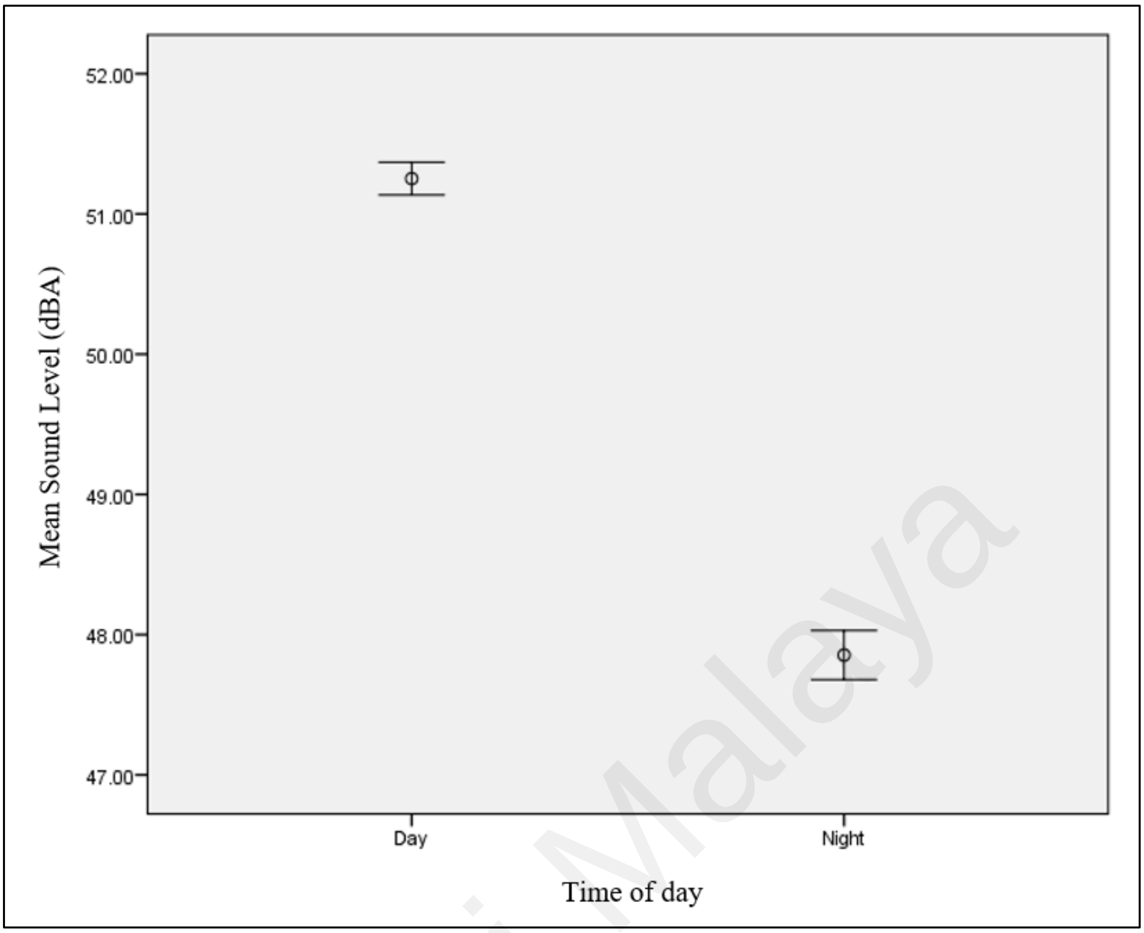


Figure 4.11: Mean plot (95% C.I) for sound level (dB_A) by day mode.

Figure 4.11 presents the study of 95% confidence interval (C.I) for mean value of sound levels for both day and night times. It clearly shows that there was no overlap between the confidence limits of the categories, statistically confirming that significantly higher sound levels were produced during day time compared to night time.

4.3.3 Noise Level (dB_A) by Location and Day Mode Interaction

This section examines the interaction of two independent variables; location and day mode by using two-way ANOVA testing with the results summarized in Table 4.11. There is significant interaction between the effect of location and day mode on the sound levels produced ($F = 175.4$, $p < 0.001$) at a 0.05 significance level.

Table 4.11: Statistic test for sound level (dB_A) by location and day mode interaction.

Location	Day mode	n	Mean	S. D.
1	Day	2571	53.04	3.417
	Night	1340	50.65	2.751
2	Day	2160	49.12	3.801
	Night	1095	44.44	3.544
F = 175.4, p < 0.001, n = number of samples in a group, S. D. = standard deviation of sound level in a group				

Figure 4.12 shows that the magnitude or mean sound levels in Location 1 decrease at a lower gradient from day (Time of day:1) to night time (Time of day: 2) as compared to Location 2 which shows a steeper drop in sound levels. In other words, when it turns to night, the sound level in Location 2 decreases by a bigger magnitude as compared to Location 1.

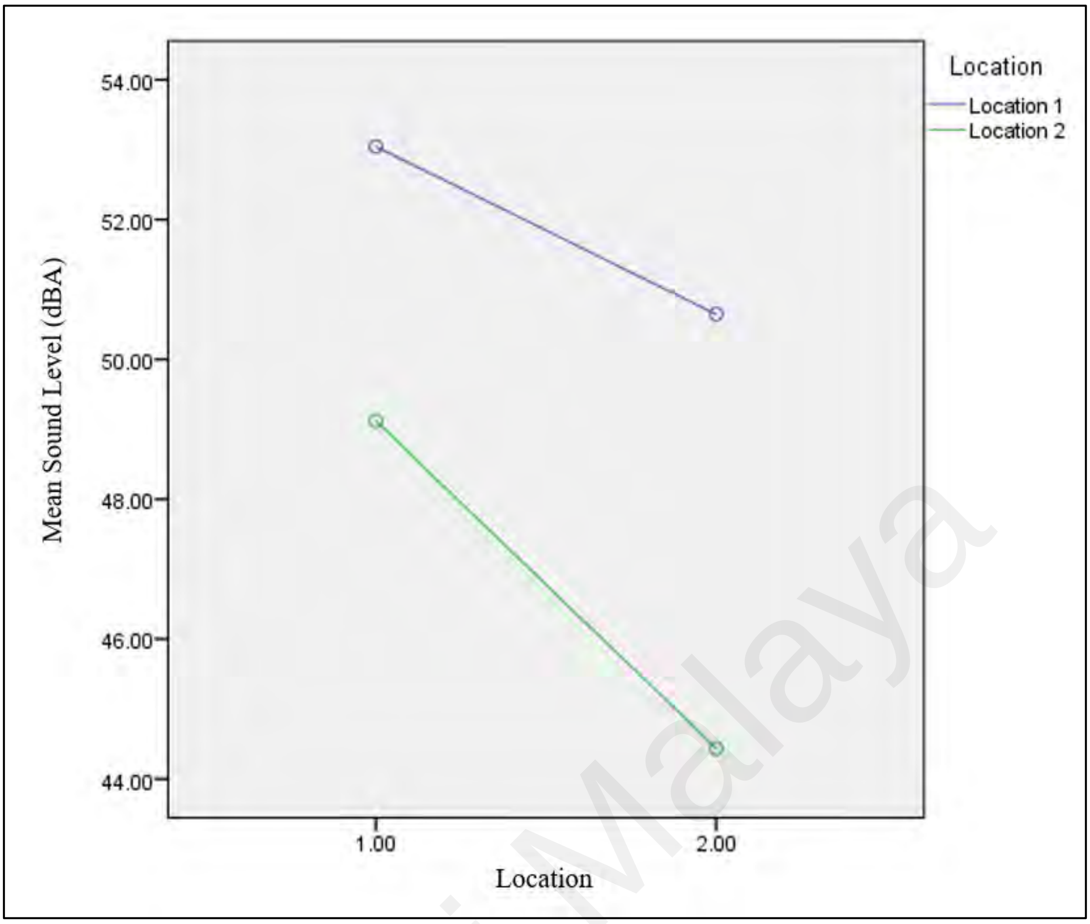


Figure 4.12: Mean plot for sound level (dB_A) by location and day mode interaction.

In both locations, day time sound levels were higher than at night, which corroborates the results explained in the previous sections. The combination of distance, rig type and enforcement of noise regulations generated this pattern of results.

4.4 Comparisons of Sound Level (dB_A) against Noise Limit

The previous section showed that there are significant differences in sound levels between location, wells and day/night mode, and thus it is important to present a detailed status of noise levels separated by frequency of limit exceedance. Mean levels alone are insufficient to understand the generated sound level trends. Limits for night time sounds are usually 5 – 10 dB_A lower to compensate for added requirements to ensure proper rest at night (Weston & Macfarlan, 2015). In this selected metropolitan city in Italy, the local council defined an absolute noise limit of 60 dB_A in the day time, and 50 dB_A for night time. The formula to calculate percentage of exceedance is given by:

$$Exceedance\ (\%) = 100\%\ x\ [n_{x,i,day} + n_{x,i,night}]/[n_{i,day} + n_{i,night}] \quad (4.1)$$

Where,

i = locations/ wells, i.e. location 1, location 2, well 1, 2, 3, 4, and so on.

$n_{x,\ i,\ day}$ = number of samples exceeded day absolute limit of 60 dB_A, in location i

$n_{x,\ i,\ night}$ = number of samples exceeded night absolute limit of 50 dB_A, in location i

$n_{i,\ day}$ = number of samples in location i during day

$n_{i,\ night}$ = number of samples in location i during night

Tables 4.12 and 4.13 shows the equivalent continuous sound level significant factors (all values are A-weighted) and the percentage of day and night time sound levels that exceeded the set limit respectively. The percentage of exceedance is an important aspect of noise studies as mean sound levels might not provide a full understanding of the noise levels generated. Radtke (2016) and Smith and Gloeckler (1991) similarly presented noise study findings in such a manner.

Table 4.12: Statistics of sound level (dB_A) by significant factors (day).

Day Mode	Category	Mean	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	Exceedance (%)
Day	Well 9	50.0	43.3	46.0	49.1	54.1	58.5	70.2	15.6%
Day	Well 12	49.6	43.7	46.4	49.0	53.0	56.3	61.9	12.1%
Day	Location 2*	49.1	41.8	45.4	48.7	52.7	55.2	62.7	10.2%
Day	Well 11	49.2	43.2	46.1	48.6	52.2	55.6	62.5	8.9%
Day	Well 10	48.4	40.6	43.7	48.4	52.1	54.1	58.6	8.8%
Day	Well 13	49.4	45.3	47.0	49.1	52.1	53.1	56.6	7.4%
Day	Well 3	53.6	47.4	49.5	53.3	57.9	60.7	70.3	5.7%
Day	Well 2	53.8	47.9	49.9	52.9	58.5	60.7	73.8	5.5%
Day	Well 8	48.5	42.3	45.1	48.4	51.7	52.2	56.8	4.9%
Day	Location 1*	53.0	47.4	49.3	52.7	57.0	58.6	63.2	2.6%
Day	Well 7 ST	53.6	47.5	50.0	53.6	57.0	58.3	62.9	2.5%
Day	Well 1	52.0	48.2	48.7	51.7	56.0	56.9	61.8	1.6%
Day	Well 6	51.8	46.6	48.7	51.3	54.7	58.3	60.0	0.9%
Day	Well 4	51.7	47.1	48.6	51.3	56.3	57.4	58.2	0.0%
Day	Well 5	52.1	48.0	49.5	52.0	54.6	55.0	58.2	0.0%
Day	Well 7	53.5	47.7	49.9	53.2	57.6	58.2	59.4	0.0%

*Location 1 and Location 2 are at overall level
Table values were sorted from highest mean sound level to lowest
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data

Table 4.13: Statistics of sound level (dB_A) by significant factors (night).

Day Mode	Category	Mean	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	Exceedance (%)
Night	Well 7 ST	50.9	45.3	47.3	51.3	53.7	54.2	56.7	63.9%
Night	Well 6	50.8	44.9	47.4	50.7	54.0	54.8	56.4	61.4%
Night	Well 2	50.9	46.3	48.1	50.5	54.7	55.9	57.7	59.4%
Night	Location 1*	50.6	45.2	47.4	50.2	54.3	55.9	58.0	53.8%
Night	Well 3	50.2	50.0	48.1	50.2	54.2	55.8	57.3	53.1%
Night	Well 7	51.2	46.2	47.3	50.1	57.8	58.7	60.1	52.2%
Night	Well 4	50.1	44.6	46.4	49.6	56	56.8	58.0	41.2%
Night	Well	50.1	46.7	47.6	49.6	52.7	53.5	55.0	39.6%
Night	Well 1	49.8	46.7	48.2	49.0	53.4	54.7	54.9	33.3%
Night	Well 13	45.1	36.1	39.9	45.5	48.7	49.2	50.3	25.9%
Night	Well 9	45.1	37.9	41.0	45.5	48.2	49.1	51.2	18.7%
Night	Well 8	44.0	36.0	38.3	44.0	48.6	49.8	57.3	18.2%
Night	Well 10	43.3	34.4	37.2	44.1	48.4	49.6	54.1	14.9%
Night	Location 2*	44.4	35.2	39.4	44.9	48.1	49.3	53.1	13.1%
Night	Well 11	44.9	38.5	41.2	45.2	47.7	48.4	54.1	12.6%
Night	Well 12	44.7	38.2	41.5	44.7	47.7	48.9	51.4	9.4%

*Location 1 and Location 2 are at overall level
Table values were sorted from highest mean sound level to lowest
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data

Location 1 produced higher mean sound levels for both day and night as compared to Location 2. Nonetheless, it is interesting to find that Location 1 had a lower rate of exceeding the limit by 2.6% compared to Location 2 of 10.2% during the day time. During the night time, Location 1 was found to have a higher rate of exceeding the absolute limit by 53.8% compared to Location 2 with only 13.1% during the night time. The effect of well activities will be described in further sections to explain this result. The percentage of deviation is higher at night due to the lower set government limit of sound level, which makes it harder to achieve for instantaneous data points (and while all other factors have remained constant e.g. sound barriers, equipment type, sensor distance). This shows that there is no direct correlation towards the noise results on both locations, and more detailed analysis needs to be done to understand the cause of these deviations by independent variables such as well activity and weather.

The study also found that wells numbers 9 and 12 in Location 2 showed a higher exceedance rate of 15.6% and 12.1% compared to other wells during day time site operation of the absolute limit (local government set limit). These high values (between 61.0 dB_A to 82.4 dB_A) occurred during drilling the highly compressive and abrasive 8.5¨-hole section and completions activities which involved heavy duty equipment being used to execute complex well operations. At night, all the wells in Location 2 showed high exceeding rates, with only wells numbers 1, 4 and 5 with an exceedance rate lower than 50%. The subsequent section of this analysis will present the findings from a detailed analysis of well activity to ascertain the cause of the high (or low) sound levels.

Figures 4.13 and 4.14 represents the results during the day and night as a bar chart. It shows the average of each location and well's percentage of exceedance to the noise limits. The y-axis in Figure 4.13 is shown from 0 to 18% to amplify the differences between different locations as the data only ranged from 0 to 16%.

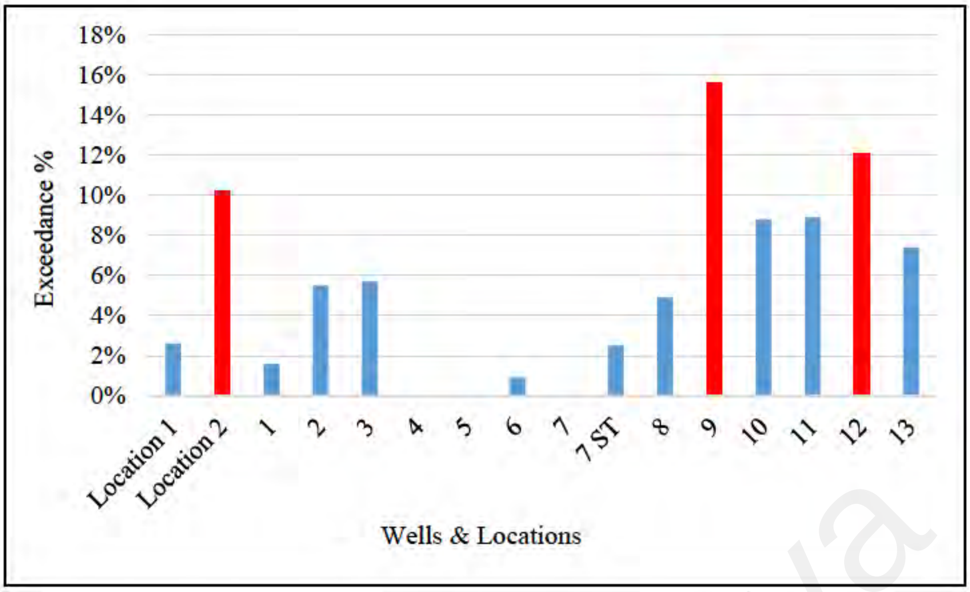


Figure 4.13: Sound level absolute exceedance rate during day (%).

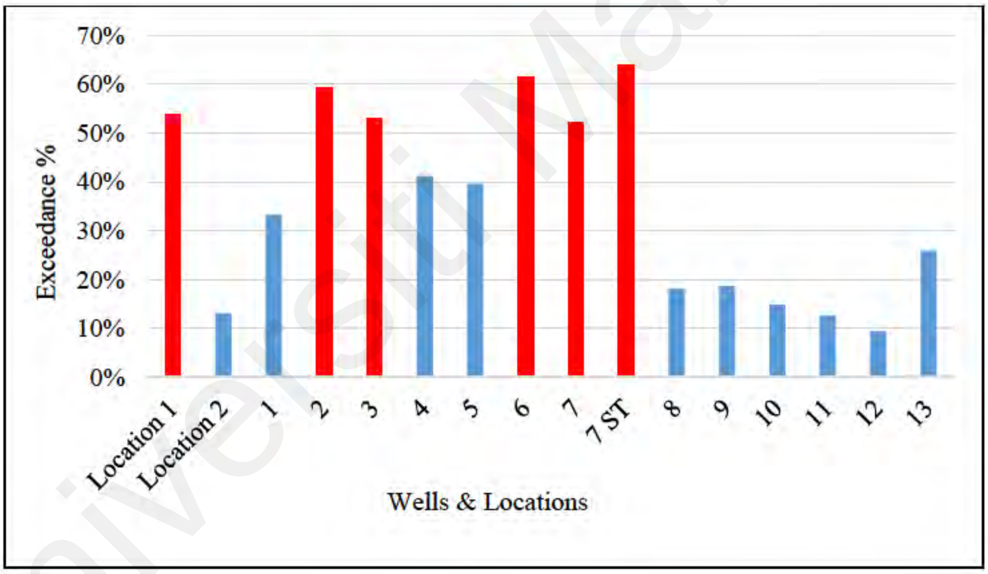


Figure 4.14: Sound level absolute exceedance rate at night (%).

Other studies of oil and gas noise show that in some instances, noise levels exceeded the corresponding limits set by the local government. One such study was by Smith and Gloeckler (1991) who found that noise levels exceeded the 80.0 dB_A limit during operating conditions. This was due to the high noise generated by the rig equipment. In relatively permanent working places such as the drill floor, shale shaker house, mud pump room and main engine room had noise exposure levels above 85 dB_A, whereas background noise levels inside living quarters and offices were 49-62 dB_A which was higher than the 45 dB_A limit for this area (Smith & Gloeckler, 1991).

Radtke (2016) similarly presented noise levels exceedance percentage at various sites (drilling, completion, fracturing, production) in the different areas (residential, commercial and industrial). Residential areas had the highest percent exceedance in the day time (68%) followed by commercial (45%), light industrial (9%) and industrial (0%). In the night time, results showed higher exceedance (due to stricter limits) in measured industries of residential (73%), commercial (68%), light industries (32%) and industrial (0%). This study employs the same manner of analysis and presentation of results.

4.5 Sound Level (dB_A) of High-Level Activities

This section analyses the impact of high level well activities on the recorded sound level (dB_A) to understand which of the activities generated the higher or lower noise values. The data is analysed by location and day mode. Understanding the cause of the high noise levels allows for applying the right mitigation measures to reduce the noise impact on the surroundings (U. S. EPA, 1974; Weston & Macfarlan, 2015). Furthermore, to assess the significant differences in sound levels (dB_A), one-way ANOVA testing was employed, and Tukey HSD test is used to test significant different pairs of high-level activities (Baloye & Palamuleni, 2015).

4.5.1 Location 1 Day Activities

An ANOVA test was conducted to evaluate the significant difference in sound levels between the high-level activities on Location 1 during the day time, shown in Table 4.14. The highest to lowest sounds generated is shown in the column ¨Ranking¨.

Table 4.14: Statistic test for sound level (dB_A) by activities in Location 1 (day).

Activities	n	Mean	S. D.	Rank of Mean
Drilling - 8.5"	618	53.8	3.23	1
Completions	478	53.5	3.69	2
Drilling - 12.25"	411	53.3	4.35	3
Rig Move	300	52.8	3.22	4
Drilling - 16"	298	52.2	2.56	5
Testing	160	52.1	3.36	6
Drilling - 23"	306	52.0	2.06	7
F = 17.9, p < 0.001, n = number of samples in a group, S. D. = standard deviation of sound level in a group				

During the day time, high level activities in Location 1 were found to have significant difference in sound level (dB_A) at a 0.05 significance level ($F = 17.9$, $p < 0.001$). Drilling the 8.5” hole section of the well was identified to exhibit the highest mean sound level (53.8 dB_A) while drilling the 23” hole section showed the lowest sound level (52.0 dB_A). It can be noticed that as the size of the drill bit gets bigger from 8.5” to 23”, the sound level (dB_A) decreases accordingly, suggesting that in Location 1, the sound increases as the bit size decreased. This is due to the higher complexities and harder formations to drill as the well depth increases, causing more resistance along the drill string translated into shock, vibrations and erratic drilling conditions thus creating higher noise at surface. Only completion activity was found to exceed the absolute sound limit more than 5% of the time. The completion activities that cause higher sound levels involve circulating and pressure testing, which at high flow rates do cause elevated hydrodynamic noise (liquid flow noise is generated by the turbulent velocity fluctuations that result from the rapid deceleration of the fluid that occurs as the flow area increases downstream of the pipe constriction) in pipes and connectors (Bies & Hansen, 2003).

Compared to other drilling activity noise studies (Emam, 2016; Melling et al., 1975; Radtke, 2016; Redman, 1986; Weston & Macfarlan, 2015), the results here are comparatively lower due to the strict noise control measured implemented, mainly the installation of sound barriers throughout the noise measurement phase. New drilling and rig move technologies have been proven to reduce noise during these activities, e.g. installing draw-works disc brake, anti-vibration pads, flexible piping, insulation/silencers (Goines & Hagler, 2007; Qui et al., 2014; Redman, 1986; Stollery, 2014; Weston & Macfarlan, 2015). Specific equipment noise surveys can also define high noise generation areas (Redman, 1986).

A Tukey HSD post hoc test was conducted to test the significant difference in mean sound level of activities and the results are summarised in Table 4.15. The Tukey HSD successfully grouped the sound level into three subgroups to represent the different sound level generated from these activities, i.e. Group 1 (lower mean sound level), Group 2 (medium mean sound level) and Group 3 (higher mean sound level).

Table 4.15: Tukey HSD test for activities in Location 1 (day).

High level activity	**n**	**Mean subgroup**		
		1	**2**	**3**
Drilling - 23"	306	52.0		
Testing	160	52.1		
Drilling - 16"	298	52.2		
Rig Move	300	52.8	52.8	
Drilling - 12.25"	411		53.3	53.3
Completions	478		53.5	53.5
Drilling - 8.5"	618			53.8
n = number of samples in a group				

Drilling the 8.5” section was found to have the highest mean sound level, results showed that 50% (Leq_{50}) of the sound level while for completion activities was more than 53.6 dB_A and 2.8% of the sound level recorded exceeded the absolute limit of 60 dB_A. Completions activity generated the second highest mean sound level, results showed that 50% of its recorded sound level were more than 52.7 dB_A and 5.2% of the recorded sound level exceeded the absolute sound limit. This means that out of 100 recorded sound level during completions activities, there will be about 5 recorded sound levels that exceeded the absolute limit of 60 dB_A during day light in Location 1.

In addition, the activities of Drilling the 23”-hole section, Testing, Drilling the 16" section, and rig move activities were found to have significantly lower sound levels. Table 4.16 presents the mean, different percentiles and most importantly the percentage of how many times the sound level (dB_A) exceeded the absolute day limit (60 dB_A) at Location 1 in the day time.

Table 4.16: Statistics of sound level (dB_A) by activities in Location 1 (day).

Activities	**Mean**	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	**Exceedance (%)**
Completions	53.5	47.7	49.9	52.7	58.0	60.2	70.3	5.2%
Testing	52.1	47.4	48.7	51.5	56.6	59.6	64.2	3.8%
Drilling - 12.25"	53.3	47.0	48.7	52.4	58.1	59.3	69.4	3.6%
Drilling - 8.5"	53.8	48.3	50.0	53.6	57.0	58.4	63.2	2.8%
Rig Move	52.8	47.3	48.9	52.6	57.0	58.3	60.9	1.7%
Drilling - 16"	52.2	47.4	49.2	51.9	55.3	57.5	58.8	0.0%
Drilling - 23"	52.0	47.4	49.2	52.2	54.4	54.9	57.1	0.0%
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data								

4.5.2 Location 2 Day Activities

To assess the differences in sound levels between high level activities at Location 2 during the day time, an ANOVA test was run. Table 4.17 reveals that there is significant difference in sound levels at a 0.05 significance level ($F = 17.4$, $p < 0.001$) as well showing the ranking of the sound levels (dB_A) from highest to lowest.

Table 4.17: Statistic test for sound level (dB_A) by activities in Location 2 (day).

Activities	n	Mean	S. D.	Rank of Mean
Plug & Abandonment	50	51.6	6.58	1
Drilling - 23"	229	49.8	3.22	2
Drilling - 8.5"	204	49.8	3.81	3
Drilling - 16"	249	49.4	3.08	4
Completions	467	49.4	4.62	5
Move	293	49.2	3.08	6
Drilling - 12.25"	268	49.1	2.99	7
Testing	400	47.5	3.42	8
F = 17.4, p < 0.001 n = number of samples in a group, S. D. = standard deviation of sound level in a group				

The plug and abandonment activity were found to have the highest mean sound value at 51.6 dB_A, followed by Drilling the 23" section with a mean sound level of 49.8 dB_A while the Testing activity showed the lowest mean sound level at 47.5 dB_A. These values are seen to be distinctly lower than sound levels recorded from Location 1 during the day time. The plug and abandonment category included activities such as cementing, drilling and pressure testing which explains the high values on Location 2 due to the type of equipment used in these operations.

A Tukey HSD post hoc test was conducted to test the significant different in mean sound level between the type of activities and the results as summarised in Table 4.18. Results showed that Tukey HSD test classified the sound level into three subgroups, i.e. Group 1 (lower mean sound level), Group 2 (medium mean sound level) and Group 3 (higher mean sound level). The results showed that the Testing activity in Location 2 during day time had the lowest sound levels (dB_A) compared to other activities, due to the intervention by the management to mitigate sounds by installing the sound barriers.

Table 4.18: Tukey HSD test for activities in Location 2 (day).

High level activity	n	Mean subgroup		
		1	2	3
Testing	400	47.5		
Drilling - 12.25"	268		49.1	
Rig Move	293		49.2	
Completions	467		49.4	
Drilling - 16"	249		49.4	
Drilling - 8.5"	204		49.8	
Drilling - 23"	229		49.8	
Plug and abandonment	50			51.6
n = number of samples in a group				

Plug and abandonment activity only occurred on Location 2 so could not be compared to data on Location 1, but it was the significantly highest sound level (dB_A) compared to other activities, because of numerous activities being categorized within the Plug and Abandonment label (cementing, drilling, pressure testing etc) which makes these results inconclusive. A similar trend in highest to lowest mean sound levels generation could be seen in both Location 1 and 2 during the day time; generally drilling, completions, rig move then testing which corroborates the results from previous sections.

Table 4.19 presents the sound level of various high-level activities at Location 2 during the day time by using mean and percentiles, as well as percentage of recorded sound level that exceeded the absolute limit (60 dB_A).

Table 4.19: Statistics of sound level (dB_A) by activities in Location 2 (day).

Activities	Mean	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	Exceedance (%)
Plug and abandonment	51.6	42.2	46.8	49.5	62.4	66.4	73.2	24.0%
Drilling - 23"	49.8	44.0	46.6	49.1	54.1	56.7	62.0	14.8%
Drilling - 8.5"	49.8	43.3	46.6	49.2	53.6	55.7	66.4	14.2%
Completions	49.4	42.3	45.5	48.7	52.8	55.9	75.4	10.7%
Drilling - 16"	49.4	43.7	46.5	49.2	52.3	54.7	59.1	9.6%
Drilling - 12.25"	49.1	43.3	46.0	48.6	52.4	53.9	59.9	9.3%
Rig Move	49.2	43.1	46.1	48.7	52.7	54.0	61.9	7.4%
Testing	47.5	40.6	43.0	47.7	51.2	52.2	58.0	4.3%
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data								

From the results, it can be observed that plug and abandonment with the highest mean sound level had 50% of its recorded data show noise higher than 49.5 dB_A and 24% of the sound level exceeding the absolute limit. Besides, activities such as Drilling the 23” and Drilling the 8.5” sections also have relatively higher percentages of sound levels that exceeded the absolute limit with 14.8% and 14.2% respectively.

4.5.3 Location 1 Night Activities

In this section, the ANOVA test was conducted to examine the sound levels between the different types of high-level activities at Location 1 during the night time. Table 4.20 shows that there are significant differences in sound levels between the activity types (F

= 17.0, p < 0.001) at 0.05 significance level. The sound level from highest to lowest is presented in Ranking column from 1 to 7.

Table 4.20: Statistic test for sound level (dB_A) by activity in Location 1 (night).

Activities	n	Mean	S. D.	Rank of Mean
Drilling - 8.5"	338	51.8	2.71	1
Drilling - 12.25"	198	51.2	6.23	2
Completions	255	50.2	1.82	3
Drilling - 23"	155	50.1	2.21	4
Drilling - 16"	146	50.1	2.67	5
Testing	92	49.6	1.95	6
Rig Move	158	49.3	1.92	7
F = 17.0, p < 0.001 n = number of samples in a group, S. D. = standard deviation of sound level in a group				

From the table, Drilling the 8.5” section showed the highest sound levels at 51.8 dB_A, followed by Drilling the 12.25” at 51.2 dB_A while Rig Moves exhibited the lowest sound level at 49.3 dB_A. The overall mean sound levels are lower here than seen in Location 1 during the day time, which can be attributed to stricter noise limits at night. The rankings here are not comparable to the ranking of activities found (due to differences in well criteria, drilling parameters and other factors such as number of persons on board, weather and installation of additional barriers which will be analysed in later sections of this study). Overall, drilling generated the highest sound levels, followed by completion activities. Rig move at night is one of the lowest resulting noise due to suspension of large vehicle movement and unsafe conditions (due to lack of natural light) that do not warrant operations at night times. Next, a Tukey HSD post hoc test was conducted to assess the significant pairwise sound level differences for all the main activities as summarised in Table 4.21.

Table 4.21: Tukey HSD test for activities in Location 1 (night).

High level activity	n	Mean subgroup	
		1	2
Rig Move	158	49.3	
Testing	92	49.6	
Drilling - 16"	146	50.1	
Drilling - 23"	155	50.1	
Completions	255	50.2	
Drilling - 12.25"	198		51.2
Drilling - 8.5"	338		51.8
n = number of samples in a group			

Tukey HSD test has successfully classified the means values into two subgroups, i.e. group 1 (lower mean sound level), and group 2 (higher mean sound level). In addition, Rig Move, Testing, Drilling of 16" section, Drilling of 23" section and Completions were found to have a significantly lower sound level (Group 1) as compared to Drilling the 12.25" section and Drilling of the 8.5" sections (Group 2) as explained above. The study further analyses the recorded sound level of high-level activities at Location 1 during night time by presenting their corresponding means, percentiles and percentages of sound level exceeding the absolute limit. Table 4.22 shows that Drilling the 8.5" with the highest sound level of 51.8 dB_A had 50% (Leq_{50}) of its data higher than 51.8 dB_A and as high as 72.5% of its recorded sound level exceeded the absolute night limit of 50 dB_A.

Table 4.22: Statistics of sound level (dB_A) by activity in Location 1 (night).

Activities	Mean	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	Exceedance (%)
Drilling - 8.5"	51.8	45.9	48.4	51.8	55.6	56.7	57.4	72.5%
Drilling - 12.25"	51.3	50.0	46.5	51.0	57.4	58.2	60.3	64.6%
Drilling - 23"	50.1	44.9	47.2	50.1	53.1	54.0	55.5	51.6%
Completions	50.2	46.2	48.0	50.1	52.5	53.2	54.3	50.0%
Drilling - 16"	50.1	46.2	47.3	49.4	53.8	54.4	55.1	39.0%
Testing	49.6	45.2	47.4	49.2	52.3	53.4	54.9	34.8%
Rig Move	49.3	45.2	47.1	49.0	51.8	52.8	53.9	32.9%
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data								

Furthermore, Drilling the 12.25" section had the second highest mean sound level of 51.3 dB_A with 50% of its data more than 51.0 dB_A. Drilling the 12.25" also showed comparable high percentage of data exceeding the absolute limit, positioned at 64.6%.

4.5.4 Location 2 Night Activities

In this section, the ANOVA test was employed to assess the sound level differences between high-level activity types in Location 2 at night. There are significant differences in recorded sound levels between the type of activities ($F = 37.0$, $p < 0.001$) at 0.05 significance level. Table 4.23 shows that Drilling the 8.5" section had the highest sound level at 46.4 dB_A, followed by Drilling the 16" section at 46.0 dB_A, and Drilling the 23" at 45.7 dB_A. It can be explained that as the drill bit (or hole size) increases, the noise levels decreased. The sizes are defined at a very early stage of the well design, which might not be easily changed during the drilling operations once begun, but might affect future well designs, providing knowledge of potential noise levels to the drilling engineers when they design wells. The highest to lowest sounds are shown in the 'Ranking' column. Night time sounds at Location 1 are higher than at Location 2.

Table 4.23: Statistic test for sound level (dB_A) by activity in Location 2 (night).

Activities	n	Mean	S. D.	Rank of Mean
Drilling - 8.5"	100	46.4	2.67	1
Drilling - 16"	118	46.0	2.59	2
Drilling - 23"	114	45.7	3.27	3
Drilling - 12.25"	136	45.3	3.28	4
Plug and abandonment	25	45.0	2.91	5
Completions	242	44.4	2.82	6
Rig Move	148	43.7	2.77	7
Testing	212	41.7	4.19	8
$F = 37.0$, $p < 0.001$ n = number of samples in a group, S. D. = standard deviation of sound level in a group				

At night time, testing posted the lowest sound levels (41.7 dB_A). Rig Move, Completions, and plug and abandonment were found to have significantly lower sound levels as compared to Drilling the 12.25" section, Drilling the 23" section, Drilling the 16" section, and Drilling the 8.5" sections. The ranking of the sound levels does not mirror the ranking of any other category. Table 4.24 presents the results of the Tukey HSD post hoc test which was conducted to assess the significant pairwise sound level differences for all the main activities at Location 2 during the night time. Tukey HSD test classified the mean sound level into four subgroups, i.e. Group 1 (lower mean sound level), Group 2 (medium low mean sound level), Group 3 (medium high mean sound level) and Group 4 (higher sound mean sound level).

Table 4.24: Tukey HSD test for activities at Location 2 (night).

High level activity	n	Mean subgroup			
		1	2	3	4
Testing	212	41.7			
Rig Move	148		43.7		
Completions	242		44.4	44.4	
Plug and abandonment	25		45.0	45.0	45.0
Drilling - 12.25"	136			45.3	45.3
Drilling - 23"	114			45.7	45.7
Drilling - 16"	118				46.0
Drilling - 8.5"	100				46.4
n = number of samples in a group					

A general trend is seen among all categories, where drilling sound levels were the highest followed by completions. Drilling large to smaller hole sizes reduced sound levels. Testing and rig move did not show similar results compared to Location 1-night time but testing was however, the lowest sound level producer at night time compared to day in both locations. There were no plug and abandonment activity recorded in Location 1 hence this variable could not be compared with results on Location 2.

The study of sound levels at Location 2 at night was further analysed by using means, percentiles and percentages of sound level that exceeded the absolute limit (50 dB_A). Drilling the 8.5" section had the highest sound level of 46.4 dB_A, 50% of its sound level above 46.8 dB_A and 28% of its data exceeding the absolute limit. Another finding worth mentioning is that Drilling the 16" had the highest percentage of sound level that exceeded absolute limit, at 31.4%. The summarized results are as shown in Table 4.25.

Table 4.25: Statistics of sound level (dB_A) by activity in Location 2 (night).

Activities	Mean	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	Exceedance (%)
Drilling - 16"	46.1	38.6	42.9	46.4	49.1	49.7	50.3	31.4%
Drilling - 8.5"	46.4	37.8	43.4	46.8	49.2	49.7	53.6	28.0%
Drilling - 12.25"	45.3	34.6	41.0	45.8	48.8	50.0	51.6	23.5%
Drilling - 23"	45.8	38.8	42.4	45.7	48.2	52.6	57.3	19.3%
Plug and abandonment	45.0	38.6	39.6	45.9	47.8	48.9	50.1	12.0%
Completions	44.5	37.6	40.5	44.7	47.6	48.3	51.2	10.3%
Testing	41.7	34.4	36.9	41.2	47.0	47.9	54.6	7.1%
Rig Move	43.7	37.9	40.3	43.6	46.9	48.1	50.6	5.9%
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data								

On the other hand, Drilling the 12.25" section was found to have a relatively high percentage of data exceeding the absolute limit at 23.5%. Overall, the sound levels generated during this study showed lower noise levels compared to the study results of Radtke (2016) potentially due to different measurement parameters, installation of sound barriers around the rig perimeter, drilling conditions, rig types, terrain and weather conditions.

4.6 Impact of Flaring Burner Enclosure on Noise Level

This section studies flaring burner enclosure installation as a factor to reduce sound levels generated during testing activities (in which flaring is a key component). Sound barriers are a relatively common noise management tool in many industries (Emam, 2016). An independent sample t test was conducted, and the results are summarised in Table 4.26.

Table 4.26: Statistic test for sound level (dB_A) by flaring burner enclosure installation.

Flaring burner system installed	**n**	**Mean**	**S. D.**
No	47	50.9	2.91
Yes	817	46.9	4.98
T = 9.56, p < 0.001 n = number of samples in a group, S. D. = standard deviation of sound level in a group			

There is significant difference in sound levels for testing activities between locations with flaring burner enclosures installed compared to locations without flaring burner enclosures installed ($t = 9.56$, $p < 0.001$) at 0.05 significance level. The overall sound levels measured were impacted by two other factors, installation of a fixed noise barrier as well as the distance from the sensor to the flare sites. Both factors dampen the noise measurements, as reported by several studies (NIOSH, 1998; Noise Pollution Clearinghouse Organization, 2017; Wang et al., 2005; Weston & Macfarlan, 2015; WHO Europe, 2009; OSHA, 2013). Even so, the installation of the flaring burner enclosure system significantly reduced the mean sound level from 50.9 dB_A to 46.9 dB_A (Figure 4.15).

This 4-dB reduction can substantially improve the living conditions of the nearby residents, since it mathematically translates to almost half of the perceived sound. Radtke (2016) reported that with the installation of sound walls, sound levels at drilling sites were reduced from 65 dB_A to 59 dB_A (6 dB_A reduction) sound levels at fracturing sites were reduced from 70 dB_A to 59 dB_A (11 dB_A reduction) 107 m from the source.

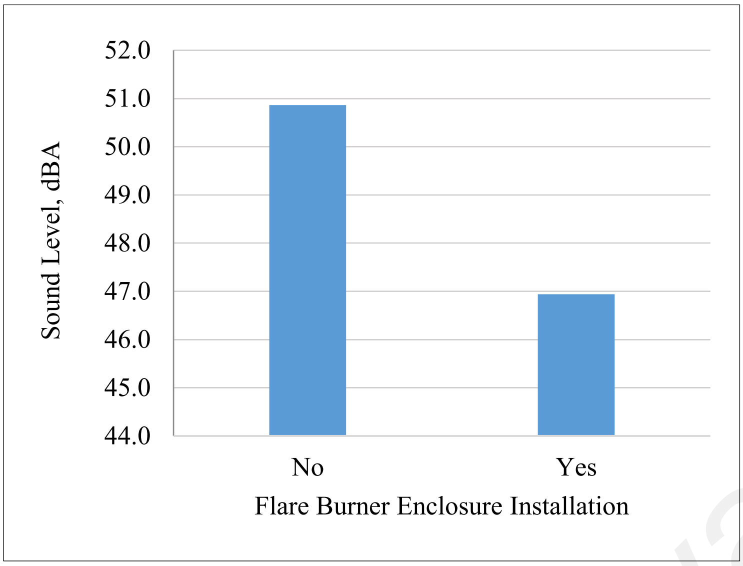


Figure 4.15: Sound level (dB_A) with/without flare burner enclosure installed.

A statistics test shows that without a flare burner enclosure installed during testing activities, the sound level did exceed the absolute limit by 12.8%. After installing the enclosure, the percentage of exceedance reduced to 7.8%. During the test, the analysis found that without the flare burner enclosure, out of 1000 sound points recorded, 128 cases exceeded the limit (60 dB_A for day, 50 dB_A for night). This study hence concludes that installing a flaring burner enclosure can significantly reduce sound levels by a mean magnitude of 4 dB_A. These results are shown in Table 4.27.

Table 4.27: Statistics of sound level (dB_A) by flare burner installation.

Flaring burner	**Mean**	**L_{99}**	**L_{95}**	**L_{90}**	**L_{50}**	**L_{10}**	**L_1**	**Exceedance (%)**
No	50.9	45.2	47.6	50.1	55.7	56.6	56.7	12.8%
Yes	46.9	35.2	40.0	47.7	52.2	53.9	59.9	7.8%
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data								

Some researchers have also suggested calculation methods for predicting the sound emission of flares (Hantschk & Schorer, 2008) which could provide a strategic manner for government councils to estimate the potential noise pollution prior to granting permission to oil and gas operators to conduct such operations and to install the right noise abatement strategies appropriately. Emam (2016) provided a comprehensive list of factors to consider when designing flare system and monitoring for potential impact reduction. These include operating range, accuracy, installation requirements, maintenance and calibration requirements, composition monitoring, temperature and pressure corrections, multi-phase capabilities, monitoring records, flow verification, flow test methods, non-clogging/non-fouling/no moving parts, stainless steel wetted parts, agency approvals for installation in hazardous locations and compliance with local environmental regulations. Further calculations can be used to model noise flaring operations by calculations using gas mass flowrates (Ghadyanlou & Vatani, 2015) to better understand the potential severity of the noise problem from flaring before taking place.

4.7 Sound Level (dB_A) by Rig Type

In this section, the study analyses the sound generated by different types of drilling rigs by ANOVA testing. There are three rig types analysed in this study (rig 1, rig 2 and rigless). The different set of equipment on each rig type generates different sound levels, based on the equipment, motor and movement mechanisms. In general, rig type 2 (being a newer generation-built rig) is the most efficient due to its ability to maintain sound levels as low as 47.5 dB_A. Rigless activity includes activities with noisy equipment such as coiled tubing units, offline testing activities, high pressure pumping and circulating systems and, in some cases, heavy equipment movement and transportation, which generates relatively high sound levels, even without a rig being utilized. The statistic test results by rig type are shown in Table 4.28. Table 4.29 shows that rig types 2 and rigless have a similar absolute exceeded limit of 11% while type 1 has the higher value, which generated the overall higher sound levels compared to all three rig types. In terms of statistical analysis, there is a significant difference in sound levels generated between the type of rig ($F = 1265.4$, $p < 0.001$) at 0.05 significance level.

Table 4.28: Statistic test for sound level (dB_A) by rig type.

Rig	N	Mean	SD	Ranking
Type 1	3500	52.3	3.58	1
Rigless	413	51.1	3.36	2
Type 2	3255	47.5	4.33	3
F = 1265.4, p < 0.001 n = number of samples in a group, S. D. = standard deviation of sound level in a group				

Figure 4.16 shows that rig type 1 has the highest sound level generated (52.3 dB_A), followed by rigless type (51.1 dB_A) and lastly rig type 2 (47.5 dB_A). Each rig 1 and rig 2 has a different set of equipment, as it was fabricated and designed by different companies. Although seemingly small, the reduction in sound levels will prove to be critical with reduced distance between the community and the drilling activity hence the type of rig is an important aspect of the noise study.

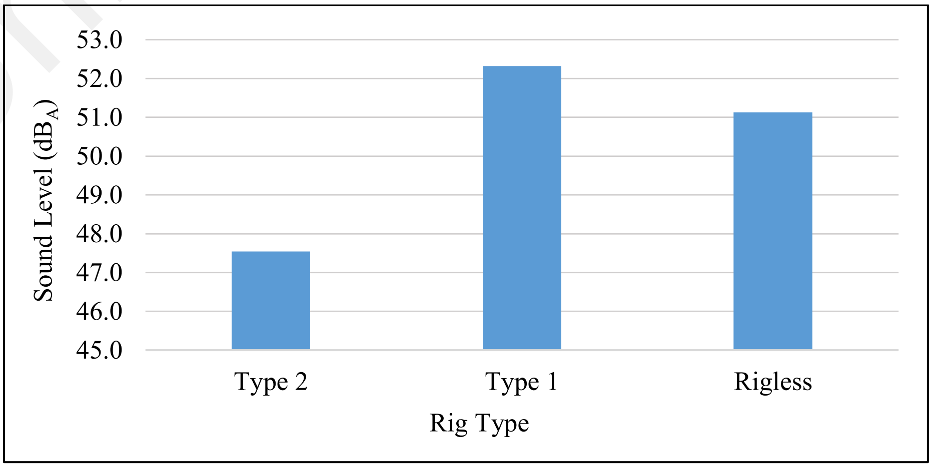


Figure 4.16: Sound level (dB_A) by type of rig.

Table 4.29: Statistics of sound level (dB_A) by type of rig.

Rig	Mean	L_{99}	L_{95}	L_{90}	L_{50}	L_{10}	L_1	Exceedance (%)
Type 1	52.3	46.1	48.6	52.0	56.5	57.9	62.0	21.3%
Type 2	47.5	37.0	42.5	47.6	51.8	53.6	61.1	11.5%
Rigless	51.1	46.9	47.7	50.4	55.1	58.7	61.8	11.1%
L_n is the n-th percentile of the noise level. E.g. L_{99} = 99th percentile of the noise level data								

Drilling contractors are coming up with more ingenious ways to reduce sound emission from drilling rigs, such as creating electric rigs, installing sound barriers around compressors and other high sound generators as well as using the produced natural gas to power rig components such as lighting, generators and others (King, 2012). Such methods could be utilized to reduce rig generated sound levels.

4.8 Factors Influencing Noise Levels

Multiple linear regression analysis was deployed to study the effect and strength of selected variables/impact factors namely rig type, number of persons on board the rig (POB), weather (e.g. Ambient Temperature (°C), Relative Humidity %, Global Radiation (W/m^2), Precipitation (mm), Wind speed (m/s), and Wind direction (°), flaring burner enclosure installation and type of activities (e.g. Drilling - 12.25", Drilling - 16", Drilling - 23", Drilling - 8.5", Move, Plug and Abandonment). Multiple linear regressions will estimate the effect of several factors simultaneously, for example, the effect of humidity was estimated by considering the existence of other factors, such as global radiation, number of people on rig, etc. Multiple linear regression was conducted using SPSS with stepwise method that omit insignificant factors, leaving only significant factors in the model.

All variables presented are significant factors for sound level changes after the stepwise procedure and they were able to explain 34.9% of changes in sound level ($F = 164.91$, $p < 0.001$). Prior to assessing the model, the study examined the value of variance inflation factor (VIF) by using the general rule of thumb in which VIFs exceeding four warrants further investigation, while VIFs exceeding 10 are signs of serious multicollinearity requiring correction. All the VIF values were below 4, indicating that there is no multicollinearity present. The results are summarised in Table 4.30.

Table 4.30: Results of multiple linear regression.

Factors	B	Beta	t	Sig.	Tolerance	VIF
(Constant)	52.896		94.57	<0.001		
Rig Type 2	-3.677	-0.427	-21.05	<0.001	0.571	1.752
Flaring Burner Enclosure	-3.475	-0.273	-14.18	<0.001	0.633	1.579
Relative Humidity (%)	0.013	0.103	5.18	<0.001	0.592	1.690
Global Radiation (W/m^2)	0.004	0.098	6.22	<0.001	0.939	1.065
Drilling - 8.5" section	1.188	0.085	4.82	<0.001	0.757	1.322
Wind direction (°)	-0.003	-0.074	-4.09	<0.001	0.721	1.386
Completions	2.215	0.061	3.66	<0.001	0.857	1.167
Rig POB (#of people)	0.022	0.056	2.59	0.01	0.504	1.984
Drilling - 12.25" section	0.412	0.036	2.19	0.028	0.886	1.129
$F = 164.91$, $p < 0.001$, $R^2 = 0.349$						

Variables such as Relative Humidity (%,) Global Radiation (W/m^2), Drilling the 8.5" section, Completions activity, number of Persons on Board (POB) and Drilling of the 12.25" section were found to have positive B values (or the regression beta coefficient), ranging from 0.004 to 2.215 dB_A. Thus, for each unit increase in relative humidity ($B = 0.013$), there will be an increase in the sound level by 0.013 dB_A. In other words, for every

10% increase in humidity will lead to 0.13 dB_A increase in sound level. In other words, higher relative humidity will lead to higher sound level.

Next, B = 0.004 indicates that each unit increase in global radiation, there will be 0.004 dB_A increase in sound level. This finding indicated that higher radiation in the area will lead to higher sound level. While undertaking activities such as drilling the 8.5" and 12.25" sections, there will be an increase in the generated sound level by 1.188 dB_A and 0.412 dB_A respectively. This shows that smaller drilling size lead to higher sound levels. Further, B = 2.215 showed that the location undergoes Completion work will likely to have 2.215 dB_A unit higher than area without Completion work. Finally, the study noticed that as the number of persons on the rig increased by 10 persons, the sound level increased by 0.22 dB_A supported by significant B value of 0.022. These factors are critical for future preparation of an environmental study or noise abatement planning, where the variables above should be considered to reduce the overall noise pollution.

Next, the study discovered that by using rig type 2, installing a flaring burner enclosure and having a higher degree of wind direction (270° to 360° facing West to North) decreases the overall sound level, given by negative B values. Therefore, using rig type 2 will help decrease sound levels by magnitude 3.687 dB_A. Installation of flaring burner enclosures likewise, lead to lower sound levels by magnitude of 3.475 dB_A. Finally, as the wind direction increases by 10 degrees, the sound level is expected to decrease by a corresponding 0.03 dB_A.

Apart from that, the relative impact or strength of factors were studied by comparing the absolute BETA values (the negative sign of the BETA value is ignored). The study found that using type 2 rig had the stronger impact in reducing sound levels with BETA = -0.427, followed by installation of flaring burner enclose with BETA = -0.273. The remaining factors had relatively moderate to weak impact on sound levels. So, to reduce noise levels, it would be prudent to focus on these two factors with higher magnitude of BETA values such as rig type and installation of flare burner enclosures.

Due to the unavailability of other similar studies, it was unable to exactly compare the results with other oil and gas noise surveys. However, these methods for analysis and comparisons of noise results present a similar methodology to other studies (Baloye & Palamuleni; 2015; Blumstein et al., 2011; Garcia & Faus, 1991; Garg et al., 2017; Morillas & Carmona, 2002; Radtke, 2016)

4.9 Limitations and Future Work

Seeing that there is limited data in the topic of noise research in the oil and gas industry, this study aims to increase the knowledge pool within the topic, focusing on well drilling and testing activity. Among the limitations of this study include the following concerns:

- Insufficient volume of data - One of the previous research gaps as highlighted by Radtke (2016) which this study covered was to sample a greater number of fracturing sites with walls and completion sites to evaluate consistency.
- Lack of a globally recognized, validated and approved method for noise collection and reporting makes for a multitude of different research methodologies and findings (Berglund et al., 1999).
- Variance in mode of measurement, whether point based or continuous (Radtke, 2016). This study addressed this issue by having a fixed noise monitoring station installed at both research sampling locations to provide continuous measurements throughout the course of this study. Optional method could be to provide each person with a personal sound level meter to track their exposure to noise throughout the work day, as well as install fixed sound level meters at the key equipment and machinery components of the rig.

To further expand upon the results of this study and provide additional insight towards noise pollution levels contributed by the drilling industry, various recommendations for future studies are hereby made:

- Map noise Risk Zones by creating a location map of high to low sound level generating equipment with varying distances by point source measurements (Melling et al., 1975)
- Conduct noise disturbance studies among urban residents and rig workers via surveys and wearing of personal sound monitoring badges to understand the impact of night time noise on exposed population (annoyance, medical issues, sleep deprivation) (Nelson, 1982)
- Quantitatively measure effectiveness of noise risk management tools and equipment (barriers, electric motors, mufflers, insulators, etc) (Mitchell, 2001)
- Calculate DNL (day-night) and L_{den} (day-evening-night) noise levels as a metric to assess annoyance (JRC European Commission, 2011; WHO Europe, 2009)
- Conduct 3D noise modelling to measure impact of height and obstacles to represent the ground morphology, related acoustic absorption criteria, existing buildings and physical barriers (Noce et al., 2013)
- Measure noise using different high- or low-frequency characteristics since noise control methods can differ quite drastically in such situations (Radtke, 2016)
- Measure indoor noise levels of residents at varying distances from the noise generating source (Boyle et al., 2017)

4.10 Summary

This section summarises the findings according to the flow of analyses conducted in this chapter. The results indicated that both locations produced higher sound levels during day time as compared to night time. The overall data measured in 2016 and 2017 showed a minimum value of 31.3 dB_A, mean of 50.1 dB_A, median of 55.3 dB_A and max value of 83.1 dB_A. This peak value occurred during extensive back reaming activities while drilling the 12.25'' hole section on Well 2 at the day time on Location 1. Location 1 showed a mean noise value of 53.0 dB_A in the day time and 50.6 dB_A at night whereas Location 2 showed overall lower values (mean noise levels of 49.1 dB_A in the day and 44.4 dB_A at night). Presence of rain or wind speeds of higher than 5 m/s was found to increase sound levels by 0.6 dB_A, thus these records were omitted from the analysis to maintain the integrity of the results. The resulting data was normally distributed, corroborated by Q-Q plot (the data that did not scatter along the diagonal) and Kolmogorov-Smirnov normality tests (lower than 0.05), thus allowing for parametric statistical testing to be used in the analysis.

The mean measured sound levels generated by drilling and well testing activities at both locations fell within the local authority limits (60 dB_A during the day and 50 dB_A at night). There were, however, various instantaneous peak sounds that exceeded the limits due to operational requirements, even with sound wall barriers installed around the rig site. All activities (drilling, completions, move, plug and abandonment and testing) had instances that exceeded day and night limits at different degrees and severities. The highest contributors to the percentage of limit exceedance were night time results in Location 1 (53.8%), followed by night time in Location 2 (13.1%), day time in Location 2 (10.2%) and finally day time in Location 1 (2.6%). During the day time, the percentage of exceedance was lower than at the night time due to stricter sound limits so additional efforts were made to control the noise. The lower results from Location 2 were potentially due to the increased distance between the sensor to the rig site (282 m) compared to Location 1 (144 m) which dampened the overall sound results. In terms of ranking of the noise contributors, drilling activities showed the highest mean sound levels (49.75 dB_A) due to the extensive use of heavy machinery used during drilling in and back reaming out of the hole. This was the case for drilling all hole sizes (23'' to 8.5''). Completions activity was the next contributor of high sound levels (49.38 dB_A), based on the use of extensive circulating/pumping equipment, operating clean out equipment and stimulation processes which involved gravel packing and acid washing activities. Rig move and plug and abandonment activities showed the lowest mean sound levels measured in this study due to less heavy-duty machinery or pumping equipment being handled (48.75 dB_A and 48.30 dB_A respectively). During rig moves, rigs are dismantled, and certain parts are moved or skid from one well to another within the same drilling area, which does not involve noisy equipment for extended periods. Testing had the lowest mean values (47.73 dB_A) due to there being strict enforcement of noise control via installation of flaring enclosures and a ban on noisy operations during night times.

This study also analysed the efficiency of the flaring burner enclosure and proved that it was successful in reducing the sound levels of flaring operations from 50.9 dB_A to 46.9 dB_A. This reduction of 4 dB mathematically translates to roughly half the actual sound to human ears. Each rig type generates different sound levels; based on the enclosures, equipment, motor and movement of mechanisms. It was found that rig type 1 generated the highest sound level (52.3 dB_A), followed by rigless activities (51.1 dB_A) and finally rig type 2 with the lowest sound level (47.5 dB_A). Rig type 2 was a more modern rig with added efficient equipment, hence generating lower mean sound levels. A multi factor analysis showed that all variables presented were able to explain 34.9% of changes in sound levels. Some variables caused higher sound levels such as weather (relative humidity and global radiation), well activities such as drilling the 8.5" and 12.25" section, completions activity and number of persons on board the rig. On the other hand, variables that reduced overall mean sound levels included installing the flare burner enclosure, using rig type 2 and having higher wind direction degree (270° to 360° facing West to North). Based on the degree of impact findings, a bigger reduction of sound levels from future drilling activities could be achieved by using rig types 2 and installing flare burner enclosures during testing activities.

CHAPTER 5: CONCLUSION

The assessment of noise pollution imposed on the local community from drilling and well testing activity during the 7-month operation campaign was conducted by first cleaning up the data prior to conducting statistical analysis. Rain (precipitation) and wind speed above 5 m/s did significantly increase the sound level from 50.0 to 50.6 dB_A, thus samples with rain and/ or wind speed more than 5 m/s was isolated from the data set. After conducting statistical analysis using IBM SPSS© software (version 23), the results showed that both locations produced higher sound levels (dB_A) during day time compared to night time. Location 1 was found to have significantly higher sound levels (52.2 dB_A) compared to Location 2 (47.5 dB_A), regardless of day/night mode due to stricter regulations for the night time. Table 5.1 shows the overall summary of sound levels obtained at Location 1 and 2 during the day and night times during this study, similarly presented by Chauhan et al. (2010).

Table 5.1: Summary of overall sound levels (dB_A).

Location	Day		Night	
	Mean noise (dB_A)	**Range (dB_A)**	**Mean noise (dB_A)**	**Range (dB_A)**
1	53.0	45.0 - 83.1	50.6	44.2 - 66.2
2	49.1	31.3 - 82.4	44.4	34.2 - 59.5

Next, the levels of noise pollution generated by drilling and well testing activities were analysed against the limits set by the local authority by measuring levels of exceedance on both sample locations (Location 1 and 2). At the day time, Location 2 showed significantly higher percentage of sound exceeding the absolute limit of 60 dB_A (10.2%) as compared to Location 1 (2.6%). At night, Location 1 was found to have the highest absolute sound limit exceedance percentage (53.8%) when compared against the set noise limit of 50 dB_A compared to Location 2 with only 13.1% in exceedance of the night limit.

A strength of factors analysis method was utilized to evaluate the noise measurements day mode, high level rig activity, weather, enclosure and impact from selected key variables (efficiency of flare burner enclosure installation, rig type, number of persons on board and weather). The relationship between type of day mode and location showed that while both locations experienced sound level reductions at night, sound levels in Location 1 decreased to a lesser extent when it was night time compared to Location 2. At Location 1, wells 2, 3, 7 and 7 ST were the significant contributors to the high sound level at the site while wells 9, 11, 12 and 13 were the significant contributors to the high sound levels at Location 2. Referring to main activities on site, results revealed that the top 3 significant contributors to high sound levels during the day time in Location 1 were Drilling - 12.25", Completions, and Drilling - 8.5", whereas the top 3 contributors to high sound levels in Location 2 during day time were Drilling - 8.5", Drilling - 23" and Plug and abandonment activities. At night, Drilling - 23", Completions, and Drilling - 12.25" were the top 3 contributors at Location 1 of highest sound levels, while Drilling - 23", Drilling - 16", and Drilling - 8.5" were the top 3 contributors of sound levels at Location 2.

The potential of the flaring burner enclosure was examined and showed that its installation reduced the overall sound level from 50.9 dB_A to 46.9 dB_A. The study also found that the type of rig produced significantly different sound levels in which rig Type 1 produced the highest sound level (52.3 dB_A), followed by rigless activities (51.1 dB_A) and lastly the rig Type 2 (47.5 dB_A). This shows that even without a rig (rigless), noise contributions can be substantial.

The multiple linear regression analysis of the relationship shows that noise in this drilling environment in the metropolitan Italian city is greatly influenced by different variables (rig type, wells, high level, barriers and weather). The results showed that rig Type 2, Flaring Burner Enclosure installation and Wind direction (°) had negative impacts (reduces sound levels) on sound measured, while Relative Humidity (%), Global Radiation (W/m^2), Drilling - 8.5", Completions, Rig POB (# of people) and Drilling - 12.25"-hole section had positive impacts on the sound level (increases sound levels).

In conclusion, the results of this study aids in understanding the sound levels generated during drilling and testing activities and the sound level exposure inflicted on the nearby population/workers of Lodi county in Northern Italy. Future works should address the limitations of this study by targeting additional drilling and testing activity locations, measure sound levels by varying distances and rig equipment components, investigate the impact of noise towards populations via detailed survey or individual noise exposure monitoring and perform noise modelling for the different environments to predict and prevent excessive noise. By understanding the breadth of the noise pollution resulting from this anthropological activity, further steps can be taken to reduce its impact towards other exposed communities. This would help provide governments and corporations create a safer living and working environment for populations to co-exist with urbanization and industrialization activities such as the energy sector.

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APPENDICES

Appendix A: Land Well Construction Activities

In drilling nomenclature, the surface ground level has a depth reference of 0 m. All depths drilled below the surface are noted in positive numbering, referring to the distance away from the surface. Depths can change depending on the lithological column of the area.

A – 30¨ conductor pipe is driven to refusal point. This is usually done prior to the start of the drilling campaign (by a driving unit, without the necessity of having a rig on site), hence no noise measurements were taken during this activity (driven to approximately 56m or refusal point)

B - 23¨ hole is drilled with a drill bit and drilling fluid, 18-5/8¨ surface casing pipe that is run down hole and cemented in place. This is to protect fresh water acquirer, which could be the water source for the community (set at approximately 299m)

C - 16¨ hole drilled with a drill bit and drilling fluid, a 13-3/8¨ intermediate casing is run and cemented to isolate the well prior to reaching the reservoir section (set at approximately 867m)

D – 12.25¨ hole drilled with a drill bit and drilling fluid, a 9-5/8¨ production casing is run and cemented to sustain the production stress and pressure loads (set at approximately 1462m)

E – 8.5¨ hole drilled with a drill bit and drilling fluid, a 7¨ secondary production casing is run and cemented to allow production fluid to be flowed to surface (set at approximately 1800m or the final well depth)