Analysis of Construction Site Noise from the Community Perspective

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A Thesis

in the

Building Science Graduate Program

Presented in Partial Fulfilment of the Requirements for the

Degree of Master of Applied Science in Building Engineering/Building Science

at the

British Columbia Institute of Technology

Burnaby, British Columbia, Canada

November 2021

This is to certify that the thesis prepared

By: M Kibria Shah

Entitled: Analysis of Construction Site Noise from the Community Perspective.

And submitted in partial fulfillment of the requirement for the degree of:

Master of Applied Science in Building Engineering/Building Science

Complies with the regulations of the Institute and meets the accepted standards with respect to originality and quality.

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Abstract

The overall research investigated intrusive noise levels from construction sites into residential communities which may be detrimental to health. This research used the drone imagery of an actual construction project to identify noise sources from the construction site and CadnaA acoustic software to predict the noise propagation from construction sites in three modelled residential communities.

Construction noise propagation and community annoyance were modelled for single-family, multifamily, and high-rise residential neighbourhoods where noise levels exceeded the recommendations of the World Health Organization and Health Canada Guidelines. When construction works continue without any noise mitigation measures, one-fourth of resident would have been overexposed according to the City of Vancouver (CoV) guidelines. Several noise control strategies were applied and finding indicated that a combination of noise controls was more effective than a single control measure.

When noise mitigations were in place, the City of Vancouver noise by-laws were found to be attainable, and no residents would have been overexposed to construction noise. However, when applying the Health Canada guidelines, which is more stringent than municipality noise by-laws, it was predicted that more than one-third of residents would be overexposed and would experience widespread annoyance with or without mitigation strategies.

The understanding of construction noise from the community perspective in this research provides a new perspective for the study of construction noise that can help regulatory entities to reduce community exposure to construction noise and it offers solutions for

construction noise-mitigating strategies to be incorporated into urban planning and public health policy.

Acknowledgement

Firstly, I would like to express my sincere gratitude to my supervisor Dr. Maureen Connelly for the continuous support of my MASc study and related research, for her patience, motivation, and immense knowledge. Her guidance and advice carried me through all the stages of research and writing this thesis. I would not have imagined having a better advisor for my MASc study. Without your precious support, it would not be possible to conduct this thesis. Thank you for being an amazing mentor and inspiring me to be a better person.

Besides my supervisor, I would like to thank the rest of the thesis committee: Dr. Bo Li, Steve Meszaros, P.Eng., Dr. Colin Novak (external examiner), for their insightful comments and encouragement, but also for the questions which widen my research from various perspectives.

I am extremely thankful and indebted to Dr. Eric Saczuk from the BCIT RPAS Hub who gave me access to the drone images of the BCIT Health Sciences Centre (HSC) construction project. Nevertheless, I am also grateful to Craig Sidjak, Joe Cosh, and Christie Paxton for allowing me to use HSC construction project data, Ryan Jacobs, and Michael Both for the consultation and valuable feedback during designing the research. My sincere thank also goes to Jessica Carolina and Matthew Johnston for training me on the CadnaA software program.

I take this opportunity to express gratitude to all of the Department faculty members and librarians for their help and support. I thank my fellow classmates and lab mates for the discussion, for the support, and for the fun we have had in the last two years. I am grateful to Omid Tamanna who was always there to assist me with the research facilities in BCIT Centre for Architectural Ecology.

Finally, I must express my very profound gratitude to my parents, my big families in Bangladesh and Singapore, and to my spouse for providing me with unfailing support and continuous encouragement throughout my years of study. This accomplishment would not have been possible without them. Thank you.

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1. Introduction

1.1 Research Background

This research aims to investigate construction noise from the community perspective. The objectives of this research project are firstly to model and predict construction noise in urban environments; secondly to investigate various noise control mitigation strategies outlined in the noise policy, land use policy, and other best practices in the construction sector. And thirdly to assess community annoyance (% Highly Annoyed) in measuring community response to the construction noise.

The United Nations (2018) report projected the rate of urbanization is increasing. Two out of every three people are likely to be living in cities or other urban centres by 2050. Although the speed of urbanization has slowed down in recent decades in Northern Africa, Western Asia, and Latin America, the world is projected to have 43 megacities, most of them in developing regions. The United Nations report also predicted nearly 90 percent of the Canadian population will live in urban areas by the year 2050 (United Nations, 2018). Metro Vancouver’s population, from a 2016 base population of 2.57 million will increase by about 1 million to 3.6 million by the year 2050 (Metro Vancouver, 2018). In order to accommodate this growth and to maintain an attractive and diverse urban environment, Metro Vancouver will need to construct more housing as well as social, transportation, and utility infrastructure. The construction will necessarily be within existing community neighbourhoods.

The construction industry affects the quality of life and influences the built environment. It helps job creation, and it accounts for 6% of global GDP. However, the construction industry is one of the largest global consumers of raw materials and it accounts for 25-40% of the worlds' total greenhouse gas emissions (World Economic Forum, 2016). Construction activities produce waste and consume a large amounts of energy (Yusof, Awang, & Iranmanesh, 2017). Construction projects can generate multiple sources of a nuisance for the neighbouring community such as noise, vibration, and light pollution (A. Gilchrist et al., 2003). Noise has a negative impact on both auditory and non-auditory health. Continuing exposure of unwanted and uncontrolled noise can lead to noise-induced hearing loss (NIHL), sleep disturbance, impaired cognition, and cardiovascular conditions (Basner, et al., 2014). The Environment Protection Act in Canada defines vibration and noise as a contaminant that can cause adverse health effects (Government of Ontario, 2020). In addition, excessive noise exposure affects students' educational outcomes and teachers who work in a noisy classroom can suffer from vocal fatigue (National Research Council, 2007). Michaud et al. (2005) estimate 2.1 million Canadians 15 years of age and over are annoyed by the environmental noise.

Although noise control and mitigation are a major concern within the industrial engineering, manufacturing, and transportation industry, there has been little interest in the construction-related noise in its surrounding. This is largely due to the impermanent nature of construction projects (A. Gilchrist et al., 2003). One aspect of construction noise is regarded as 'occupational noise', generally defined by a relationship between total noise exposure and perception, by which construction workers exposed to a high level of construction noise can cause noise induced hearing loss (NIHL). In British Columbia, the background noise level in the construction project is usually above 80 dBA and construction workers often get exposed to more than 85 dBA which exceeds the noise limit set out by provincial regulations (Stuart, 2000). WorkSafe BC creates policies, guidelines, and standards relating to noise control and mitigation for construction workers. WorkSafeBC regulators do not address there is relationship between construction activities and noise annoyance and a recent study in Vancouver suggests the construction noise has far-reaching consequences for the general public that go beyond those faced by industrial workers (Hong et al., 2019). Vancouver, one of the fastest-growing cities in Canada, issues an average of 5731 new construction permits per year, among them 20 to 30 percent of permits issued to large construction projects valued at >$20 million. Given the sheer scale of the construction sector, even a marginal increase will bring major benefits to the community and the country as a whole. The importance of construction noise control and its impact on the community has become more evident as increased construction, demolition, and reconstruction projects are carried out in urban areas. Therefore, this research will investigate construction site noise and its impact on the affected community.

Environmental noise is regarded as any unwanted sound generated by human activity (Murphy et al., 2009). A common source of environmental noise, also called non-occupational noise, includes noise from roads, rail and air, music systems (amplified sound), neighbours, small machinery, air conditioners, and as well as construction noise.

Unlike road traffic noise or aircraft noise, construction noise affects people working inside construction sites and also who lives or works adjacent to a construction site (Liu et al., 2017). Noise generated from a construction site can significantly impact people’s lives in the neighbouring communities when the construction sites are in proximity with the communities. This research will focus on the construction noise that impacts the community.

1.2 Construction project and Community

The construction industry is diverse and complex in nature. A construction project can affect all people, organizations, and institutions within a community. The Major classification of construction includes housing, non-residential building, heavy civil, utility, and industrial. Vancouver City defines construction that includes "the erection, alteration, repair, relocation, dismantling, demolition and removal of a building, structural maintenance, painting, land clearing, earthmoving, grading, excavating, the laying of pipe and conduit (whether above or below ground level), street building, concreting and the installation, alteration or removal of construction equipment, components and materials in any form or for any purpose, and includes any work being done in connection therewith" (City of Vancouver, 2020).

A construction project is complex and requires significant resources and masterful execution by a variety of skilled professionals and craftsmen workers under Project Manager leadership (Sears et al., 2015). The purpose of construction project management is to implement a project so that deliverables can meet scope requirements on budget and schedule and at acceptable risk, quality, safety, and security levels (Federal Transit Administration, 2012).

The life cycle of a construction project starts with the inception and through the design, construction to completion, and project delivery. Figure 1 indicates the main elements of a construction project life cycle. Various aspects of a life cycle are frequently handled by various individuals and not all organisations are involved in the project all the way from the beginning to the end of a building project (Fewings, 2005).

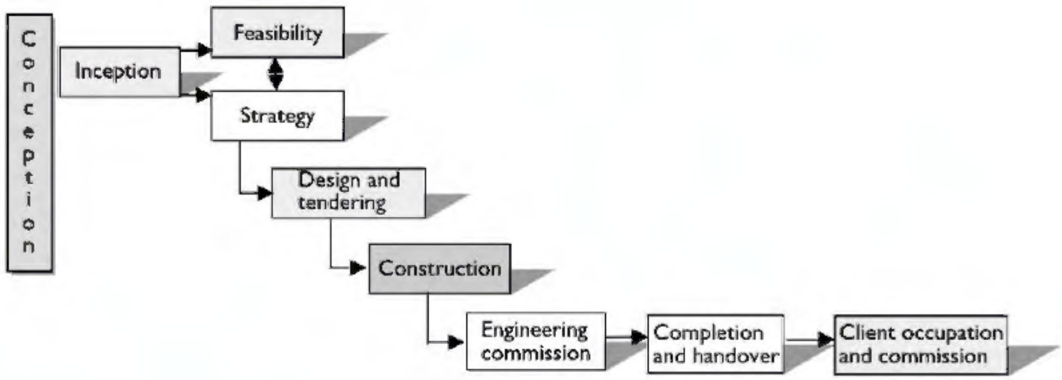


Figure 1 Life cycle of construction projects.

The structure of a particular construction project is based on one of many project delivery methods that best meet the unique needs of each owner and their project. When selecting the project delivery method, it is important for the owner to consider all three of these areas and the options within each shown in Table 1 (Design-Build Institute of America, 2015).

Table 1 An example of project delivery method selection

Project Delivery Systems	Procurement Methods	Contract Formats
Construction Management at Risk **(CMR)** also known as CM/GC	Best Value **(BVS)**	Cost Plus Fee
Design-Bid-Build **(DBB)**	Low Bid	Guaranteed Maximum Price **(GMP)**
Design-Build **(DB)**	Negotiated	Lump Sum (or Fixed Price)
Multi-Prime **(MP)**	Qualifications-Based **(QBS)**	Target Price
	Sole Source (or Direct Select)	Unit Price

Items listed in alphabetical order.

A study by Hale et al. (2009) makes a comparison between two project delivery methods - design/bid/build and design/build method - for two identical buildings constructed for US Navy Bachelor Enlisted Quarters. Project duration, project duration per bed, time growth, cost growth, and cost per bed were statistically compared. The result showed the design/build project delivery method performs better than the design/bid/build project in almost every measure. From Table 2, it is evident that a project constructed with the design/build method requires less time than constructed with a design/bid/build method which ultimately indicates that the surrounding community had to suffer from less exposure to the project construction activities and noise.

Table 2 Empirical Comparison of Design/Build and Design/Bid/Build Project Delivery Methods

Statistics	**Design/Build**	**Design/Bid/Build**
Project Duration -Total Project Duration -Fiscal Year Duration -Project/Construction Start Duration	 667 days* 864 days* 667 days*	 1398 days 1026 days 771 days
Project Duration per Bed -Total Project Duration -Fiscal Year Duration -Project/Construction Start Duration	 2.64 days/bed* 3.55 days/bed* 2.64 days/bed*	 7.00 days/bed 5.08 days/bed 3.70 days/bed
Time Growth	76.39 days*	193.85 days
Cost per Bed with Other Costs	$60,909	$69,760
Cost per Bed	$57,776	$67,152
Cost Growth	2.00%*	4.02%

* Statistically significant at $p < 0.05$

Construction noise exposure is also influenced by scheduling work activity. The combined noise level produced by the concurrent operation of multiple activities may not be significantly higher than the noise level produced by the individual operation. Construction noise pollution also can be minimized by optimizing site layout planning as observed by Ning et al. (2019).

The nature and management of a construction project not only impact project deliverables it also affects the neighbouring communities. A common definition of a community is proposed by MacQueen et al. (2001) as "a group of people with diverse characteristics who are linked by social ties, share common perspectives, and engage in joint action in geographical locations or settings". McMillan & Chavis (1986) proposed the sense of community "is a feeling that members have of belongings, a feeling that members matters to one another and to the group, and a shared faith that members needs will be met through their commitment to be together". Joseph R. Gusfield (1978) identified that the term community has two major uses such as "territorial and geographical" and "relational". The first is concerned with neighbourhood, town, city, and the latter is relating to "quality of character of human relationship, with reference to location". However, the term community presented in this research will apply to territorial communities (neighbourhoods) only.

1.3 Construction project in site context

With the rapid phase of global urbanisation, land-use zoning has played an increasingly important role in urban planning and development (Yong et al., 2010). Regional land-use policy and zoning provide guidelines for future design and development by regulating the use and density of land, buildings, and other structures to be built.

Construction activities are carried out in both urban and non-urban settings. According to the Vancouver (2010) land use designations, urban land uses consist of three types of establishment – general urban, industrial and mixed employment area. Whereas, non-urban land uses are classified as rural, agricultural, conservation, and recreational area. A general urban area is a high-density residential neighbourhood that requires the provision of urban service infrastructures such as transit and sewer.

Construction projects such as residential, commercial, industrial, highways, utility construction take place everywhere in urban and non-urban. Construction noise impacts the respective soundscape of noise-sensitive areas in a community such as residential buildings, institutions, children and senior care facilities, medical facilities, and spiritual areas.

The Centre for Disease Control (CDC) introduced a 'place-based' organizing framework for social determinants of health and identified the neighbourhood and the built environment are key determinants of health outcomes (Healthy People, 2020). Marmot et al. (1995) identified community context as a major determinant of the health outcomes. MacQueen et al. (2001) argued that public health policies, guidelines, and initiatives generally are defined at the regional and national levels. However, the intervention and prevention are taking place at the community level. Recognition of these facts has led to growing demands for community engagement as an effective tool for understanding public health issues like environmental noises.

This research will investigate and analyse construction noise from the community perspective. The literature review in the following section examines the impact of urban development and the potential health impact and reduction in the wellbeing of residents living near the construction projects. There are limited studies related to construction noise, especially in terms of community response. However, the literature review provides a platform to address the specific research themes of construction noise propagation in residential neighbourhoods, construction noise mitigation, and the adoption of recommended noise criteria defined by the City of Vancouver and Health Canada.

2. Literature review

2.1 Noise and vibration in construction

2.1.1 Sources of construction noise

Construction processes are often associated with excessive noise generated by construction activities and processes. Construction activities that generate noise include demolition work, site preparation work, building maintenance repair work, and operation of construction vehicles. Other sources of construction noise include the operation of different tools and machines such as pile driver, concrete pouring, earth moving machines, concrete breaker, machines for demolition work, compressor, dust collector, waste collector, earth moving machines, pneumatically-driven tools, and machines, and engines (Kantová, 2017). Table 3 provides a list of the construction equipment and their associated noise levels.

Table 3 Noise levels generated by selected construction equipment (noise level measured at 15 m; used equipment >5 years old). (A. Gilchrist et al., 2003)

[illegible]

With regards to the operation mode and noise source, construction machinery and equipment can be classified into two categories such as stationary and mobile. In a construction site, more than one type and the number of equipment are operating simultaneously. For example, when two excavators each emit 83 dBA, the total combined noise level at the site would be 86 dBA. If there is any dump truck (84 dBA) moving around two excavators, then the total noise level will increase to 88 dBA. Lee et al. (2015) studied the influence of multiple noise sources in a construction site. This study shows the influence of combined noise on annoyance is significantly higher than the annoyance caused by individual noise.

2.1.2 Acoustic characteristics of construction noise

Construction processes and activities exhibit many different types of noise such as background noise, idling noise, blast noise, impact noise, rotating noise, intermittent noise, howling, screeches, and squeals etcetera. Different forms of construction noise generated in different stages of construction have acoustic characteristics in terms of power, spectral and temporal aspects. A noise emission evolution study by Ballesteros et al. (2010) was conducted during the construction of a housing block of 26 flats in Spain. The sound emission data, measured 1.5m away from the perimeter of the site, for each stage of the construction process were collected over a 13 months period. A spectral analysis, shown in Figure 2, was carried out to characterise the noise emitted in the construction process in different stages and comparison made between stages of the construction. Due to the heavy machinery that emits constantly high noise, the excavation stage has a different spectrum than others. However, other stages of the construction process show similar spectral trends other than the variability of the peak at low frequency. Within the excavation stage, low-frequency sound exceeds 75 dB, over 15 dB above the remaining construction stages.

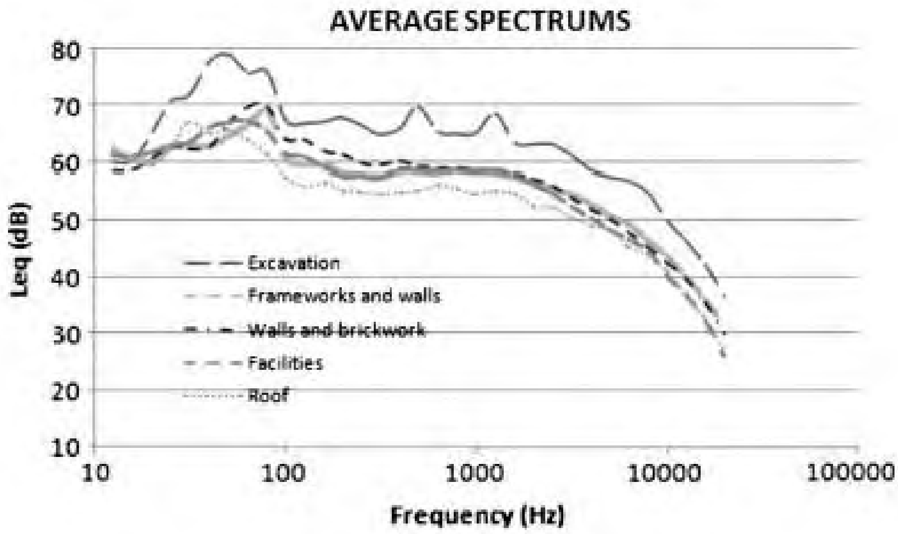
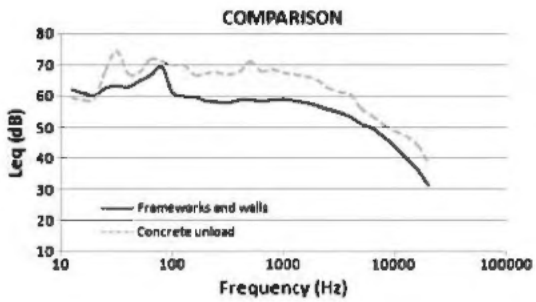
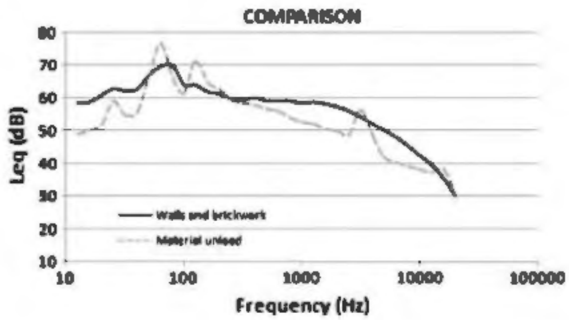


Figure 2 Average spectrums of the analysed stages

This study also shows, as illustrated in Figure 3, a specific task within a construction stage has a noise spectrum that is different from that of the other task. Concrete unloading during the frameworks and walls erection stage is characterised by a higher noise levels and a flatter spectrum due to the nature of noise emitted by the extraction pump used in the cement mixer. Another specific task is material unloads during the walls and brickwork stage also characterised by fast decreasing of medium and high frequencies but with four notable peaks. This study also noted that the noise emitted in this construction site was within the legal limits for the occupational noise exposure of workers, but annoyance caused to the workers was high due to the presence of low-frequency components and the variability of levels.



(a)



(b)

Figure 3 (a) Comparison with concreate unload, and (b) comparison with material unload

Another study by Lee et al. (2015) also supports this finding where foundation-stage construction machines have relatively higher sound pressure levels (SPL) below 800 Hz than at high frequency. Researchers observed the relationships between noise annoyance and the calculated psychoacoustics metrics such as loudness, sharpness, roughness, and fluctuation strength of the construction noise. They found loudness was the dominant factor and roughness was the second greatest contributing factor to the perception of annoyance. Their study also shows that pile driver and breaker noise were found to have much larger temporal variance which contributes to subjective impressions of annoyance for combined construction noise.

2.2 Impact of construction noise

2.2.1 Effect on human health

Based on frequency, amplitude, and exposure duration, noise can harm human health in both auditory and non-auditory ways. In an occupational setting, noise is generated during the process of work activities and operations. Prolonged exposure to excessive noise can result in noise-induced hearing loss (NIHL) which is permanent and irreversible. An industrial worker can develop permanent hearing impairment if the noise exposure level is beyond 80 dB during 40 years of working a 40-hour workweek (World Health Organization, 2018). Occupational noise is one of the most common occupational health problems around the globe. Each year about 22 million US workers are exposed to hazardous workplace noise (CDC, 2020). WorkSafeBC (2017) statistics indicate there were 37,000 accepted cases reported related to NIHL in BC for the period between 2006 to 2016.

Environmental noise is no longer considered only as a cause of nuisance but also a concern for public health and environmental health. Noise affects a large number of people, particularly in urban areas. In European Union, more than one million healthy life years also known as disability adjusted life years (DALY) are lost annually due to community noise exposure World Health Organization (2011). DALY is a common unit used to measure the burden of disability associated with a disease or disorder. DALY is calculated by summing the number of years of life lost (YLL) and the number of years lived with disability (YLD).

$$DALY = YLL + YLD \quad (1)$$

$$YLL = N \times L \quad (2)$$

Where, N is the number of death and L is the standard of life expectancy the age at which death occurs.

$$YLD = I \times DW \times L \qquad (3)$$

Where, I is the number of incident cases, DW is disability weight, and L is an average duration of disability in years.

Although the DALY method provides a standardized estimate of the health risk due to the noise and it is the most common approach used in health risk assessment accepted by WHO, this method requires detailed data on noise exposure, the outcome, and exposure-response relationship. Very often these data are not always available and come with significant limitations. DALY estimation can suffer from a considerable degree of uncertainty if the exposure-response data for a population base is not available. Hence, the DALY method requires subject matter experts with methodological guidance in order to make state-of-the-art review of the exposure-response relationship, health outcome data, and other uncertainty and limitations.

There is already a wide body of scientific evidence by Nugent (2010), as shown in Table 4, concerning the impact of noise on annoyance, communication, performance and behaviour, mental health, sleep, and cardiovascular functions including the relationship with hypertension and ischemic heart disease. As an example, the best acoustic indicator of the effect of learning and memory on the dimension of performance is L_{eq} with a threshold of 50. In addition to the well-known non-auditory effects of community noise, recent epidemiological studies reported noise-induced sleep disturbance caused by community noise has a relationship with breast cancer, stroke, type 2 diabetes, and obesity (Belojević & Paunović, 2016).

Table 4 Effects of noise on health and wellbeing

Effect	Dimension	Acoustic indicator *	Threshold**
Annoyance disturbance	Psychosocial, quality of life	L_{den}	42
Self-reported sleep disturbance	Quality of life, somatic health	L_{night}	42
Learning, memory	Performance	L_{eq}	50
Stress hormones	Stress Indicator	L_{max} L_{eq}	NA
Sleep (polysomnographic)	Arousal, motility, sleep quality	$L_{max,\ indoors}$	32
Reported awakening	Sleep	$SEL_{indoors}$	53
Reported health	Wellbeing clinical health	L_{den}	50
Hypertension	Physiology somatic health	L_{den}	50
Ischaemic heart diseases	Clinical health	L_{den}	60

Note: * L_{den} and L_{night} are defined as outside exposure levels. L_{max} may be either internal or external as indicated.
** Level above which effects start to occur or start to rise above background

A quasi-experimental research conducted by Ng (2000) investigates the effects on young female college resident students as a multi-purpose building was constructed beside their university student resident hall. A three-storey, 41,000 square-foot building was constructed next to the student residence. One edge of the construction site was 15 feet away from the 'Near Wing' (noisy side) of the residence hall and the sound level measured at the end of the residence hall was as high as 80 dB. Construction works include excavation, foundation, structural steelworks and continue from morning till late afternoon for a year. 94 students from different parts of the resident hall (Near Wing, Central Wing, and Far Wing) participated in completing the questionnaire, 27 agreed to keep an activity log for a week. Data collected included: sound level measurement (in the resident's room with a window open/close), questionnaires, activity logs, resident turn over records, and systematic observation of windows open or closed. Data analysis indicates the negative effect of construction noise on resident's life. Construction noise caused student residents to be distracted, have difficulty with relaxing, and be woken by the construction noise, which can affect mental health. These effects were significantly more severe for the residents closest to the construction site than those further away.

Figure 4 the pyramid of effects illustrates and represents how exposure to noise affects the health and wellbeing of a population. When a certain population group is subjected to excessive noise, a number of people will develop negative feelings. Stress reactions, changes in the sleep-stage, and other biological and biophysical effects will occur within a part of this exposed population. In turn, these may increase the risk factors, such as blood pressure. Such causes will also grow into clinical problems such as depression and cardiovascular disorders for a relatively small portion of the population, which can potentially further increase the death rate.

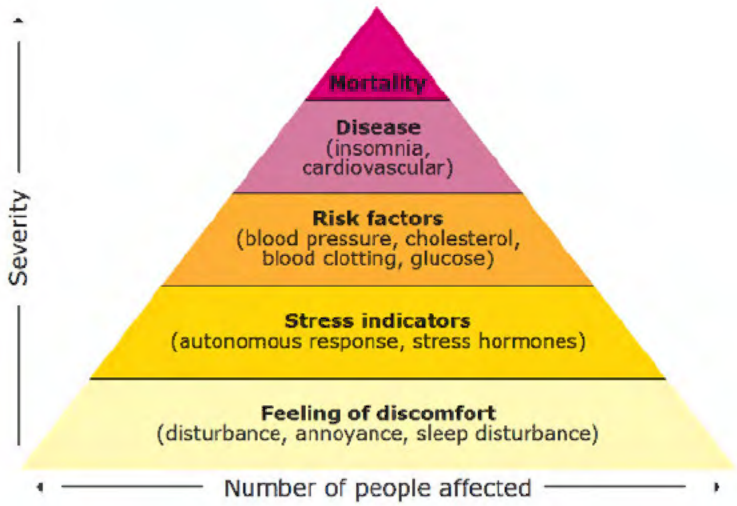


Figure 4 Severity of noise effects (Nugent, 2010)

Emerging health evidence also suggests that older adults and young children may be at greater risk within a population, due to environmental noise. In addition, studies show that lower-income communities in Toronto, who already experience poorer health, are often more likely to be exposed to noise than higher-income individuals (Toronto Public Health, 2017). Other studies in Seoul, South Korea (Park et al., 2018), California, USA (Gunier et al., 2003), Montreal, Canada (Carrier et al., 2016; Dale et al., 2015), USA (Casey et al., 2017) and European Region (Dreger et al., 2019) found that lower neighbourhood socioeconomic status (SES) and neighbourhood with a larger proportion of minority residents are negatively impacted by noise levels associated with higher community noise levels.

2.2.2 Effect on urban and surrounding ecosystems

Rapid urbanization and urban expansion modify local and regional ecosystems. Construction activities can have a significant impact on their surrounding environment. Noise emitted from a construction site can affect non-human populations and can impact the survival of ecosystems. Pearce-Higgins et al. (2012) in the UK observed how wind farm construction sites impacted bird populations. They analysed 10 bird species in 18 wind farm construction sites together with 12 reference sites and the result showed the upland bird species populations had disturbance displacement during the construction period. This research concluded with several recommendations such as installing construction barriers or screens in order to limit disturbance zone, establishing a time or place to avoid breeding times. The EUROBATS good practice guideline by Rodrigues et al. (2014) also recommends minimizing disturbance for bats during the construction phase of wind turbines and other supporting infrastructure as the noise and vibration from construction can impact their hibernation period.

Several other studies found construction noise impacts animals and wildlife at both the individual and population levels (Blickley & Patricelli, 2010). In the terrestrial environment disrupting social interaction between birds, reduces breeding success and population decline (Parris, 2015). Demolition noise was found to be associated with the individual-level behavioural and physiological changes in giant pandas in the zoo (Powell et al., 2006). Construction noise decreased reproductive efficiency in mice by decreasing live birth rates and increasing the number of stillborn pups (Rasmussen et al., 2009). Reducing noise levels below 50dB in urban gardens can attract more bird species (Patón et al., 2012).

The noise emitted during the pile-driving activities in offshore wind turbine construction can affect coastal mammals. Marine mammals use sound for communication and foraging. Madsen et al. (2006) studied the shallow-water species of marine mammals during offshore wind farm construction. They found pile-driving activities had the highest sound levels and generated intense impulse noise during construction which disrupts the behaviour of mammals at the range of several kilometres. They also highlighted that construction noise can accelerate the complete or temporary displacement of local mammals from an area. This displacement can have more impact on mammal's food source and breeding cycle, and it may become severe if large wind firm construction projects are materialized. Thompson et al. (2010) found harbour porpoises exhibit disturbance and highlighted uncertainty over cetacean distribution due to pile-driving noise during the installing of the wind turbine.

2.2.3 Economic and social cost

Besides auditory and non-auditory health effects, communities around construction sites also experience negative impacts such as economic losses. The economic losses, often called social costs, "refer to the monetary equivalent of consumed resources, loss of income and loss of enjoyment experienced by parties not engaged in the contractual agreement, solely due to a construction process" (Gilchrist & Allouche, 2005). Scholars in different fields proposed numerous definitions of social cost. Table 5 shows presents a definitions social costs proposed by different authors.

Table 5 Definitions of social cost in existing body of knowledge (Çelik et al., 2017)

Author	Year	Concise definition of the social cost	Area of research
Field	1997	Social costs are the overall impact of an economic activity on the welfare of society, social costs are the sum of private costs arising from the activity and any externalities.	Environmental economics
McKim	1997	The cost of construction to society which is not included in the construction bid.	Underground infrastructure systems
McKim and Kathula	1999	The overall impact of a construction activity on the welfare of society	Infrastructure management systems
Allouche et al.	2000	Generated costs due to execution of a construction project incurred by the parties involved in the contractual agreement	Evaluation of construction technologies
Rahman et al.	2005	The construction, maintenance, repair, rehabilitation any renewal of municipal infrastructure cause considerable disruption and inconvenience, that cannot be easily quantified, to a municipality and to the general public.	Municipal infrastructure management
Yu and Lo	2005	The construction social costs are external costs of a construction project that are undertaken by the public rather than by the project participants.	Road works
Tanwani	2012	Construction causative adverse impacts that neighbouring communities are inevitably being exposed to due to implementation of construction projects	Traditional construction methods
Apeldoorn	2013	Costs associated with the construction works that are paid for by the community at large, and not realized as a cost that is included in the tendered contract price	Water pipeline projects
Çelik	2014	Cost of alteration in the daily routine of third parties who react to alleviate the consequences of construction-borne disruptions on their common life patterns	Building construction projects

The impact of noise or even health is not explicitly identified by Çelik et al. (2017) in Table 5. However, the key notion for all the various meanings of social construction cost is that people, their economic activities, health, and social well-being are adversely affected by the construction activities that are carried out within their neighbourhoods.

Andrew Gilchrist & Allouche (2005) propose construction noise pollution as a construction social cost in urban environments. The development of their concept map (Figure 5) for social cost classification emphasized to the construction phase rather than the cost/benefit of the final product to the local economy. In Figure 5, the authors classified adverse impact social cost indicators into four main groups, namely: traffic, economic activities, pollution, and ecological/social/health systems. It is interesting to note the noise is considered as an adverse impact. However, the authors did not identify a social cost indicator.

However, the relationship among construction-related impacts, and social cost indicators, and valuation methods show construction noise can cause productivity reduction, increase property damage, and health cost (Figure 6). Noise, as an adverse impact, is identified with the social cost indicators of productivity reduction, property damage, and health cost. The valuation method identified includes human capital and contingent valuation technique. Another study by Andersson & Ögren (2007) also categorized the social costs of noise exposure into three groups, resource cost (in the form of medical and health care), opportunity cost (in the form of loss of production), and Dis-utility (in the form of other negative influences resulting from noise exposure.

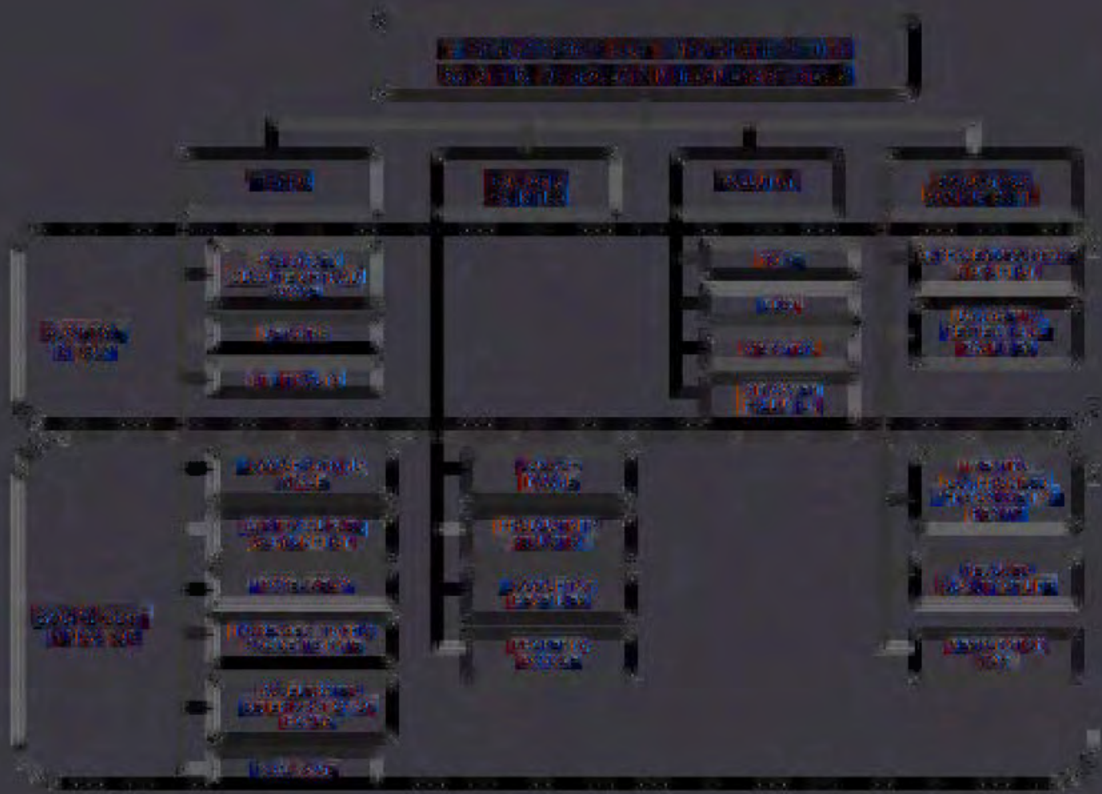


Figure 5 Concept map for social cost classification associated with construction projects.

Figure 6 Relationships among impacts, social cost indicators and valuation methods

During the design and execution of construction projects, financial interests and expectation is considered only for parties contractually involved in construction projects, and community interest is often ignored. Traditionally, the social cost was not included in the estimation and bidding stage of construction projects. However, recent research demonstrates the importance of including social costs. A time-dependent construction social costs model proposed by Yu & Lo (2005) calculated the daily social cost and found it could be more than five times higher than the construction cost of a road expansion project in Taiwan.

Recent research by Xiao et al. (2016) estimated the social cost due to the construction noise emitted from earthwork operations in Beijing, China based on loss of disability-adjusted life years (DALY). Firstly, a quantitative model based on exposure-response relationship is developed to assess the health impairments such as cardiovascular disease, cognitive impairment, sleep disturbance, and annoyance, and authors used DALY as an indicator of damage. For example, a function used for risk factor for annoyance ($R_{daytime}$) is achieved by Equation (4):

$$R_{daytime} = 9.994 \times 10^{-4} (L_{dn} - 60.3)^3 - 1.523 \times 10^{-2} (L_{dn} - 60.3)^2 + 0.538 \times (L_{dn} - 60.3) \quad (4)$$

Unlike the original DALY estimation method (Equation 1), the authors developed a modified DALY estimation model based on the methodology of the population attributable fraction (PAF), in which relative risk (RR) is a key factor. The modified DALY estimation (Equation 5) subsequently gives the equation for calculating the environmental impact of construction noise, EI_c.

$$DALYs_c = DALYs_d - DALYs_b = \Delta \left[n\ (L) \times R\ (L, c)\ \times (1 + DW \times D) \right] \quad (5)$$

Where, $DALYs_c$ = DALY caused by construction noise L_c

$DALYs_b$ = DALY caused by background noise L_b

$DALYs_d$ = DALY caused by environmental noise level L_d

From Equation (5), the environmental impact of construction noise expressed in Equation (6):

$$EI_c = \sum_L \Delta V \left[n\ (L) \times R\ (L, c)\ \times (1 + DW \times D), c \right] \quad (6)$$

Where, n(L) = density of exposed persons at different noise levels

R = risk factor

L = exposed noise level

c = personal characteristics such as age and gender

DW = disability weight

D = average duration of disability in years

Then this study calculated the economic value of the construction noise based on the DALY and value of statistical life year (VSLY)

$$EI_c = DALYs_c \times VSLY \quad (7)$$

After that, this proposed model is applied to a construction project where two excavators worked daily from 11:00 pm to 6:00 am in a construction site with a total workload of 400,000 m^3. The excavation site was surrounded by six buildings including hotels and residential buildings, within 100 m distance (Figure 7).

Figure 7 Locations of the observation points and adjacent buildings

Noise measurement data was collected at construction noise sources, at site perimeter, and the indoor noise levels in the adjacent building. The data collection method used field monitoring and acoustic simulation software to generate sound pressure levels in dB (Figure 8).

Figure 8 Sound map of the construction site and its vicinity.

Noise data, population-related data such as size, age, and gender were collected and by using Equation 4 and Equation 6, this study calculated the economic value of the construction noise based on the DALY and value of statistical life (VSL). Based on the analysis, the total health risk for the neighbouring community was 34.5 DALYs and the expected social cost estimated at almost 20.47 million yuan ($3.9 million).

This research further found that building occupants closer to the noise source and without noise barrier faced significantly more health risks than occupants of building with increased distance. People aged between 45 and 54 were found most vulnerable to construction noise with a risk of sleep disturbance. The case study concluded that the individual health effect evaluated from the construction noise was limited but the social cost of the noise was significant.

2.3 Construction site noise control

2.3.1 Policy and regulations

This section introduces regulatory components of construction noise, which influences community soundscapes, in selected countries and jurisdictions. This literature review illustrates the policy formulation approach taken within noise guidelines, demonstrating how different jurisdictions use policy tools as means of controlling the adverse impact of construction noise on the surrounding community.

According to the World Health Organization (1999) (WHO) guidelines for community noise, noise management policies were developed based on three principles such as the precautionary principle (reducing noise level at the lowest possible level in a particular situation), the polluter pays principle (noise pollution cost bears by the party responsible for the source of noise), and the prevention principle (using land-use planning to reduce noise level). The WHO guidelines (1999) present recommended community noise limit for the specific environment, in Appendix A. Each limit is based on the total environmental noise from different noise sources such as air-land traffic, industrial, construction, transportation, domestic, and noise from leisure activities. The guideline does not deal with the noise limit at the sources but rather outlines limits at the receptors in different environments. However, the latest WHO guideline (2018) advanced policy, regulation and methodology and was developed based on four guiding principles of reducing (exposure to noise), promote (intervention to reduce exposure), coordinate (approaches to control noise sources), and involve (inform and involve communities potentially affected by a change in noise exposure. The WHO guideline (2018) guideline recommends reducing noise levels produced by different sources such as road traffic noise, railway noise, aircraft noise, wind turbine noise, and leisure noise. This significantly moves the responsibility of mitigating noise pollution to the generators of the noise and away from the receptors.

Noise management guidelines or regulations are developed based on the government policy framework and for that reason, the nature and implementation of noise guidelines vary from one country to another. Although there are many noise managements legal frameworks available, Hede (1998) proposed a collaborative approach for formulating environmental noise policy in Australia (Figure 9). This model has six stages and associated with each stage there is a group of 'policy players' ideally participating in the development and implementation of community noise management policy. He also argued that the collaborative approach can be effective for the long term because the noise policy developed by this framework is based on the full range of input available from all policy players and community stakeholders. It is noted that the absence of acoustic expertise and community stakeholders during the policy adoption stage.

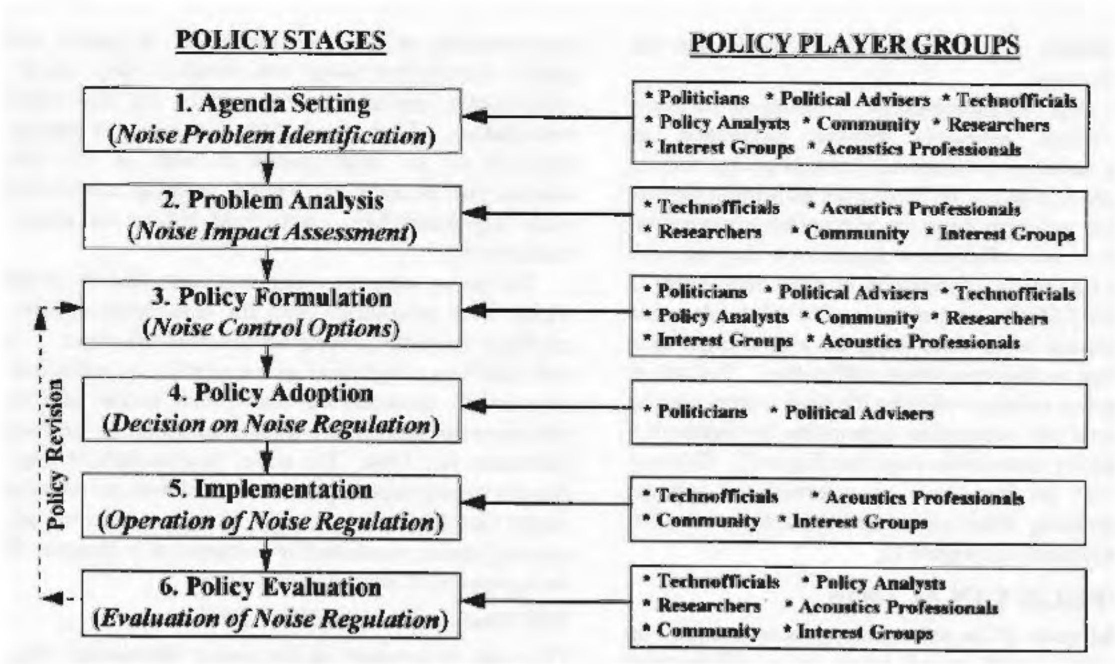


Figure 9 A model of the policy process for the community noise management

Policy, guidelines, and recommended limits relating to construction noise exposure to communities are very diverse around the globe. Construction noise control guidelines are adopted in many regions with different degrees of comprehensiveness and varying level of sophistication. A common trend observed among all reviewed guidelines appeared to be each individual jurisdiction has developed the construction noise guideline based on sensitive land uses and duration of exposure.

Granneman (2013) studied the regulations for the control of construction noise in different countries. He observed construction noise control regulations do not exist at the national level but at the local and differ between Germany and the Netherlands. As an example, in Germany, control measures are required if the construction noise exceeds 5 dBA above the noise limit shown in Table 6.

Table 6 Construction noise limits in Germany

Table 6a – Noise limits according to AVV-Baulärm

[illegible]	[illegible]	Duration	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

[illegible]

Note: Corrections to the noise limits of Table 6a should be applied according to specific resting hours shown in Table 6b.

Table 6b – Time corrections related to average duration of building activities

[illegible]		[illegible]
[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]

Granneman also looked into the construction noise limit in the Netherlands which is based on the construction phase, type of equipment/activity, and distance from the receptors. A relatively high noise limit (maximum 80 dBA) is allowed within a limited time period. Figure 10 illustrates the day value due to construction activities at a various distances, up to 60 dBA no limit in days and >80 dBA is prohibited (0 days). For example, pile driving at the distance shorter than 60m from the receptor is not possible as this exceeds the maximum

80 dBA limit. These limits cause problems in urban situations and an exemption is required without further mitigation.

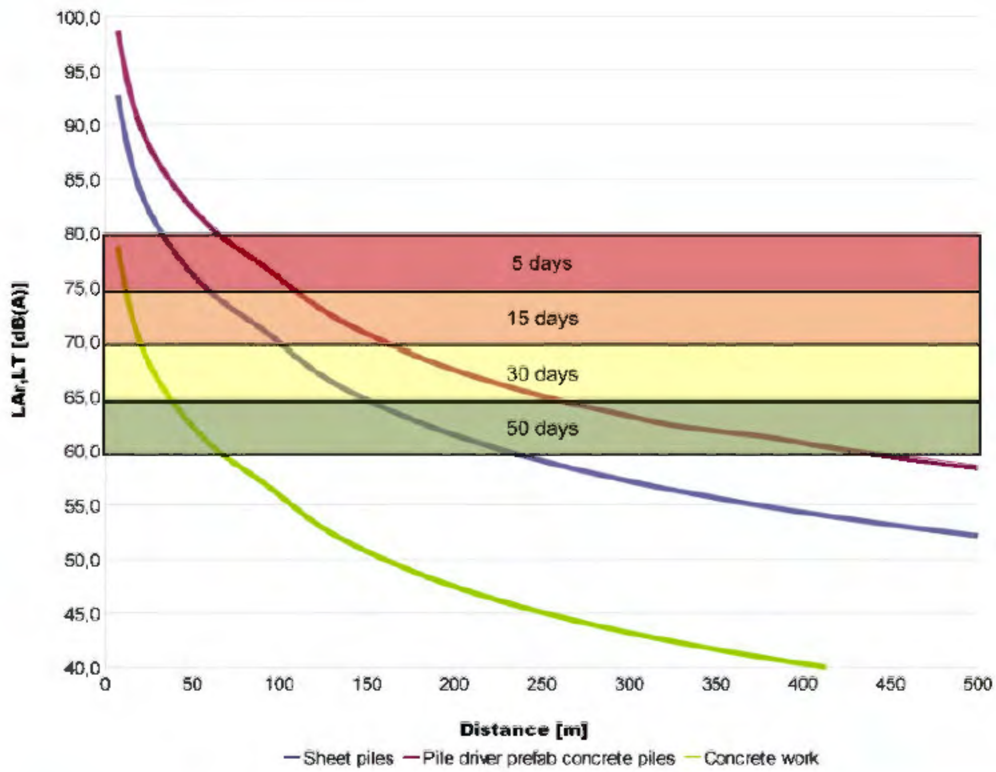


Figure 10 Occurring noise levels due to different building activities in relations to distance.

From the above discussion, it is evident that construction noise control regulations vary significantly, even between two neighbouring countries such as Germany and Netherlands. Hence, the following literature review will further explore the extent of regulations in other countries.

According to the interim construction noise guideline from New South Wales (NSW) Australia, construction works are allowed on Monday to Friday 07:00 am to 06:00 pm, on Saturday 08:00 am to 01:00 pm and no construction work on Sundays or public holidays (State of NSW, 2009). Construction works outside the recommended standards hours are also applicable if approved by the regulator. The 'Management Level, $L_{Aeq\ (15\ min)}$' of construction noise in residential communities is set at 10 dBA above the ambient noise level for recommended hours and 5 dBA above the ambient for outside the recommended standard hours. The 'Management Level, $L_{Aeq\ (15\ min)}$' of construction noise for other sensitive land use such as schools, hospitals, and active recreation areas have a different allowable limits based on the principle that the characteristic activities for each of these land uses are not disturbed (Table 7). Construction noise limits to industrial premises (75 dBA) and offices, retail outlets (70 dBA) are also set by this guideline.

Table 7 Noise at sensitive land uses (other than residence) in NSW, Australia.

Land use	Management level, $L_{Aeq\,(15\,min)}$ (applies when properties are being used)
Classrooms at schools and other educational institutions	Internal noise level 45 dB(A)
Hospital wards and operating theatres	Internal noise level 45 dB(A)
Places of worship	Internal noise level 45 dB(A)
Active recreation areas (characterised by sporting activities and activities which generate their own noise or focus for participants, making them less sensitive to external noise intrusion)	External noise level 65 dB(A)
Passive recreation areas (characterised by contemplative activities that generate little noise and where benfefits are compromised by external noise intrusion, for example, reading, meditation)	External noise level 60 dB(A)
Community centres	Depends on the intended use of the centre. Refer to the recommended 'maximum' internal levels in AS2107 for specific uses.

On the other hand, South Australia state in Australia has a different approach than the state of NSW to manage construction noise. According to the Environment Protection (Noise) Policy 2007 South Australia Part 6 Division 1, construction activities allow from 7:00 am to 7:00 pm week Monday to Saturday and no construction activity on Sundays and holidays (State of South Australia, 2008). The noise generated from construction activity is defined as 'noise with an adverse impact on amenity' if the source noise level exceeds 45 dBA (continuous) and 60 dBA (maximum) levels. Construction sites are required to implement mitigation measures beyond this level. However, if the measured ambient noise level is higher than the continuous and maximum level, the construction noise is no longer deemed as 'noise with an adverse impact on amenity'.

The National Environmental Agency (2020) prescribe a construction noise limit in Singapore. Construction work is prohibited (exception is given case-by-case basis) on Sundays and public holidays. Table 8 shows the maximum allowable noise level from a construction site. Guidelines for environmental noise control in Malaysia, Taiwan, and Hong Kong have an almost similar approach to Singapore in controlling construction noise.

Table 8 Maximum permissible noise levels for construction work in Singapore.

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	

Health Canada (2017) suggest another approach and noise limits based on the duration of the construction project. For the short-term construction project (duration <12 months), the Health Canada guideline uses the mitigation noise level indicator (MNL). The MNL is the noise level at which construction noise is to be mitigated. This is based on population density, construction duration, presence of tonal and impulse noise, and the type of community. For example, the suggested basic MNL for receptors in quiet suburban and rural areas is 47 dBA (population density: 249 person/km^2) and for the urban residential communities (2493 person/km^2) the suggested MNL is 57 dBA (Table 9). However, a correction factor for various scenarios such as project type, season, and location are applied to calculate a final MNL. An example from Table 10 is a construction project occurs during the winter in a very noisy urban (24,925 person/ km^2) community, the suggested MNL is 87 dBA, an increase by 40 dBA from the basic suggested MNL level and 20 dBA in the summer months when Canadian are outside more often or have the window of their resident open.

Table 9 Suggested construction noise MNL by Health Canada.

Suggested Basic MNL 47 dBA Ldn* *Suggested MNL for various scenarios*		
Community Description	**Applied Correction Factors**	**Suggested MNL**
Quiet suburban or rural community	+0 dBA Ldn	47 dBA Ldn
Normal suburban community	+5 dBA Ldn	52 dBA Ldn
Urban residential community	+10 dBA Ldn	57 dBA Ldn
Noisy urban community	+15 dBA Ldn	62 dBA Ldn
Very noisy urban community	+20 dBA Ldn	67 dBA Ldn
Additional Corrections If applicable, add any or all of the following corrections:		
Construction duration less than two months	+10 dBA Ldn	
Winter (or windows always closed)	+5 dBA Ldn	
Negligible tonal or impulsive noise[§#]	+5 dBA Ldn	

Table 10 Suggested MNL for a project in very noisy urban community by Health Canada.

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]		[redacted]

For the long-term construction project (duration > 12 months), Health Canada uses a separate indicator, high annoyance, where a change in percent highly annoyed (% HA) is measured. Michaud et al. (2008) also found %HA provides a usable exposure-response relationship on how an average community reacts to noise levels. The %HA indicator is also aligned with the environmental assessment under the Canadian Environmental Assessment Act.

The day-night rating level L_Rdn is used to calculate %HA. L_Rdn is a 24-hour energy average rating level with a +10 dB adjustment for night-time rating level and is calculated using Equation (8):

$$L_Rdn = 10\ log_{10}\ [\left(15 \times 10^{(0.1 \times L_Rd)}\right) + \left(9 \times 10^{(0.1 \times (L_Rn+10))}\right)/24] \qquad (8)$$

Where, L_Rd is day-time rating level and L_Rn is the night-time rating level.

L_Rdn values are required for baseline and construction ≥ 1 year in order to calculate the relevant change in %HA values due to the project noise.

After that, the energy summation of baseline and construction L_Rdn values ($L_Rdn_{(baseline\ and\ construction)}$) is calculated for the construction phase using the Equation (9):

$$L_R dn_{(baseline\ and\ construction)} = 10\ log_{10}(10^{(.01\times construction\ L_R dn)} + 10^{(.01\times baseline\ L_R dn)}) \qquad (9)$$

Then, the %HA is calculated using the Equation (10):

$$\%HA = 100\ /\ [1 + e^{(10.4-0.132*L_R dn)}] \qquad (10)$$

The %HA (baseline), %HA (construction), and %HA (baseline and construction) is calculated by substituting appropriate L_Rdn into Equation (10).

Finally, the change in %HA for project construction is calculated by subtracting %HA (baseline) from %HA (baseline and construction).

Noise mitigation measures are advised (a) when a change in the calculated % HA at any given receptor exceeds 6.5% and (b) when the baseline noise level exceeds an Ldn of 75 dBA, even if the change in %HA does not exceed 6.5%.

BC Oil & Gas Commission adopt separate good practice guidelines for environmental noise criteria for wells, facilities, and liquefied natural gas facilities. According to the guideline, a well and facility operation should meet a permissible sound level (PSL) 40 dBA Leq (night-time) at the nearest or most impacted or at 1.5 km from the well or facility fence line (BC Oil & Gas Commission, 2018). There is no specific noise limit for construction activities in the oil and gas facilities. However, the best practice guideline allows construction activities to happen between the hours of 07:00 and 22:00 hrs.

Noise control by-law by the Vancouver City limits the construction noise at 85 dBA, measured at the property line of the construction site which is nearest from the receptor (City of Vancouver, 2020). The noise by-law also allows construction activities between 7:30 am and 8:00 pm on any weekday, and between 10:00 am to 8:00 pm on any Saturday for private property construction. No construction activity is allowed on Sundays and statutory holidays. For street construction, construction activities allow between 7am and 8pm on any weekday or Saturday, and between 10:00 am and 8:00 pm on any Sunday or holiday. When the nature of the construction activities requires to work beyond the allowable hours, an exception permit up to 180 days is granted.

Besides regulatory requirements, national and international voluntary standards for building rating systems adopted noise criteria to reduce the impact of environmental noise from building and/or sites on community noise. LEED (Leadership in Energy and Environment Design), BREEAM (Building Research Establishment Environment Assessment Method), WELL (WELL Building Standard), and Passive House Canada have prescribed noise levels at the building exterior, inside the building, acoustic rating for building components that should meet the acoustical requirement of respective building rating systems. However, the exterior noise source is considered to be road and railway noise and not specific to construction noise.

Gilchrist et al. (2003) summarized the maximum noise level permitted in selected municipalities in North America (Table 11). It shows restricted hours for construction activities vary between large and small cities. Canadian municipalities adopted a single number values for maximum allowable noise levels, whereas USA municipalities have different numbers based on residential, industrial, and commercial zones.

Table 11 Maximum allowable noise levels in selected North American municipalities. (A. Gilchrist et al., 2003)

City	Zone[a]	Max. noise level (dBA)		Restriction time[c]
		Daytime	Nighttime[b]	
Large cities (population > 500 000)				
Seattle, Wash.	Res.	55	45	2200–0700
	Com.	60	60	
	Ind.	70	70	
Baltimore, Md.	Res.	90	55	
	Com.	90	62	
	Ind.	90	75	
Houston, Tex.	Res.–Com.–Ind.	65	58	2200–0700
New York, N.Y.	Res.–Com.–Ind.	64–74		1800–0700
Los Angeles, Calif.	Res.–Com.–Ind.	75		2100–0700
Calgary, Alta.	Res.–Com.–Ind.	85	85	2200–0700
Toronto, Ont.	Res.–Com.–Ind.	85		1800–0700
Vancouver, B.C.	Res.–Com.–Ind.	85		2000–0700
Edmonton, Alta.	Res.–Com.–Ind.	85	60	
Québec City, Que.	Res.–Com.–Ind.	55	50	2300–0700
Medium cities (population 100 000 – 500 000)				
New Orleans, La.	Res.	70	60	2200–0700
	Com.	75	65	
	Ind.	85	85	
Salt Lake City, Utah	Res.	55	50	2100–0700
	Com.	60	55	
	Ind.	80	75	
Miami City, Fla.	Res.	65		1800–0800
	Com.	66		
	Ind.	75		
Hamilton, Ont.	Res.–Com.–Ind.	85		2300–0700
Winnipeg, Man.	Res.–Com.–Ind.	na		2200–0700
Halifax, N.S.	Res.–Com.–Ind.	na		2130–0700

Note: na, no noise limit is specified.
[a]Com., commercial; Ind., industrial; Res., residential.
[b]If values are listed for nighttime construction, the nighttime is defined by the restricted time.
[c]Time restrictions listed are for weekdays and nonstatutory holidays.

The policy discussion showed that construction noise emission control regulations largely depend on how local authority formulate the policies and guidelines. It is also observed that in most cases higher construction noise levels are accepted with means of restriction in places such as exposure duration, period of construction, and noise control mitigation plan.

2.3.2 Engineering and management strategies

There are several engineering and management strategies available to mitigate excessive construction noise. This includes controlling to reduce the noise level at the design phase, control adaption through construction contract, controlling at the noise source, along the transmission path, and mitigation at the receiver. There is a considerable amount of information available to control construction noise through engineering and management means. Instead of a detailed discussion of this topic, a brief overview is presented.

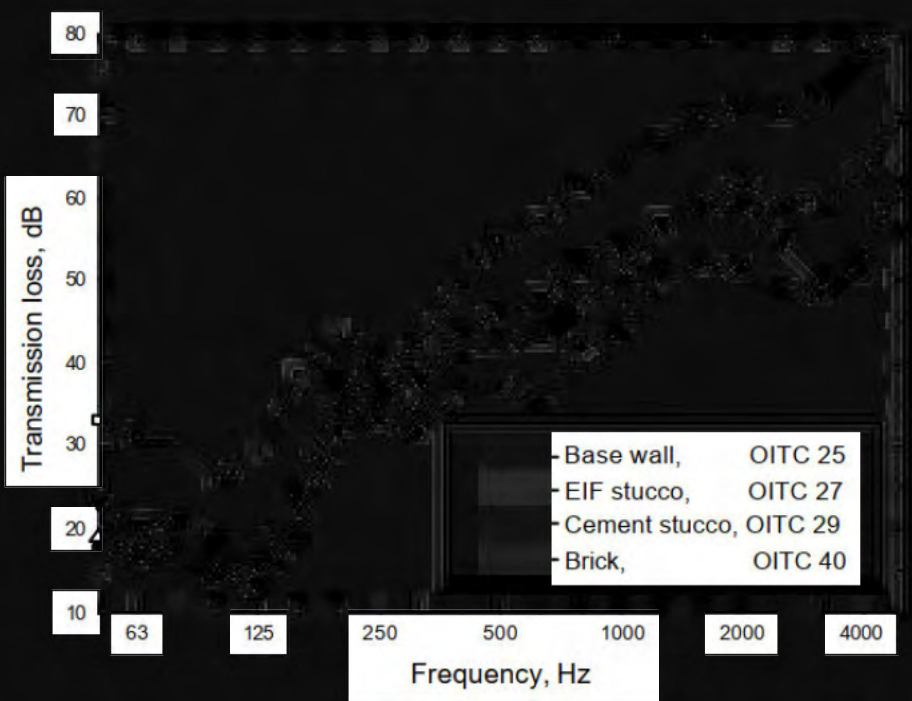
The construction noise handbook by the Federal Highway Administration (2011) presents a number of noise mitigation techniques and options that can be applied in construction sites (Table 12). Previous scholars applied and tested a number of mitigation techniques to control noise in a construction site. Gilchrist et al. (2003) noted new equipment (< 5 years) emits less noise than the same equipment >5 years old. Thalheimer (2000) utilized a noise barrier that provided a noise insertion level of 10 to 15 dBA. He also found acoustical window treatment at the receptor end as a cost-effective means in controlling temporary construction noise which can provide an extra 10 dBA reduction.

Table 12 Overview of mitigation options.

Design Options
Design and Project Layout
Sequence of Operations
Alternative Construction Methods
Contract Specifications/Special Provisions
Operational Constraints
Time Periods and Duration
Specified Equipment
Noise-Related Incentives/Disincentives
Training Programs for Contractor
Mitigation at the Source
Stationary Equipment
Mobile Equipment
Selection of Equipment
Inspection/Maintenance Programs
Equipment Operation Training
Mitigation Along the Path
Natural Shielding
Temporary Shielding
Permanent Shielding
Mitigation at the Receiver
Building Envelope Improvements
Masking
Relocation of Residents
Public Involvement and Project Coordination
Critical components of the overall mitigation strategy. Should be considered during all phases of a project.

Building envelope assemblies can provide sufficient noise reduction at the receiver end, inside the home. Building envelope acts as a sound barrier between environmental noise and building occupants. Together with air attenuation, ground effect, climatic impacts, and noise barriers, the building envelope is one of the key attenuation mechanisms to control outdoor noise propagation into the building. If sound design, construction, and assembly are ensured, the building envelope can control sound transmission throughout the building, maintain conditions for good speech intelligibility, and maintain sound isolation for speech privacy.

Regardless of the noise source, the building envelope keeps the outside noise out. The construction industry prefers to use single number rating for building assemblies. The single number ratings are biased by the low-frequency sound transmission performance of the assemblies. However, sound transmission is frequency-dependent, where low frequencies transmit through assemblies which otherwise reduces mid and high-frequency transmission. The Outdoor-Indoor Transmission Class (OITC) rating is a single number rating of the sound transmission loss of a constructed assembly. It is a more reliable rating than Sound Transmission Class (STC) rating for exterior noise ingress since it also accounts for the low-frequency noise commonly emitted from transportation and construction. ANSI S12.60, section 5.4 code outlines the minimum OITC ratings for walls and roofs ranging from 30 to 56 based on different outdoor noise levels. According to the International Green Construction Code (IGCC) code, when a residential building is situated in close proximity to a relatively high noise source, the OITC rating 40 or STC rating 50 is required for the building envelope, wall, and roof-ceiling assemblies of that building.


Transmission loss, dB
80
70
60
50
40
30
20
10
63
125
250
500
1000
2000
4000
Frequency, Hz
Base wall, OITC 25
EIF stucco, OITC 27
Cement stucco, OITC 29
Brick, OITC 40

OITC of the same base wall was further improved after attaching the gypsum board using resilient channel shown in Figure 12.

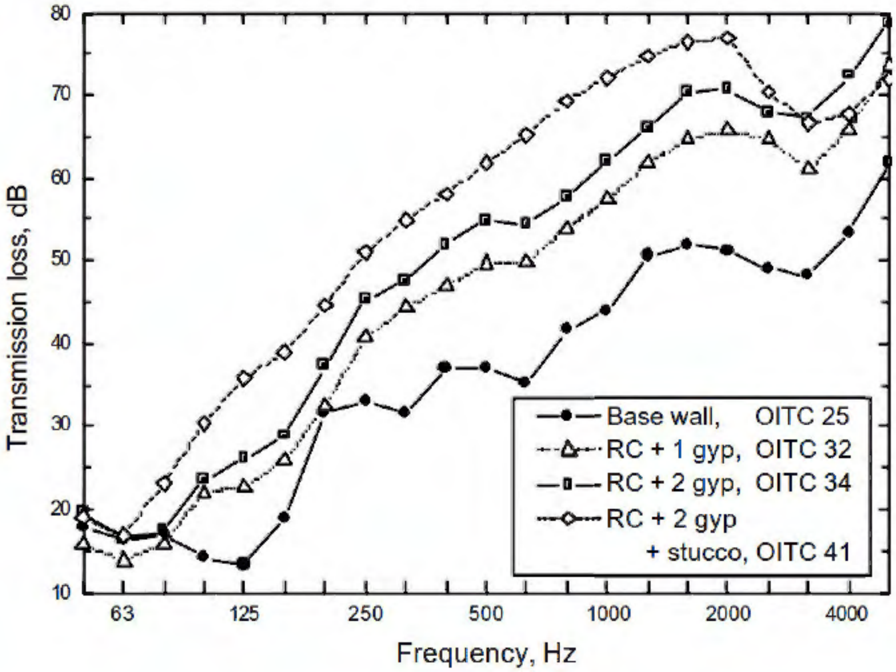


Figure 12 Effect of resilient channel on OITC rating

Further research by Bradley (2003) found a typical window with double glazing (with 13 mm air space) have an OITC rating of about 22 dB. However, when a conventional storm window is added with a 76 mm air space, the OITC rating increased up to 30 dB. A sloping roof on raised heel wood truss with asphalt shingles on the exterior, two layers of 13 mm gypsum board mounted on a resilient channel in the interior, and R40 insulation provides an OITC of 43dB.

Another research by Connelly (2017) also found the variation of wall assemblies, wall materials, envelop design effects OITC rating of rainscreen wall assemblies. Connelly conducted acoustical measurement of 54 rainscreen wall assembly with three conditions such as fully sealed exterior cladding, with a single drainage gap, and with drainage and a top ventilation gap. The overall test results showed the OITC and STC ranges of 54 tested assemblies were in the range of 26 to 30 and 37 to 47 respectively.

Other factors such as windows opening/closing, connecting assemblies, doors, pipes, vents, flanking paths, envelop design, materials can affect the envelope's overall OITC rating. Canada Mortgage and Housing Corporation (CMHC) sets interior noise levels for residential buildings. According to the CMHC, interior residential noise limits for outdoor sources (e.g., traffic noise) should not exceed the A-weighted 24-hour equivalent (Leq) sound level of 35 dBA, 40 dBA, and 45 dBA for bedrooms; living, dining rooms, and recreational rooms; and kitchen, bathrooms, and hallways respectively (Canada Mortgage and Housing Corporation, 1981).

Some of the other path control strategies have noise reduction capacities such as equipment enclosure (10 to 20 dBA), moving noisy equipment from the receptor (6 dBA reduction by doubling the distance) and active noise control strategy has the potential to be used in construction as well (A. Gilchrist et al., 2003).

Among all other noise mitigation strategies, community engagement throughout the entire project duration is found to be an essential component of the overall mitigation plan. An ongoing public involvement program can help establish trust and foster community acceptance of the construction project. Federal Highway Administration (2011) suggest relevant community stakeholders can be involved through a number of outreach techniques such as meeting, hearings, and workshops, site visits, newsletters, websites, and phone hotlines, TV, radio, public displays, surveys, and interviews. Good community relation and communication with an effective monitoring and complaint response mechanism can improve mitigating community noise complain during the construction (Towers, 2001). A community is more likely to accept noise, make an appropriate adjustment to limit noise exposure, and less likely to report fewer noise-related complain when community consultation with mitigation plans take place during the early phase of the project (Health Canada, 2011). However, this does not reduce exposure and all health impacts.

2.4 Community response to construction noise

Ng (2000) stated that one of the major noise annoyances in urban areas can arise from construction activities. Residents have apparently been annoyed because of disruption to their construction activities (Åhrlin, 1988).

A study by Hong et al. (2019) uses longitudinal administrative data of noise complaints in Vancouver to examine the spatio-temporal relationship between construction activities and noise annoyance. Citizen noise complaints data from 2011 to 2016 were analysed by a generalized mixed effect model. An analysis of spatio-temporal patterns of construction and noise complain shows both construction activities and noise complaints have been increased (Figure 13a). The noise complaints aligned with the construction activities (Figure 13b).

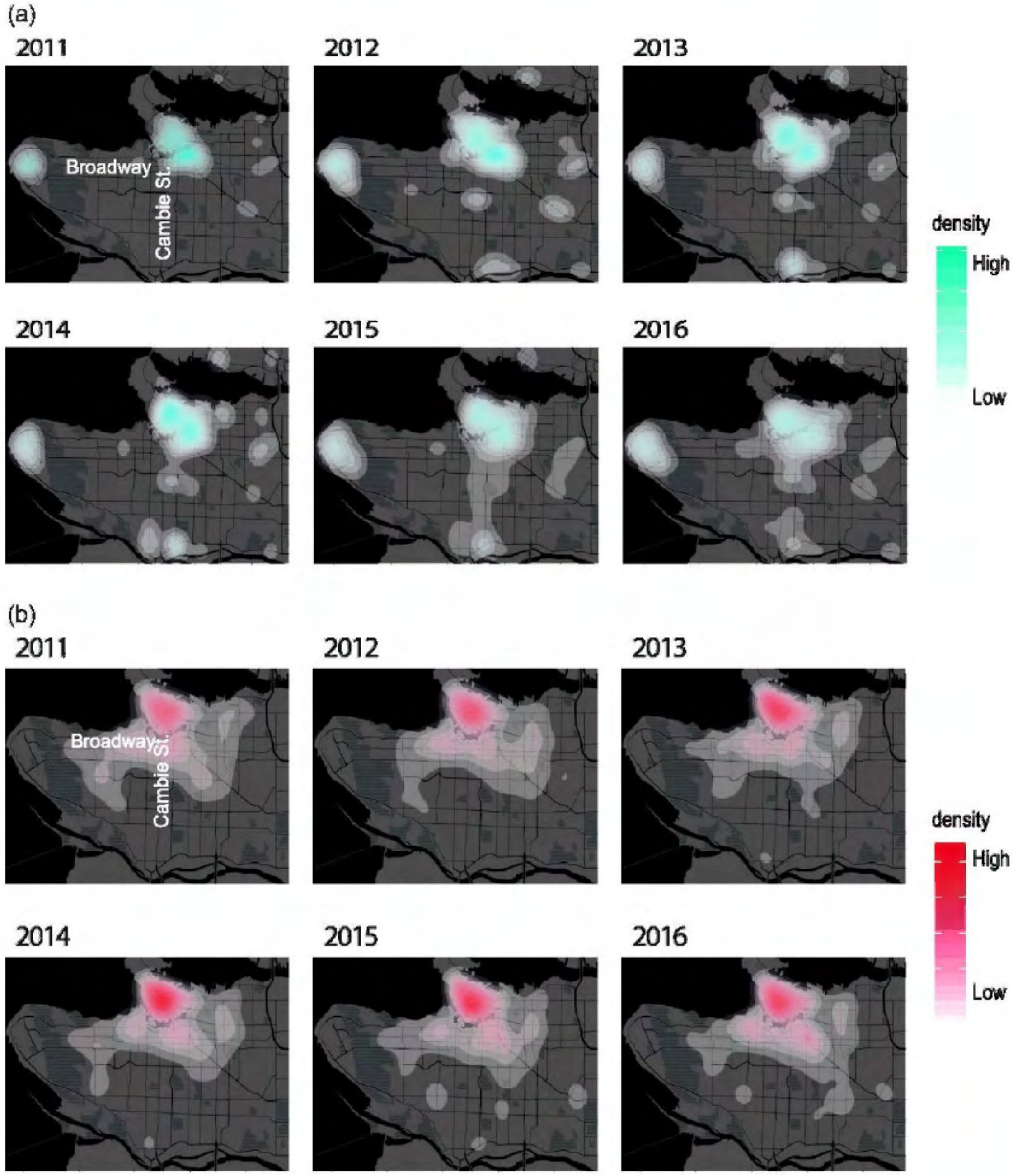


Figure 13 Spatio-temporal patterns of (a) major construction and (b) noise complain by year in Vancouver.

This mixed effect model results also confirm the similar pattern as observed in the spatio-temporal analysis. The study showed that a one-unit increase in construction activity increased around a 6% higher rate of noise complaints. Another trend also observed that residents reported more complain during the after-hour than regular hours and this is increasing exponentially (Figure 14).

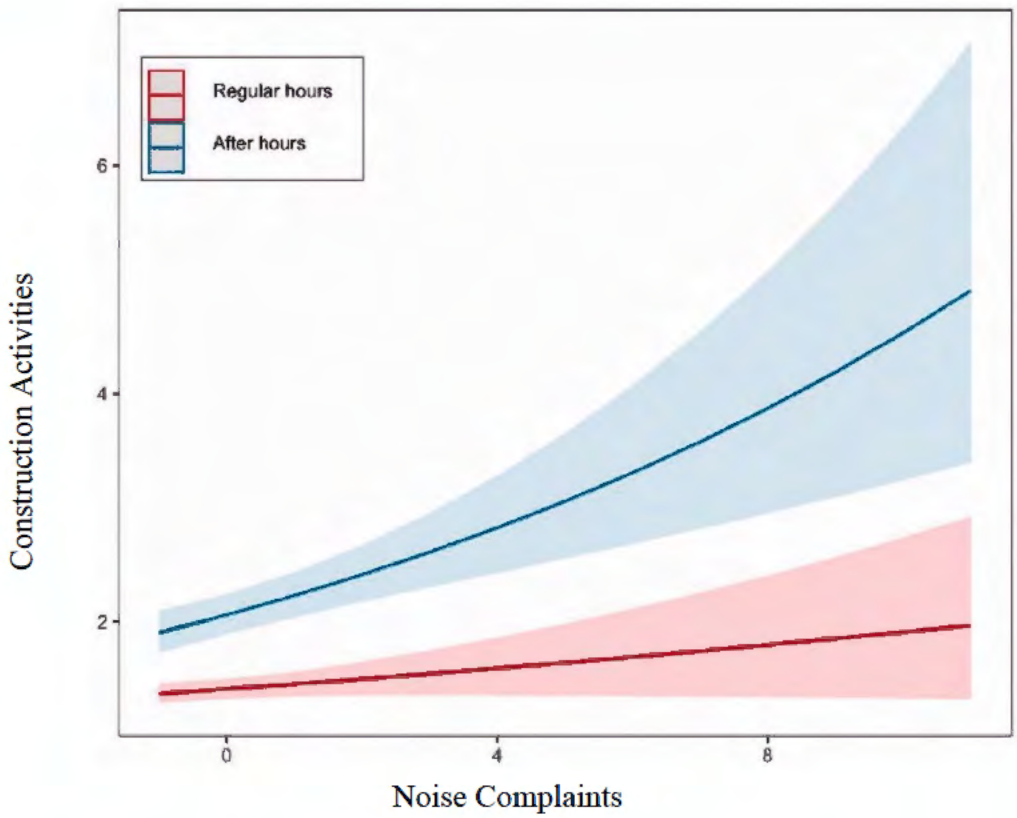


Figure 14 Effect of interaction between construction activities and after-hours reporting on noise complaints in Vancouver.

New York city received 37,806 construction noise complaints in 2015, a significant rise from 14,259 in 2010. Most of these complaints are reported during the after-hour when construction activities are approved with After Hours Variances permit (New York City Department of Buildings, 2017). In China, construction-related noise complain increased sharply, about 50.1% of noise complaints were attributed to construction noise for the period between 2013 and 2015 (Liu et al., 2017). Construction noise is the biggest source of environmental noise pollution in Korea as well. Noise complaints data in Seoul, Korea shows 76.8% of noise complain was related to noise emitted from the construction site (Seoul Metropoliton Government, 2020).

3. Problem statement

Urban development and construction activities generate jobs and contribute to the economy. However, the discussion from this literature review shows that the positive aspect of urban development comes at an expense of the health and wellbeing of residents living near the construction projects due to increase exposure to excessive noise. The health impact is even higher for vulnerable population groups and noise from a single construction site can possibly impact a large number of residents in a high-density urban community. In comparison with other environmental noise such as transportation noise, there are only a few studies related to construction noise, especially in terms of community response. This research will investigate and analyse construction noise from the community perspective. More specifically, the following research questions will be investigated:

1. How does construction noise propagate and affect ambient background in single-family residential, multifamily residential, and high-rise residential neighbourhood?
2. Can the construction noise be mitigated?
3. Is the Sound Pressure Level (SPL), as a recommended noise descriptor by the City of Vancouver sufficient and how does SPL align with Health Canada's recommended indicator of change in percent highly annoyed (% HA)?

4. Methodology

This research modelled, predicted construction noise, and estimated a community response to noise levels from a construction project in urban environments. Firstly, a noise propagation model of an actual construction site was built in CadnaA software. Sound propagation from the site was generated over the time frame of the excavation stage. Secondly, the model construction site was imported into 3 neighbourhood scenarios. Thirdly, noise mitigation strategies, with different configurations were applied to the models to better assess effectiveness. Finally, community annoyance was calculated to compare with Health Canada guidelines.

This research adopted empirical data collection and model simulation methods, both practical research tools widely used in environmental science, building science, and engineering. Empirical research has certainty which increases the internal validity; however, the empirical research method poses several limitations such as the difficulty of collecting data from multiple sources (time-consuming), different collection locations or environments (expensive), data unavailability or administrative restrictions. Model and simulation methods offers multiple advantages that suit the nature of this research. Computational modelling is a method for summarizing existing information, enabling the qualitative and quantitative comparison of competing theories, and facilitating the analysis of complex data (Atwell et al., 2016). Models can be developed on a variety of scales with different levels of details depending on available data and mathematical and computational tools. As an example, in this research with respect to the effect of noise mitigation strategies, modelling can make prediction of construction noise propagation, and facilitate estimation of community annoyance as an adverse health outcome.

In building a prediction model for this study, conditions considered were a) the model could evaluate multiple noise sources present at site, b) the model was able to predict the necessary construction noise descriptors such as Ld, Ldn, and Ln, c) the model was current and relevant with regards to the environmental noise standards and guidelines, and d) the model was suitable to predict noise in accordance with the City of Vancouver Noise Control By-law.

This research developed a noise prediction model using the Computer Aided Noise Abatement (CadnaA) computer software. CadnaA software is developed by DataKustik GmbH and the algorithms used by CadnaA are consistent with international standards such as ISO 9613-2 and the City of Vancouver directives and guidelines. CadnaA software is able to analyze noise from multiple sources and calculate the noise levels at any location using the spatially accurate project site plan. CadnaA has the capability to simulate a series of point, line, and area emission sources. In order to predict the outdoor noise propagation, CadnaA software takes into account the effect of topography, buildings and structures, ground covers, ground absorption, reflections, temperature/humidity, wind condition, barriers (either natural or man-made), and terrain. CadnaA simulation tool parameters are listed on Appendix C. In line with the ISO 9613 standard, CadnaA software takes into account the nominal mid-band frequencies between 31.5 Hz and 8,000 Hz range and does not account for the low-frequency noises. Therefore, this study investigates airborne noise from construction sites and does not address low frequency ground vibration.

The following relevant guidance documents, standards, regulations reviewed to model and estimate the appropriate construction noise and community response, include:

a) WorkSafeBC Occupational Health and Safety Regulation

b) World Health Organization noise guidelines

c) Health Canada noise guidance

d) City of Vancouver Noise Control By-law

e) ISO 1996-1:2016 Acoustics — Description, measurement and assessment of environmental noise — Part 1: Basic quantities and assessment procedures

f) ISO 1996-2:2017 Acoustics — Description, measurement and assessment of environmental noise — Part 2: Determination of sound pressure levels

g) ISO 9613-2:1996 Acoustics — Attenuation of sound during propagation outdoors — Part 2: General method of calculation

h) Federal Highway Administration (FHWA) Highway Construction Noise Handbook

4.1 Modelling of construction site noise

The goal for noise propagation modelling of an actual construction site was to simulate the noise propagation pattern of the construction site. This research used an actual construction site currently under construction at the BCIT Burnaby campus. The construction of four-storey, 9909 square-meter (106,660 square-feet) building started in October 2019 and the completion is expected by the end of 2021.

Firstly, this research collected, and analysed drone captured visual data relating to construction stages and progress from the beginning of the project till 1-storey up, i.e., the first-floor slab above grade was completed. The visual data included images of equipment and activities on-site during the site preparation, excavation, and foundation stages. The images were captured every two weeks during the one-year duration of this study. 18 images that describe the actual site condition and construction progress in stages till 1-storey up were selected.

Secondly, these 18 images were converted as 3D models to input into CadnaA software as the base of noise propagation model. Together with a comprehensive construction schedule, review facilitated by the contractor site superintendent, analysis of drone images was conducted in order to identify construction noise sources.

Thirdly, sound power levels of construction equipment were established using the published literature from Federal Highway Administration (2011) and manufacturer's specifications. Sound power level of each construction equipment found in the drone images were used into CadnaA software as an input for noise propagation model.

4.2 Construction noise modelling in local study areas

A Vancouver neighbourhood was selected to represent different urban forms of residential and mix-use neighbourhoods. The selected neighbourhood was identified as the Local Study Area (LSA) and modelled with the CadnaA software. This allowed flexibility within the CadnaA model to work with increasing densification of the neighbourhood. The boundary of LSA depends on the two factors (a) the lateral distance beyond which construction noise impacts are not expected to occur, (b) the distance beyond which daily-average noise levels from project-related noise would not be expected to exceed Canada Mortgage and Housing Corporation (1981) guidelines.

The LSA selected for this research is located at Cambie St and W King Edward Ave. In the model receptors were placed on the selected location of the CadnaA model at the height of 2 m at the building façade. Figure 15 shows the LSA boundary and receivers' location.

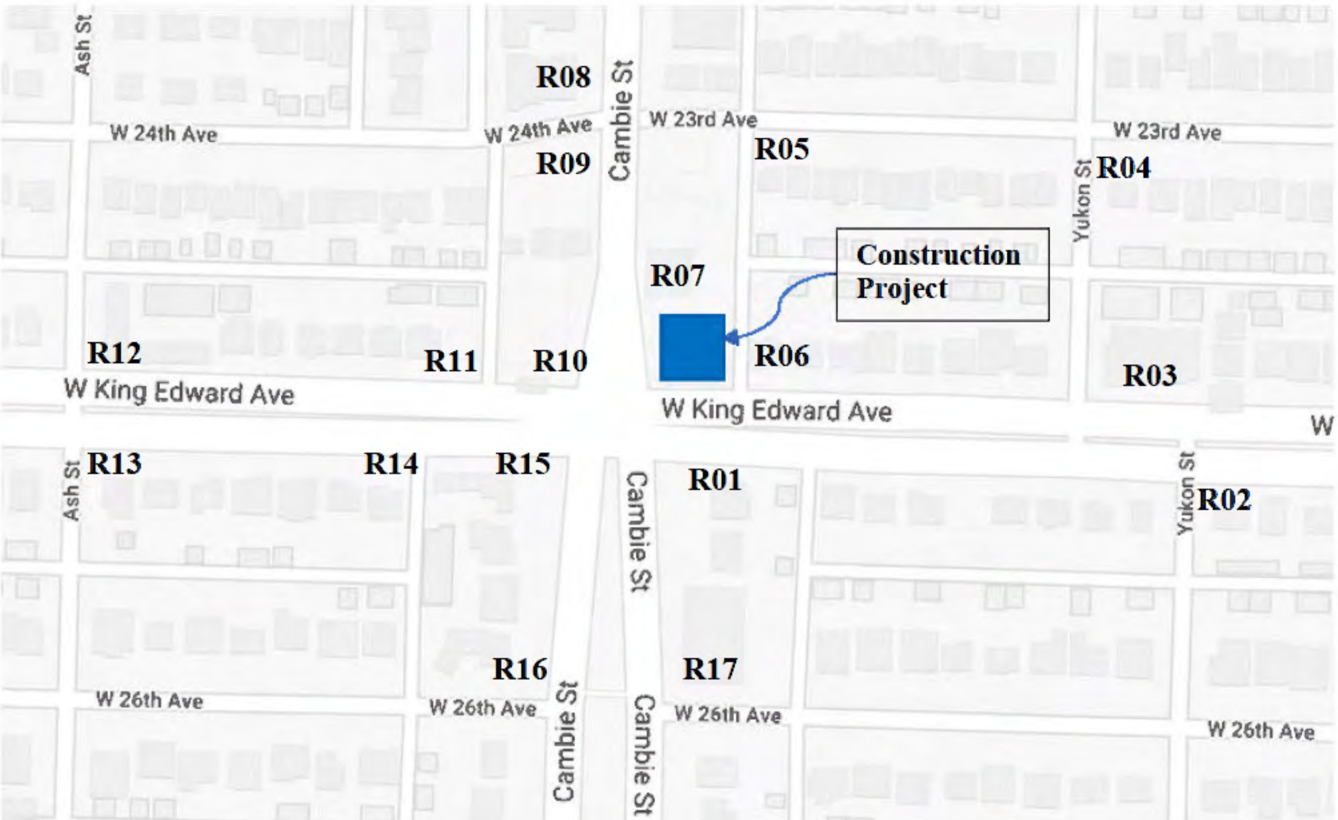


Figure 15 Local study area and Receivers

By increasing densification of LSA, the following three types of LSA were modelled to represent a densifying urban neighbourhood in Vancouver.

LSA 1: Single family residential (SFR) throughout.

LSA 2: Mixed use on ground level and multi-family residential above on arterial road, and reminder the as SFR

LSA 3: Towers on arterial roads and the remainder as mixed-use multi-family residential.

The neighbourhood scenarios LSA 1, LSA 2, and LSA 3 were created in SketchUp and modelled in CadnaA software. The LSA baseline noise is the traffic noise level from the existing road traffic retrieve from VanMap. The latest vehicular traffic data found in the database were from 2011. Therefore, an average of annual 4% increase of traffic volume was estimated to calculate the neighbourhood baseline noise until 2021. The 4% increase is addressing the increase in traffic in Vancouver city. The possible vehicle per day differences between LSA1, LSA 2 and LSA 3 neighbourhood was not modelled. Therefore, traffic count data and baseline noise model input were assumed to remain the same for all three modelled neighbourhood scenarios. A summary traffic volume data is provided in Appendix D.

The speed limit and percentage of day/night traffic was kept constant at 50 km/hr and 90/10 respectively for all road sections. The percentage of heavy vehicle was assumed to be 5% for the arterial roads and around 1.5~2.5 % for the connector roads.

4.2.1 Populations in modelled neighbourhoods

According to Statistics Canada, the average household size varies on the structural type of dwellings. The average household size in Vancouver is 3.0, 1.8 and 1.6 for single-detached house, apartment in a building that has fewer than five storeys and apartment in a building that has five or more storey respectively. Based on the Statistics Canada data, this research had estimated the number of residents in the modelled LSAs and shown in Table 13.

Table 13 Distribution of persons living at receiver locations in the local study areas

	LSA 1	LSA 2	LSA 3
Number of single-detached house	136	83	83
Number of apartments in a building with <5 storeys	0	452	344
Number of apartments in a building with 5 or >5 storeys	0	390	840
Total number of structural type of dwellings	136	925	1267
Total number of persons live in LSAs	408	1687	2213
Estimated distribution of persons exposed at modelled receiver points:			
R1	3	58	231
R2	3	30	30
R3	3	44	44
R4	3	3	3
R5	3	3	3
R6	3	29	29
R7	3	58	58
R8	3	3	3
R9	3	58	58
R10	3	58	231
R11	3	44	44
R12	3	72	72
R13	3	44	44
R14	3	44	44
R15	3	44	231
R16	3	96	96
R17	3	96	96
Note: Refer to Figure 15 for Receivers (R) location			

As tabulated in Table 13, the modelled LSA 1 was comprised of 136 single family detached houses. The height of the detached houses was 3 m. In the LSA 2, 4 storeys and 6 storeys multifamily residential houses with apartments were located on the arterial roads and remaining streets were single family detached houses. In the LSA 3, three 24 storeys towers were modelled around the junction of W King Edward Ave and Cambie St and remainder as mixed-use multi-family residential. Based on the structural type of dwellings, it was estimated 408 persons live in LSA 1, 1687 persons live in LSA 2 and 2213 persons live in LSA 3. This research also made further breakdown of approximate number of persons residing at each of the receiver points as shown in Table 13.

4.3 Sensitivity of the CadnaA model

The modelling of construction noise and traffic noise propagation and attenuation was conducted using standard algorithms built into CadnaA software. The algorithm used by CadnaA are consistent with International Organization for Standardization 9613 (1&2): Attenuation of Sound During Propagation Outdoors (ISO 9613). The sound levels are calculated using the ISO 9613-2 standard (ISO 1996), the indicated accuracy ± 3 dBA is acceptable at the source to receptor distance of up to 1,000 m.

4.4 Application of noise mitigation strategies

In order to reduce the construction noise impact on the community, a number of noise mitigation strategies were applied. Firstly, noise barriers of 3 m, 5 m, and 10 m high at the construction project perimeter were applied. Secondly, equipment noise enclosure for drill rigs were simulated by reducing the sound power 10 dB for drill rigs used during the S9 stage of the construction. Finally, the combination of noise barrier and equipment enclosure were applied and modelled in the CadnaA. Noise barriers used in the CadnaA model are standard barriers. Uses of different type of barriers, e.g., cylindrical barrier, T-shaped barrier, barriers inclined to the left/right was excluded in order to keep the modelling within the research scope.

4.5 Determination of community annoyance

As discussed in the literature review section, Health Canada uses the percent highly annoyed (% HA) indicator to measure the community annoyance. The day-night level Ldn is used to calculate %HA. First, Ldn was calculated for neighbourhood baseline noise and construction noise. Second, the total Ldn was calculated prior to the %HA (baseline), %HA (construction) and %HA (baseline and construction) was calculated. Finally, the change in %HA for project construction is calculated by subtracting %HA (baseline) from %HA (baseline and construction).

Health Canada guideline estimates and recommends neighbourhood baseline noise level for different types of community. Population density (number of people per square kilometer, P/km^2) is used to classify communities. For example, a population density of 7913 P/km^2 is defined as ‘Noisy Urban Residential’ area which is typically situated near relatively busy roads and a population density of 2493 P/km^2 is defined as ‘Urban Residential’ an area not immediately adjacent to heavily travelled roads. According to the 2016 Census, Vancouver city has 5493 P/km^2. The modelled neighbouhood in this research best fit under the Noisy Urban Residential community. Modelling input configurations and baseline model input parameters are listed in Appendix C and Appendix D respectively.

5. Results and Analysis

Each of the LSA, the baseline noise and construction noise emission were modelled in the CadnaA software. In total there were 99 models, CadnaA ran at approximately 2 hours and 45 minutes to complete each model.

5.1 Evaluation of noise at actual construction site

18 drone images which represents different stages of project construction stages were collected and analyzed. Refer to the Appendix E for full size of drone images. The first drone image was recorded on Oct 29 2019. It is clear from the image that the construction work is at the site preparation stage. Loader, excavators, concrete pumps are seen on the drone image. The key activities at this stage recorded was site leveling, removing existing concrete slabs, material movement, removal of existing pipelines from the site and the vicinity, and drain constructions. This trend continues until January 2020.

Deep excavation activities start in the week of Feb 13, 2020, followed by pilling and drilling works. The construction site activity was increasing at this stage. Additional construction equipment such as mobile crane, compactor, drill rig, pilling rigs, tower crane, scissors lift, power trowel was brought into the site as seen on the drone images and tabulated in Table 14 and Table 15. Piling works started on Feb 29, 2020, and there was total 72 piles inserted by the end of Mar 12, 2020. Excavation works continued gradually downward below the grade level. On the week of May 3, 2021, the excavation depth reached at 4.1 m depth. Soon after the excavation work, the shotcrete pouring works commenced at P1 basement area. The southern half of P1 basement shotcrete completed on

May 18 and the other half of P1 basement shotcrete pouring works finished on May 31, 2020.

Concrete pouring works for P1 roof was completed in two stages. First half of the P1 roof concrete pouring completed on June 30 2020 and the remaining part completed on July 10. 2020. Finally on the week of July 21, 2020 the construction for Level 1 roof was completed.

Table 14 List of noise sources in drone images

Oct 29 2019	**Nov 13 2019**	**Nov 25 2019**
Loader Excavator -1 Excavator -2 Concrete Pump-1 Concrete Pump-2 Dump Truck Garbage Truck Pick up Truck	Excavator Loader Forklift Dump Truck Garbage Truck Pick up Truck	Excavator Loader Dump Truck Garbage Truck Pick up Truck
Dec 8 2019	**Dec 28 2019**	**Jan 26 2020**
Forklift Dump Truck Garbage Truck Pick up Truck	Forklift Dump Truck Garbage Truck Pick up Truck	Excavator -1 Excavator -2 Loader Forklift Dump Truck Garbage Truck Pick up Truck
Feb 13 2020	**Feb 29 2020**	**Mar 17 2020**
Excavator Compactor Dump Truck Garbage Truck Pick up Truck	Excavator Compactor Piling Rig-1 Piling Rig-2 Dump Truck Garbage Truck Pick up Truck	Excavator -1 Excavator -2 Drill Rig Compactor Dump Truck Garbage Truck Pick up Truck
Mar 31 2020	**Apr 18 2020**	**May 3 2020**
Excavator -1 Excavator -2 Drill Rig Mobile Crane Dump Truck Garbage Truck Pick up Truck	Excavator -1 Excavator -2 Drill Rig Mobile Crane Dump Truck Garbage Truck Pick up Truck	Excavator -1 Excavator -2 Drill Rig Dump Truck Garbage Truck Pick up Truck
May 18 2020	**May 31 2020**	**Jun 18 2020**

Excavator -1 Excavator -2 Drill Rig	Excavator -1 Excavator -2 Tower Crane MEWP Garbage Truck Pick up Truck	Excavator Loader Tower Crane MEWP Forklift Garbage Truck Pick up Truck
Jun 28 2020	Jul 12 2020	July 30 2020
Excavator -1 Excavator -2 Grader Tower Crane Loader Garbage Truck Pick up Truck	Excavator Loader -1 Loader -2 Tower Crane Power Trowel-1 Power Trowel-2 Garbage Truck Pick up Truck	Loader Tower Crane Garbage Truck Pick up Truck

By using the published literature and manufacturer's specification, the noise level of construction equipment established, listed on Table 15. Other factors such noise source height, equipment operating time, and acoustical use factor are presented.

Table 15 Sound power level of construction equipment

Drone Image #, Date taken	Source Name	Acoustical Use Factor (%)	Noise Level (dBA)	Operating Time		Source Height [m]
				Day [min]	Night [min]	
1. Oct 29, 2019	Loader	40	93	240	0	0
	Excavator -1	40	87	240	0	0
	Excavator -2	40	87	240	0	0
	Concrete Pump-1	30	85	180	0	0
	Concrete Pump-2	30	85	180	0	0
	Dump Truck	10	88	60	0	0
	Garbage Truck	10	94	60	0	0
	Pick up Truck	10	80	60	0	0
2. Nov 13, 2019	Excavator	40	93	240	0	0
	Loader	40	87	240	0	0
	Forklift	40	87	240	0	0
	Dump Truck	10	88	60	0	0
	Garbage Truck	10	94	60	0	0
	Pick up Truck	10	80	60	0	0

3. Nov 25, 2019	Excavator	40	93	240	0	0
	Loader	40	87	240	0	0
	Dump Truck	10	88	60	0	0
	Garbage Truck	10	94	60	0	0
	Pick up Truck	10	80	60	0	0
4. Dec 8, 2019	Forklift	40	87	240	0	0
	Dump Truck	5	88	30	0	0
	Garbage Truck	5	94	30	0	0
	Pick up Truck	5	80	30	0	0
5. Dec 28, 2019	Forklift	40	87	240	0	0
	Dump Truck	5	88	30	0	0
	Garbage Truck	5	94	30	0	0
	Pick up Truck	5	80	30	0	0
6. Jan 26, 2020	Excavator -1	40	87	240	0	0
	Excavator -2	40	87	240	0	0
	Loader	40	87	240	0	0
	Forklift	40	87	240	0	0
	Dump Truck	25	88	150	0	0
	Garbage Truck	10	94	60	0	0
	Pick up Truck	15	80	90	0	0
7. Feb 13, 2020	Excavator	40	87	240	0	-1
	Compactor	20	84	120	0	-1
	Dump Truck	40	88	240	0	0
	Garbage Truck	10	94	60	0	0
	Pick up Truck	40	80	240	0	0
8. Feb 29, 2020	Excavator	40	87	240	0	-1.5
	Compactor	20	84	120	0	-1.5
	Piling Rig-1	20	115	120	0	-1.5
	Piling Rig-2	20	115	120	0	-1.5
	Dump Truck	40	88	240	0	0
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
9. Mar 17, 2020	Excavator -1	40	87	240	0	-2
	Excavator -2	40	87	240	0	-2
	Drill Rig	20	115	120	0	-2
	Compactor	20	84	120	0	0
	Dump Truck	40	88	240	0	0
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
10. Mar 31, 2020	Excavator -1	40	87	240	0	-2.5
	Excavator -2	40	87	240	0	-2.5
	Drill Rig	20	115	120	0	-2.5
	Mobile Crane	16	85	96	0	0
	Dump Truck	40	88	240	0	0
	Garbage Truck	15	94	90	0	0

	Pick up Truck	40	80	240	0	0
11. April 18, 2020	Excavator -1	40	87	240	0	-3.5
	Excavator -2	40	87	240	0	-3.5
	Drill Rig	20	115	120	0	-3.5
	Mobile Crane	16	85	96	0	0
	Dump Truck	40	88	240	0	0
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
12. May 3, 2020	Excavator -1	40	87	240	0	-4.1
	Excavator -2	40	87	240	0	-4.1
	Drill Rig	20	115	120	0	-4.1
	Dump Truck	40	88	240	0	0
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
13. May 18, 2020	Excavator -1	40	87	240	0	-4.1
	Excavator -2	40	87	240	0	-4.1
	Drill Rig	20	115	120	0	-4.1
14. May 31, 2020	Excavator -1	40	87	240	0	-4.1
	Excavator -2	40	87	240	0	-4.1
	Tower Crane	16	85	96	0	25
	MEWP	20	94	120	0	-4.1
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
15. Jun 18, 2020	Excavator	40	87	240	0	-4.1
	Loader	40	87	240	0	-4.1
	Tower Crane	16	85	96	0	25
	MEWP	20	94	120	0	0
	Forklift	40	87	240	0	0
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
16. Jun 28, 2020	Excavator -1	40	87	240	0	-4.1
	Excavator -2	40	87	240	0	-4.1
	Grader	40	86	240	0	-4.1
	Tower Crane	16	85	96	0	25
	Loader	40	87	240	0	-4.1
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
17. July 12, 2020	Excavator	40	87	240	0	0
	Loader -1	40	87	240	0	0
	Loader -2	40	87	240	0	0
	Tower Crane	16	85	96	0	25
	Power Trowel-1	25	98	150	0	0
	Power Trowel-2	25	98	150	0	0
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0
	Loader	40	87	240	0	0

18. Jul 30, 2020	Tower Crane	16	85	96	0	45
	Garbage Truck	15	94	90	0	0
	Pick up Truck	40	80	240	0	0

Note:
a) Source height 0 denotes equipment is located on grade level
b) Source height '-' denotes equipment is located below grade level
c) Piling works started on Feb 29, 2020, and ended on Mar 12, 2020
d) May 18, 2020: shotcrete pouring for P1 basement (southern half)
e) May 31, 2020: shotcrete pouring for P1 basement (northern half)
f) June 30, 2020: concrete pouring for P1 roof (southern half)
g) July 10, 2020: concrete pouring for P1 roof (northern half)
h) July 21, 2020: concrete pouring for Level 1 roof.

The construction noise emission for the BCIT SHS building construction project modelled on CadnaA software, Figure 16. As seen from the CadnaA simulations, the construction noise level slowly increased during the site preparation stages and reached peak levels during the excavation and foundation stages. Excavation and foundation stages lasted for around 4 months with noise emission in the range between 85 and 100 dBA. As seen from the CadnaA simulation, noise levels start to reduce after the foundation stages.

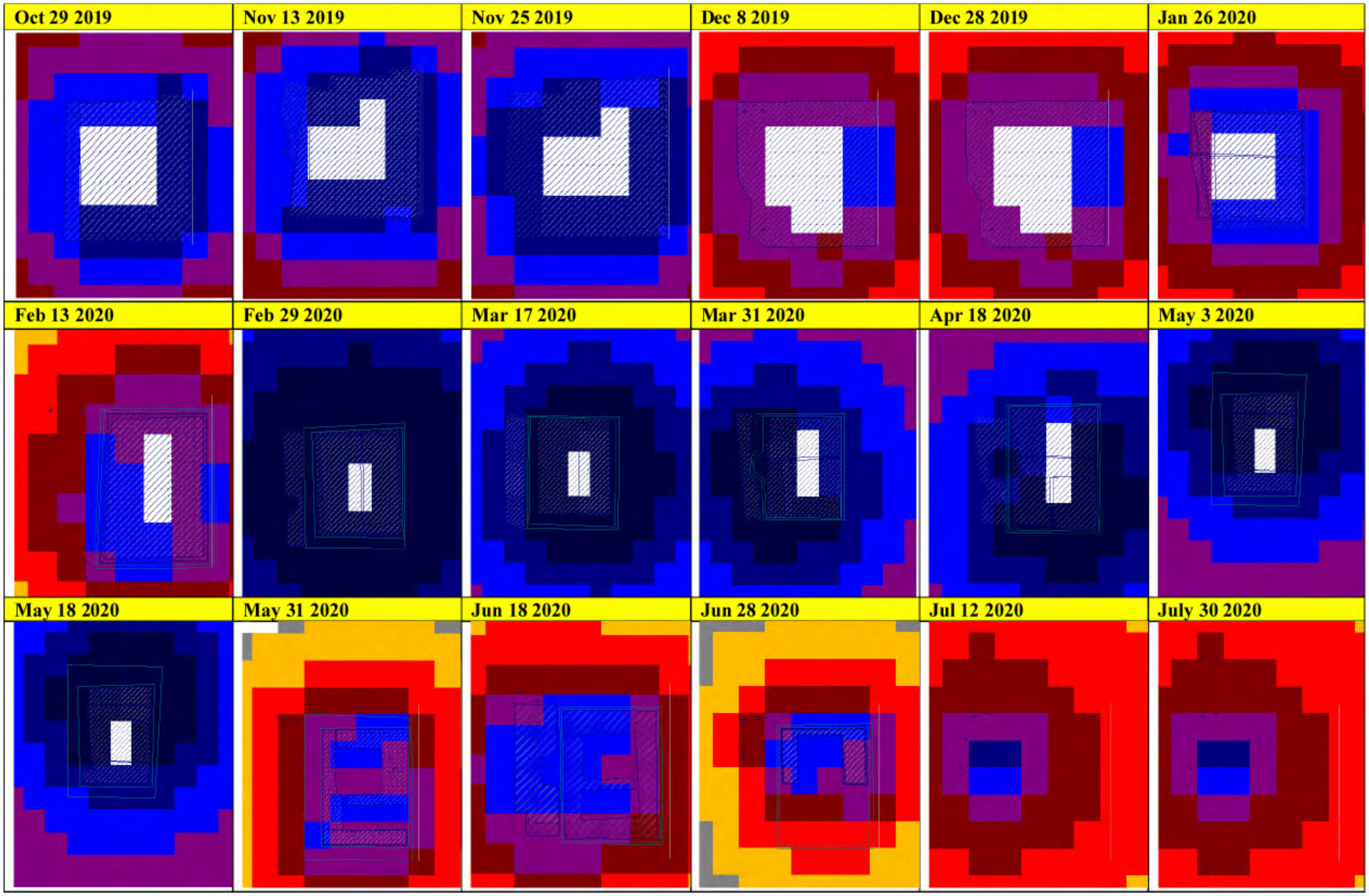

Oct 29 2019
Nov 13 2019
Nov 25 2019
Dec 8 2019
Dec 28 2019
Jan 26 2020
Feb 13 2020
Feb 29 2020
Mar 17 2020
Mar 31 2020
Apr 18 2020
May 3 2020
May 18 2020
May 31 2020
Jun 18 2020
Jun 28 2020
Jul 12 2020
July 30 2020

Figure 16 BCIT SHS project construction noise propagation in different project stages

From the CadnaA noise propagation models, construction daytime noise levels are measured at the project perimeter, as shown in Table 16. Construction noise level during the site preparation stages (S1-S3) fluctuates between 76 to 84 dBA. Noise level reached its peak up to 99 dBA (S9) when the excavation, piling, drilling, foundation works were being carried out (S7-S17). At the end of the foundation works, construction noise starts to drop to around 70 dBA.

Table 16 BCIT SHS Project Construction Noise

Drone Image #	Construction stage	Receiver Height [m]	Construction Noise, Ld [dBA]
S1	Site preparation	1.5	84
S2	Site preparation	1.5	84
S3	Site preparation	1.5	84
S4	Site preparation	1.5	76
S5	Site preparation	1.5	76
S6	Site was snow covered. No visible noise sources observed		
S7	Foundation Works	1.5	81
S8	Foundation Works	1.5	75
S9	Foundation Works	1.5	99
S10	Foundation Works	1.5	93
S11	Foundation Works	1.5	90
S12	Foundation Works	1.5	92
S13	Foundation Works	1.5	89
S14	Foundation Works	1.5	89
S15	Foundation Works	1.5	72
S16	Foundation Works	1.5	74
S17	Foundation Works	1.5	63
S18	Parkade construction	1.5	70
S19	Parkade construction	1.5	67

5.2 Evaluation of neighbourhood baseline and construction noise

Neighbourhood baseline noise estimation:

The baseline noise input parameter i.e., vehicular traffic data was used to model the neighbourhood baseline noise level. Neighbourhood baseline noise descriptor Ld, Ln and Ldn were calculated from the CadnaA model.

Figure 17 shows the CadnaA noise propagation model in LSA 1 neighbourhood. The neighbourhood baseline noise at the arterial road intersection appeared to be higher than noise level at the connector roads. Receiver points R7, R10 and R15 located around the arterial road intersection and projected to be above 70 dBA. Figure 18 shows the detail background noise level Ld, Ln and Ldn for LSA 1.

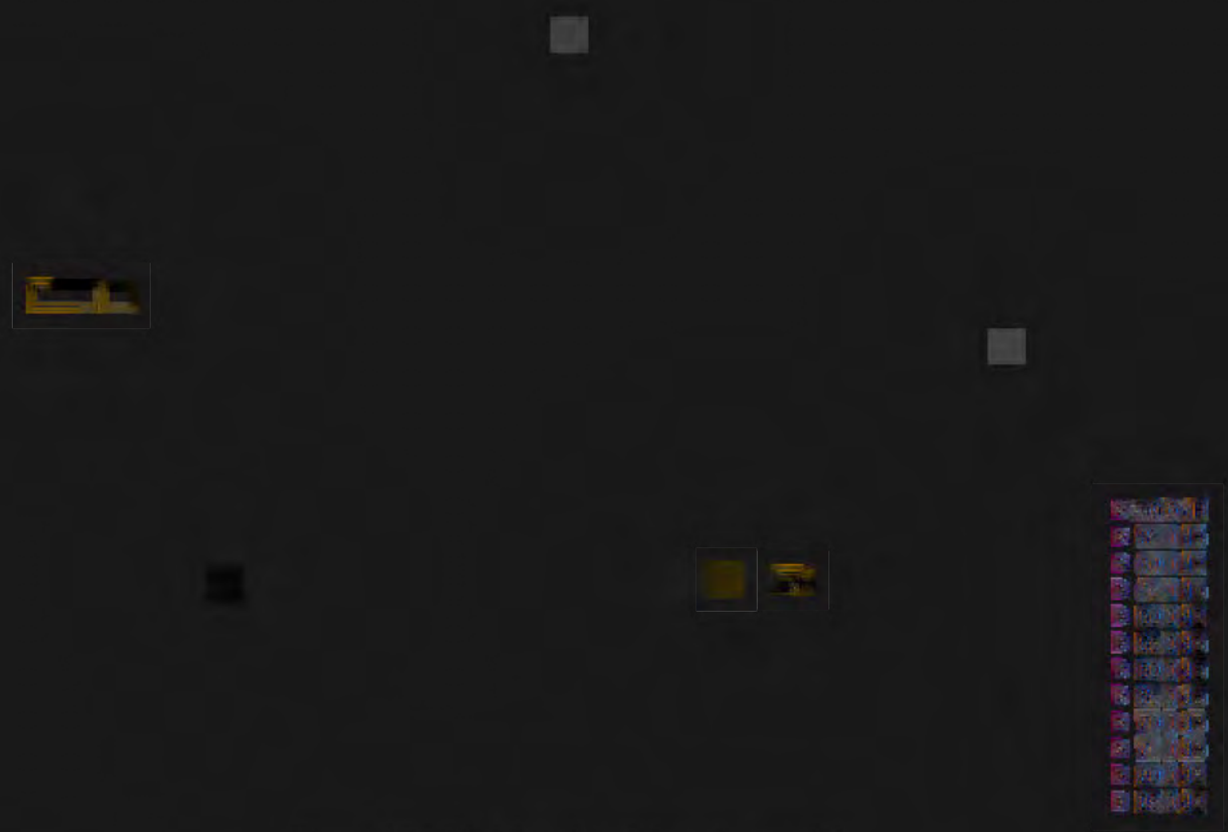


Figure 17 LSA 1 baseline Ldn noise model

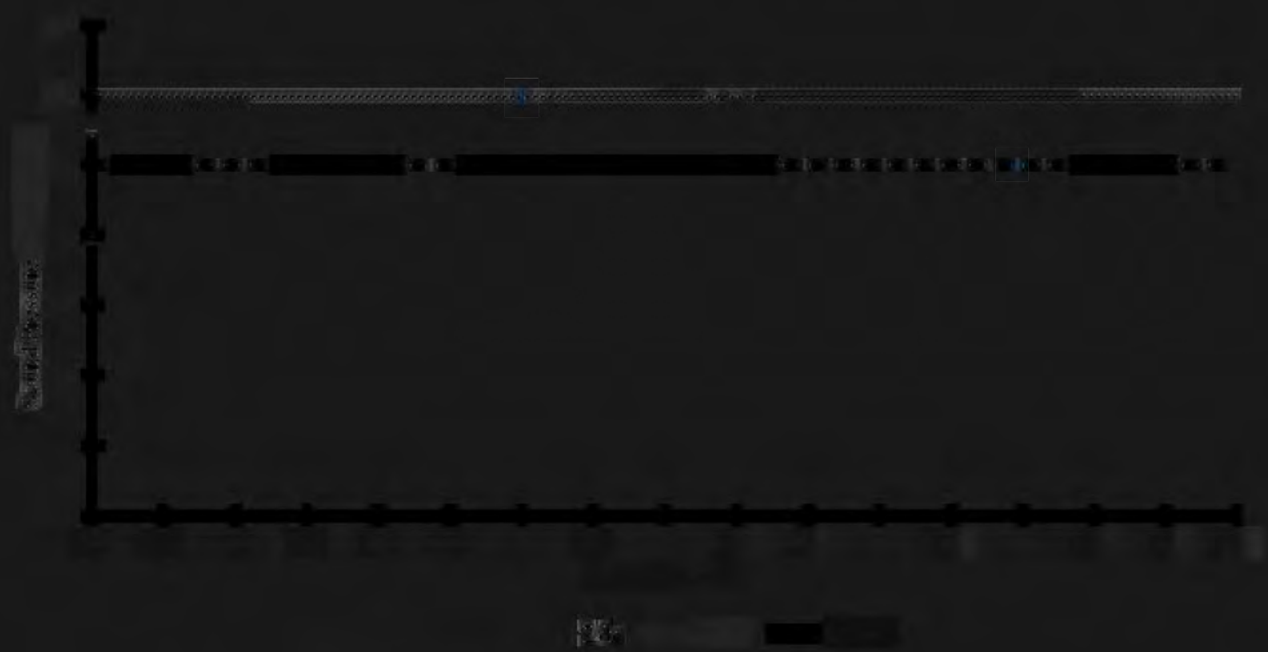


Figure 18 LSA 1 baseline noise levels

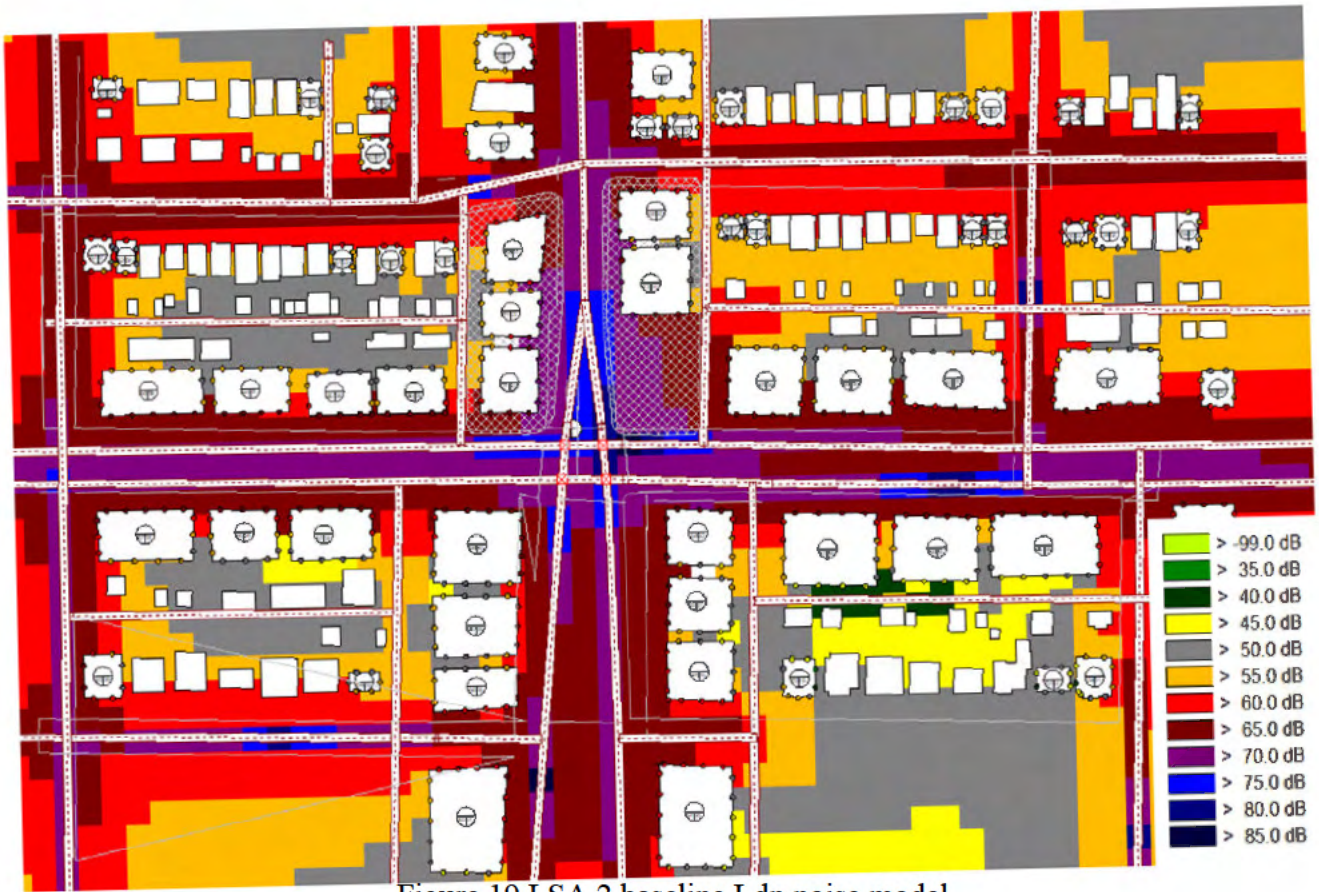


Figure 19 LSA 2 baseline Ldn noise model

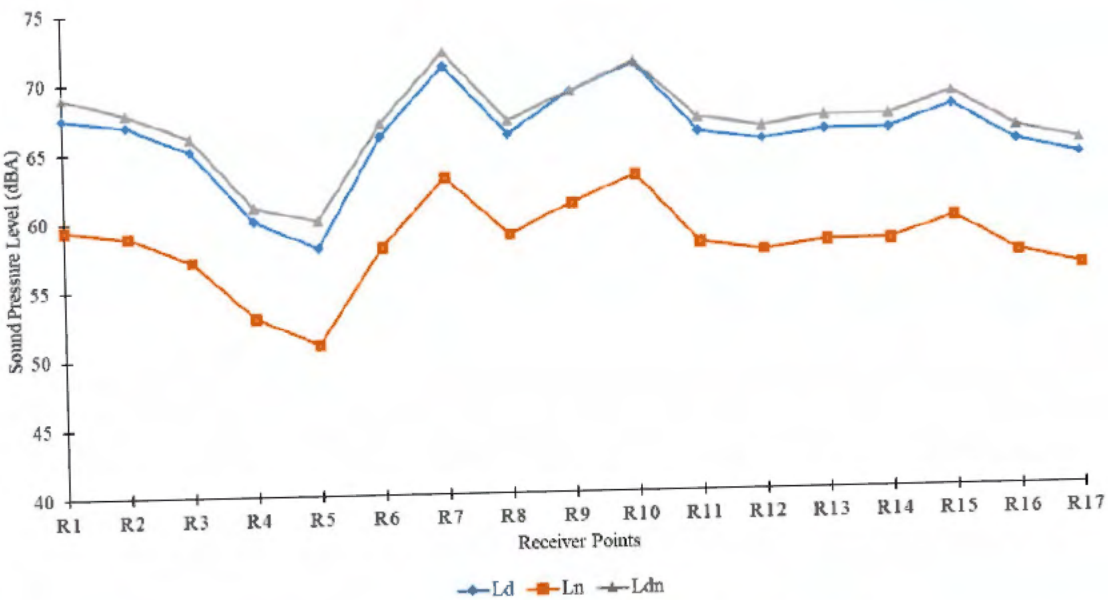


Figure 20 LSA 2 baseline noise levels

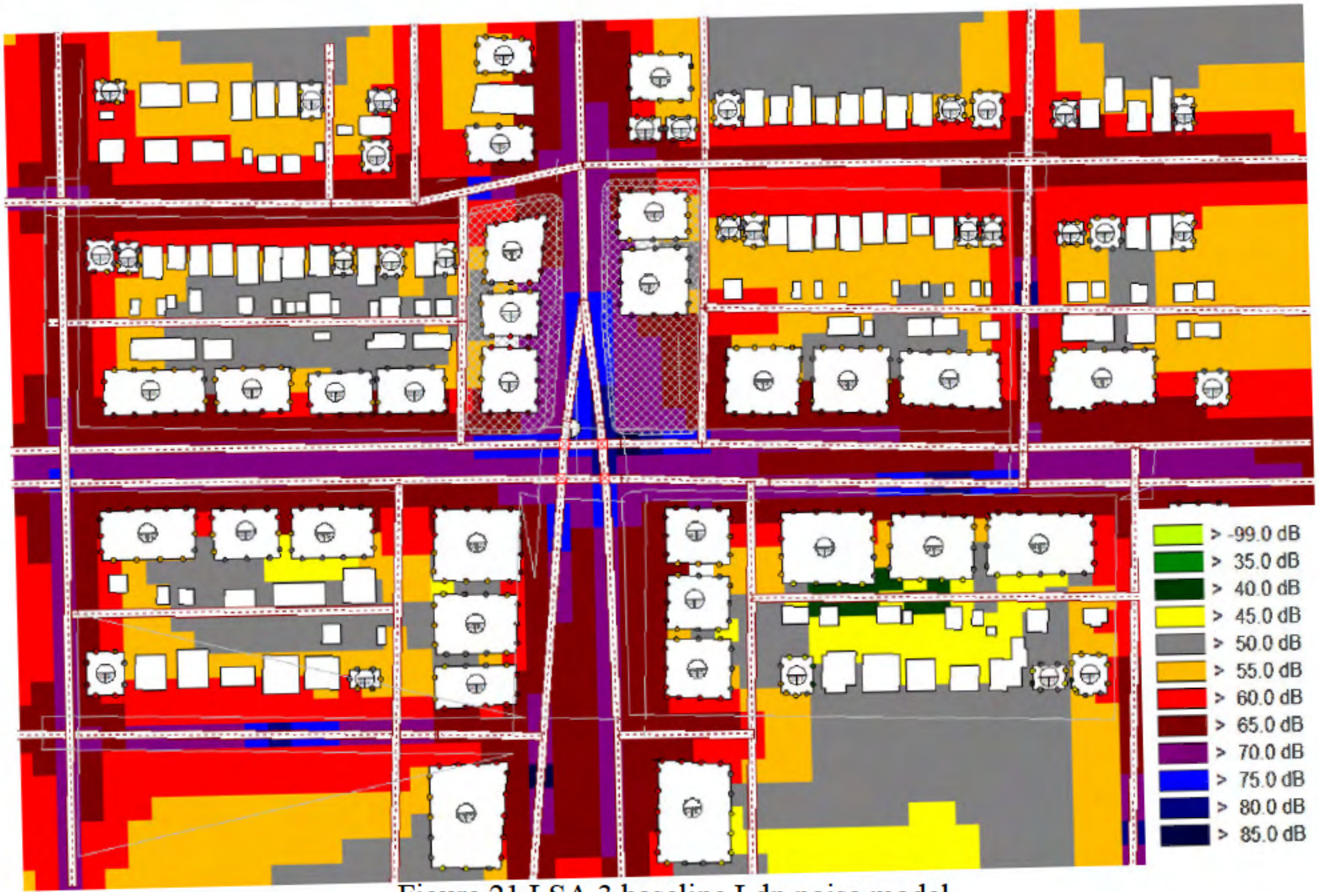


Figure 21 LSA 3 baseline Ldn noise model

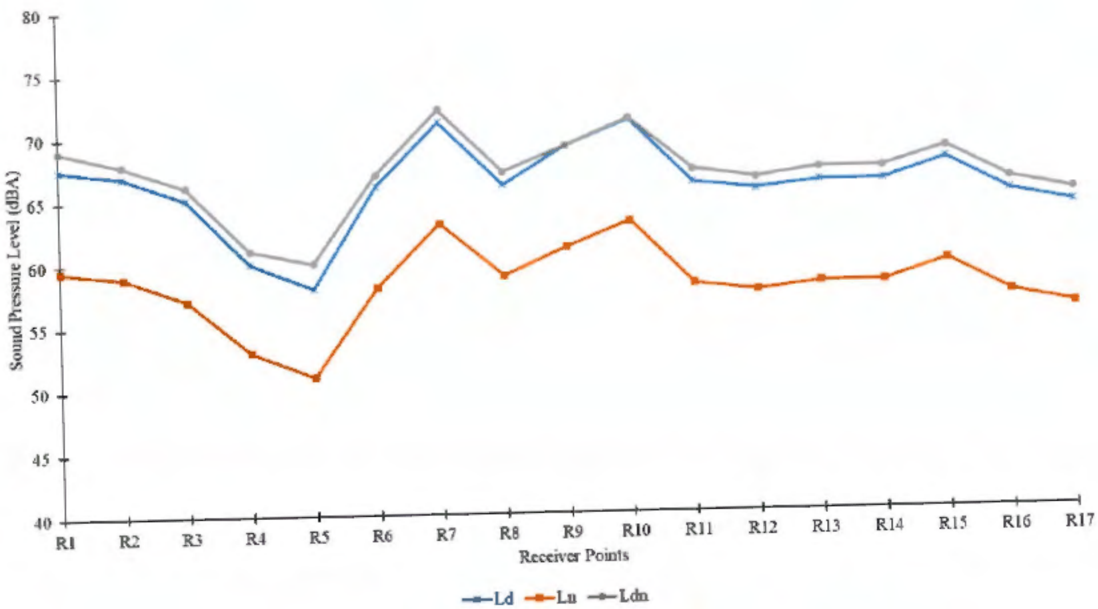


Figure 22 LSA 3 baseline noise levels

The City of Vancouver (CoV) noise bylaw divided the city, based on maximum permitted noise level, into three types of community zone such as Quiet Zone, Activity or Event Zone and Intermediate Zone. According to the CoV noise bylaw, any noise originating from the street is deemed as noise originating from the Activity Zone. The permitted noise level, outlined in the CoV noise bylaw, at the Activity Zone is 70 dB for daytime and 65 dB for nighttime. The background noise level, both daytime and nighttime, for all the Receiver Point in LSA 1 meets the CoV noise bylaw, Figure 18. However, Receiver Point 7 and 10 in LSA 2 and LSA3 exceeded daytime noise level by 1 dB, whereas nighttime background noise levels LSA 2 and LSA 3 does not exceeded, Figure 20 and Figure 22.

The recommend maximum baseline noise levels Ldn (dBA), by Health Canada, for Noisy Urban Residential is in the range of 63 to 67. The Ldn (dBA) values for LSA 1, LSA 2 and LSA 3, modelled in the CadnaA, are in the range from 61 to 71, from 60 to 70, and from 60 to 72 respectively. It can be seen from the Figure 17 to Figure 22 that the baseline noise level for LSA 1, LSA 2 and LSA 3 significantly more that the Health Canada recommended baseline noise for the Noisy Urban Residential neighbourhood. Furthermore, Health Canada recommends implementing noise control measures when the baseline noise level exceeds an Ldn of 75 dBA.

Neighbourhood construction noise estimation:

The construction noise consists of neighbourhood baseline noise and noise emissions from the construction equipment, identified from the drone image #S9, at which stage construction noise found to be the highest (Ld=99 dBA) in the actual construction project. Therefore, the neighbourhood construction noise modelling was carried out based on the S9 stage of the BCIT SHS construction project.

BCIT SHS construction project was modelled into three neighbourhoods (LSA 1, LSA 2 and LSA 3) to understand how the noise propagation at the different receiver location varies across the neighbourhoods, shown in Figure 23 to Figure 28.

Figure 23 LSA 1 construction Ldn noise model

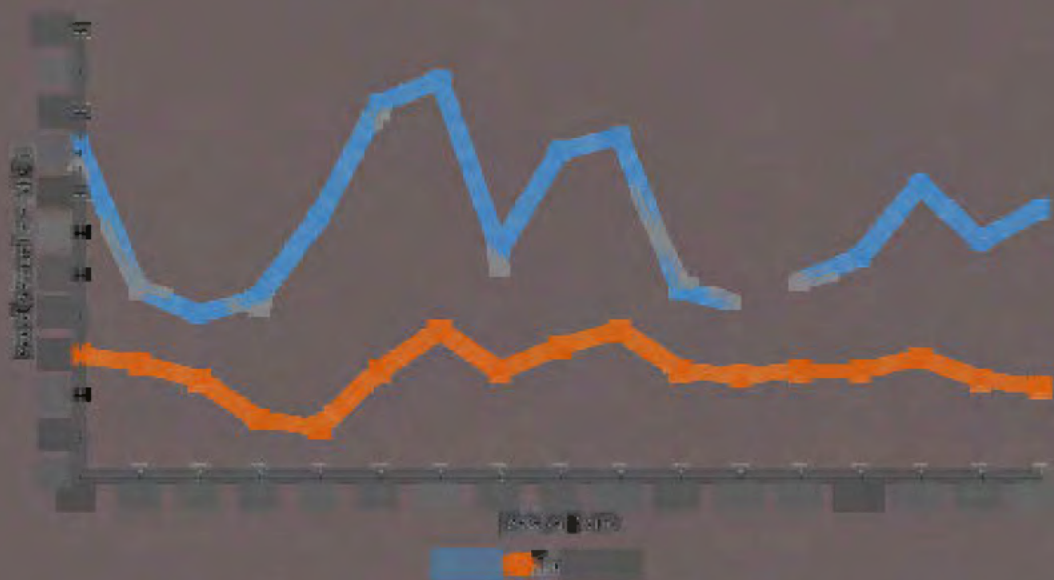


Figure 24 LSA 1 Construction noise levels (Refer to Figure 15 Section 4.2)

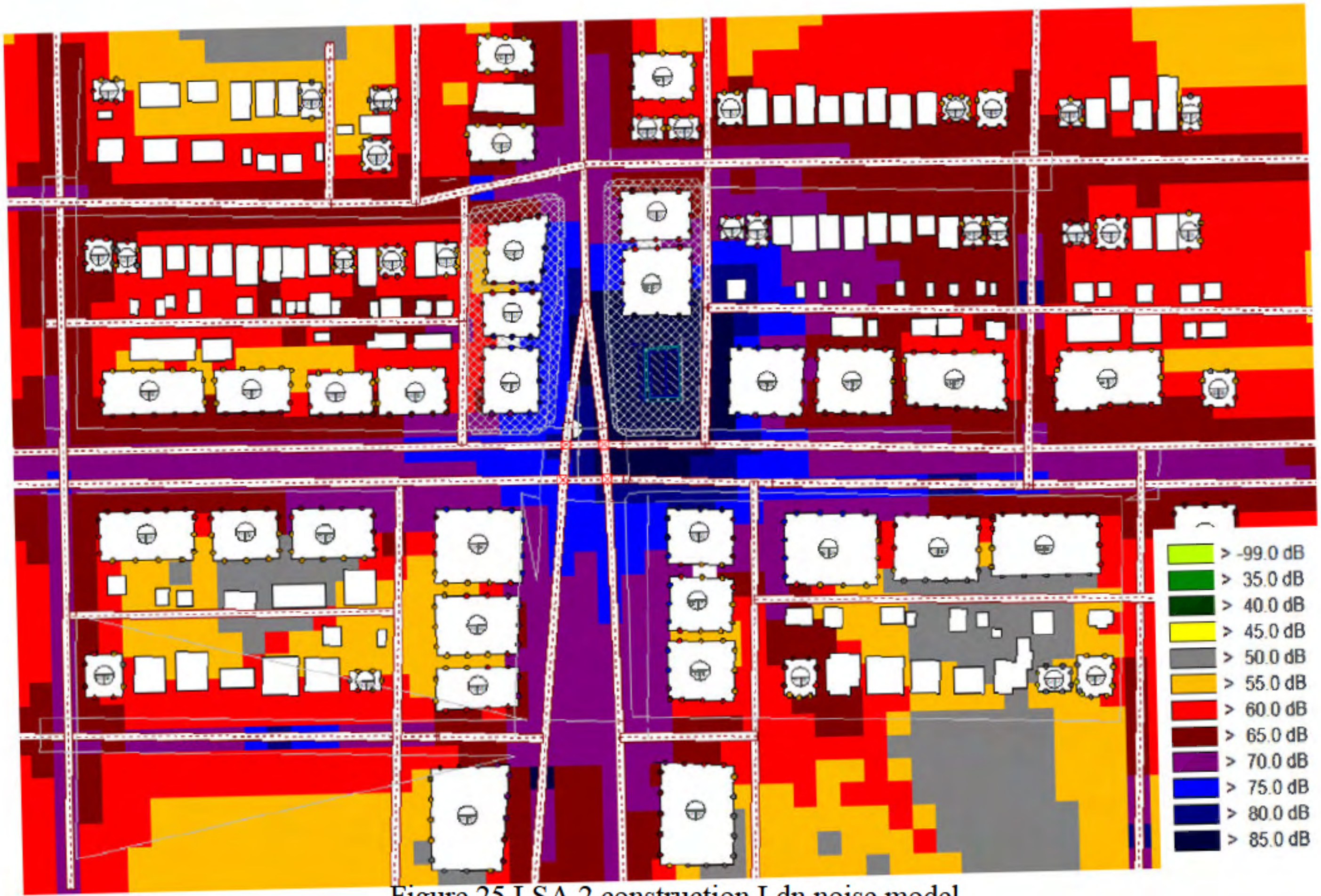


Figure 25 LSA 2 construction Ldn noise model

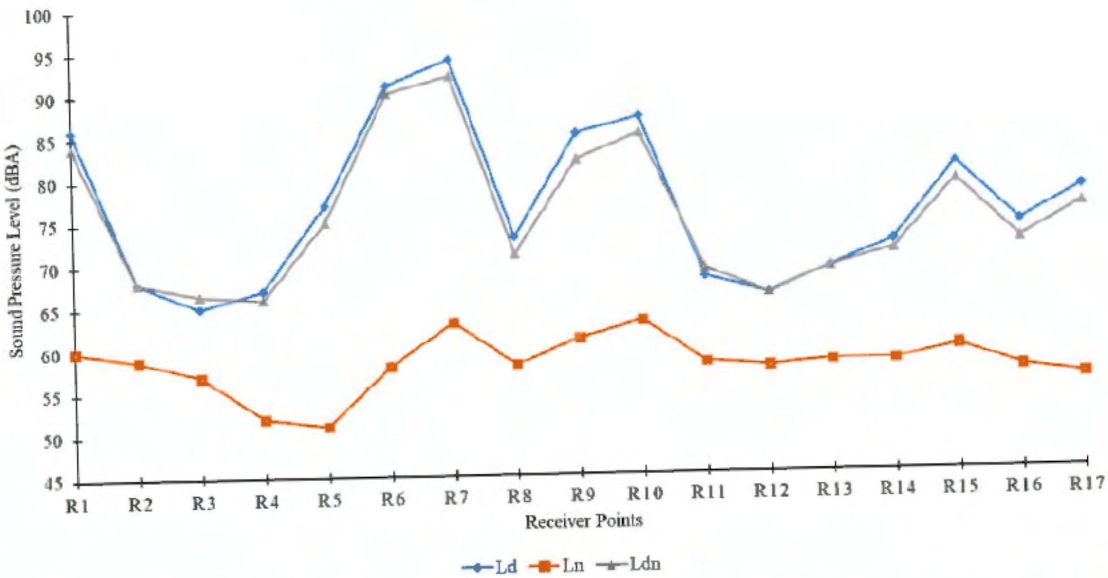


Figure 26 LSA 2 Construction noise levels (Refer to Figure 15 Section 4.2)

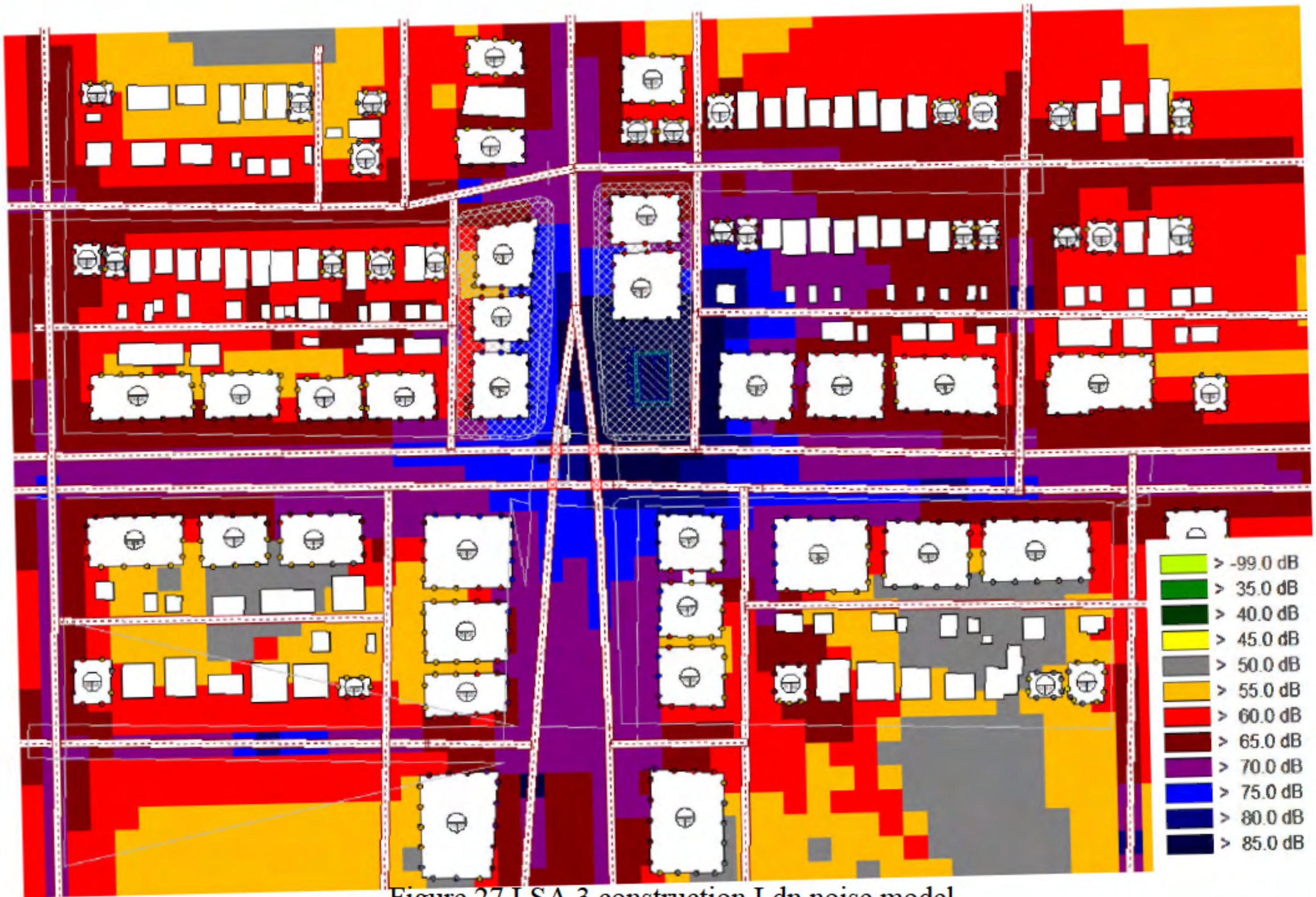


Figure 27 LSA 3 construction Ldn noise model

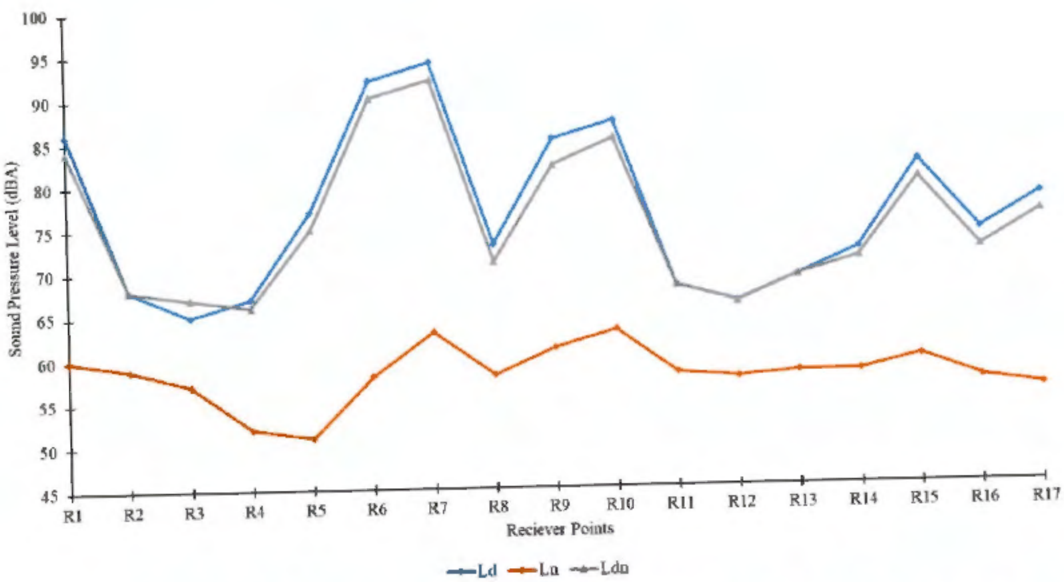


Figure 28 LSA 3 Construction noise levels (Refer to Figure 15 Section 4.2)

As can be seen from the Figure 23 to Figure 28 above, the construction noise levels (Ldn, dBA) on building facades among LSA 1, LSA 2 and LSA 3 neighbourhood are fluctuated between 66 to 92. Receivers points closest to the construction site reported higher noise levels as compared to receivers' points which are further from the construction site. This trend remains same throughout all three modelled neighbourhood, as summarized in Table 17 (refer to the Appendix F for detail data). Receivers point R7 in LSA 1, which to closest to the construction site, received highest noise level, 91 dBA.

Table 17 Evaluation of neighbourhood SPL evaluation

Receivers	**Ldn baseline [dBA]**			**Ldn construction [dBA]**		
	LSA 1	**LSA 2**	**LSA 3**	**LSA 1**	**LSA 2**	**LSA 3**
R1	68	69	69	77	84	84
R2	68	68	68	69	68	68
R3	66	66	66	67	67	67
R4	62	61	61	67	66	66
R5	61	60	60	76	75	75
R6	67	67	67	84	90	90
R7	71	72	72	91	92	92
R8	68	67	67	72	71	71
R9	68	69	69	74	82	82
R10	71	71	71	77	85	85
R11	66	67	67	72	69	68
R12	66	66	66	67	66	66
R13	66	67	67	68	69	69
R14	66	67	67	70	71	71
R15	69	69	69	74	79	80
R16	67	66	66	70	72	72
R17	66	65	65	70	76	76
Min	61	60	60	67	66	66
Average	67	67	67	73	75	75
Max	71	72	72	91	92	92

Findings illustrate that Ldn baseline are similar across LSA. Ldn Construction can be similar or Δ6+ across the LSA.

In LSA 2, receiver points R1, R2, R3, R6, R7, R9, R10 and R17 are 6-storey building and R3, R11, R12, R13, R14, R15, and R16 are 4-storey building with floor height of 3.6m. Remaining of the receiver points are in single storey.

In LSA3, receiver points R1, R10 and R15 each are 24-storey high rise towers with floor heights of 3.6m. R2, R3, R7, R9, and R17 are 6-storey buildings and R6, R11, R12, R13, R14, and R16 are 4-storey building. Remaining of the buildings are single storey. At R1, 1st floor façade received 80 dBA, then noise level increase to 84 dBA till 9th floor followed by returned to 80 dBA for 12th floor to 24th floor. A similar trend observed for the construction noise at R10 and R15 where a 4 to 5 dBA noise increased at the middle section of the buildings and noise level remain same for the lower and upper section of the buildings.

Generally, buildings receive noise from all directions. The lower floor noise was relatively smaller than the middle floor because of the barrier such as trees and walls. Noise levels at the upper floors attenuates with increasing height.

5.3 Evaluation of neighbourhood community annoyance

As discussed in the literature review section, Health Canada uses the percent highly annoyed (% HA) indicator to measure the community annoyance. The day-night level Ldn is used to calculate %HA. At first, Ldn was calculated for both neighbourhood baseline noise and construction noise. Then Ldn total was calculated prior to the %HA (baseline), %HA (construction) and %HA (baseline and construction) was calculated. Finally, the change in %HA for project construction is calculated by subtracting %HA (baseline) from %HA (baseline and construction), as shown in Table 18. Receiver points in all three modelled neighbourhood exceeded %HA recommended limit except for the R12 in LSA 2 and LSA 3.

Table 18 Evaluation of neighbourhood %HA evaluation

Receivers	**%HA baseline [%]**			**%HA construction [%]**			**Change in %HA between baseline and construction**		
	LSA 1	**LSA 2**	**LSA 3**	**LSA 1**	**LSA 2**	**LSA 3**	**LSA 1**	**LSA 2**	**LSA 3**
R1	19	22	19	46	67	67	27	45	47
R2	19	19	19	27	26	26	8	7	7
R3	16	16	16	22	22	23	7	7	7
R4	10	9	9	19	18	18	10	9	9
R5	9	9	7	40	38	38	31	30	31
R6	17	17	17	66	81	81	48	64	64
R7	26	29	29	83	85	85	57	56	56
R8	19	17	17	34	30	30	14	13	13
R9	19	22	22	38	61	61	18	39	39
R10	26	26	26	48	70	70	21	43	43
R11	16	17	17	31	27	25	15	9	8
R12	16	16	16	22	22	22	7	**6**	**6**
R13	16	17	17	23	27	27	8	9	9
R14	16	17	17	27	30	30	12	13	13
R15	22	22	22	39	52	55	17	30	33
R16	17	16	16	29	32	32	11	16	16
R17	16	14	14	27	42	42	11	28	28

5.4 Application of noise mitigation measures into neighbourhoods

Figure 29, Figure 30, and Figure 31 shows the construction noise level (Ldn) and reduction of noise levels due to different noise mitigation medium, for LSA 1, LSA2 and LSA 3 respectively.

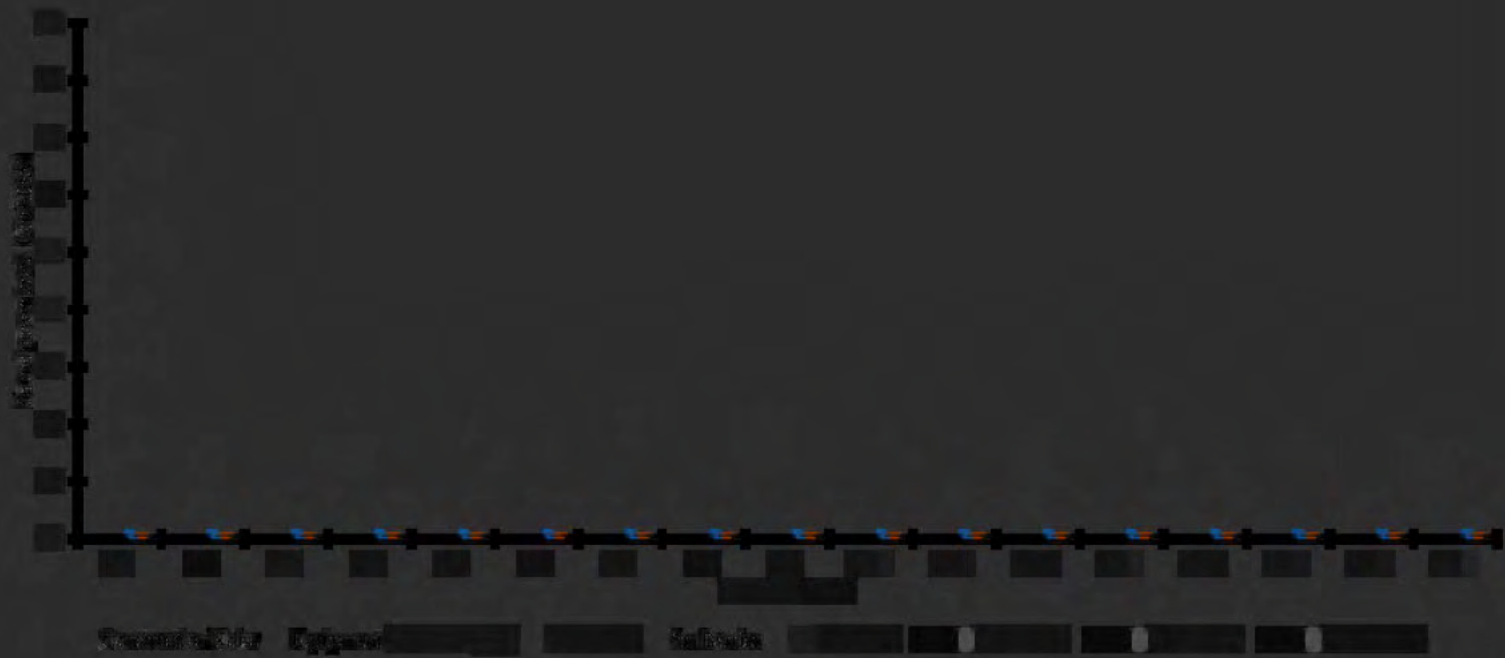


Figure 29 LSA 1 Construction noise mitigation application

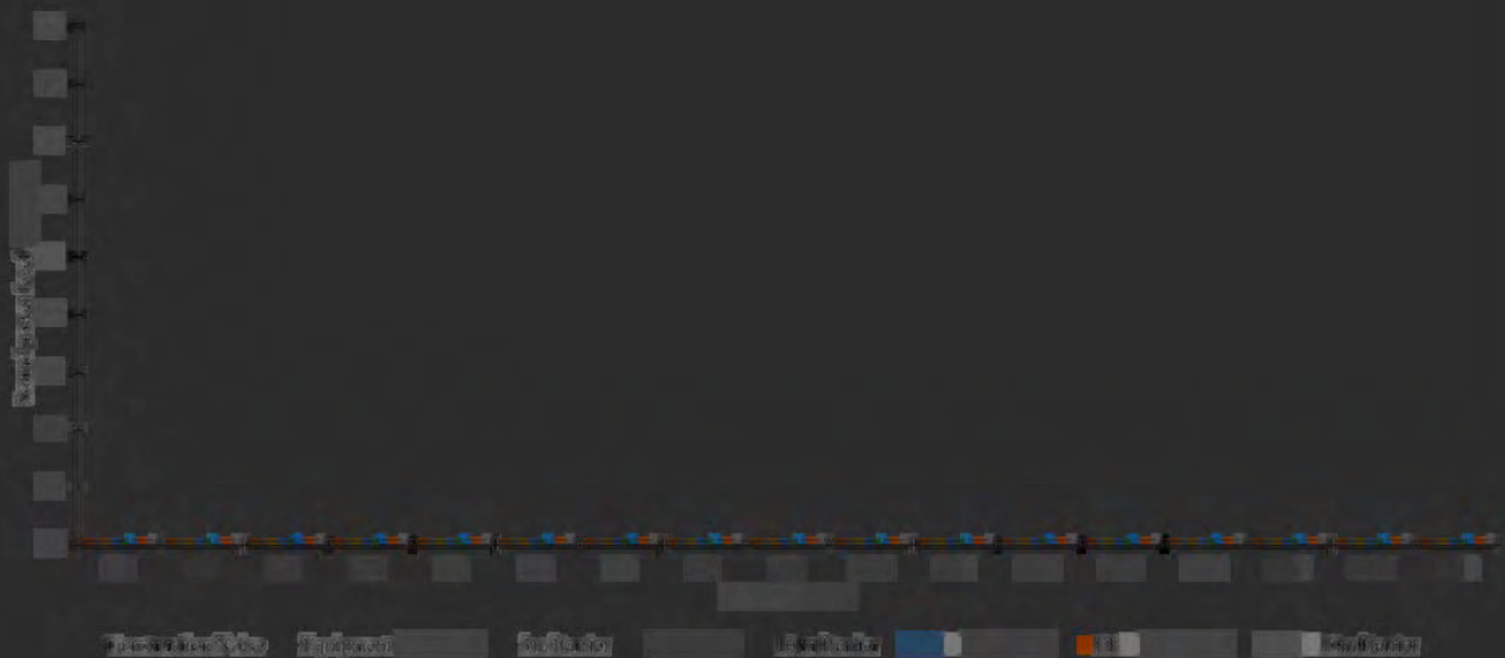


Figure 30 LSA 2 Construction noise mitigation application

Figure 31 LSA 3 Construction noise mitigation application

The analysis reported in Figure 29, Figure 30, and Figure 31 is based on the noise reduction level due to the application of noise mitigation strategies. For LSA 1, due to the 7 different type of noise mitigation measures, receiver points R1, R5, R6 and R7 has noticeable ΔdBA, as shown in Table 19. At R6 and R7, attenuation was achieved up to four-fold when equipment enclosure and 3m high noise barrier were applied together. Noise attenuation at other receiver points is barely noticeable except for R4 where 6 dBA attenuation (noticeable) was achieved by using 10 m barrier. It is evident that application of two control measures (e.g., equipment enclosure and 3 m high barrier) gives higher attenuation for LSA 1. For LSA 2 and LSA 3, maximum noise attenuation was achieved up to 23 dBA, as shown in Figure 30 and Figure 31. Noise attenuation level achieved by using noise control measures is summarized in Table 19, Table 20, and Table 21 for LSA 1, LSA 2, and LSA 3 respectively.

Table 19 LSA 1 noise attenuation by mitigation measures (ΔdBA)

	R 1	R 2	R 3	R 4	R 5	R 6	R 7	R 8	R 9	R10	R11	R12	R13	R14	R15	R16	R17
Equipment Enclosure (EE)	7	1	0	4	9	9	10	4	5	5	5	0	1	3	5	3	3
3 m Barrier	5	1	1	4	6	9	12	2	3	3	5	0	1	2	1	1	3
5 m Barrier	7	1	1	4	10	12	16	3	4	4	6	1	1	3	2	2	3
10 m Barrier	8	1	1	6	12	13	18	4	5	5	6	1	2	4	2	2	4
EE + 3 m Barrier	8	1	1	5	13	17	20	4	5	5	6	1	2	4	5	3	4
EE + 5 m Barrier	9	1	1	5	14	17	20	4	6	6	6	1	2	4	5	3	4
EE + 10 m Barrier	9	1	1	5	15	17	20	4	6	6	6	1	2	4	5	3	4

Table 20 LSA 2 noise attenuation by mitigation measures (ΔdBA)

	R 1	R 2	R 3	R 4	R 5	R 6	R 7	R 8	R 9	R10	R11	R12	R13	R14	R15	R16	R17
Equipment Enclosure (EE)	12	0	0	3	10	15	13	3	10	11	2	0	2	3	9	5	9
3 m Barrier	4	0	1	4	7	7	3	3	2	2	2	0	1	1	3	4	7
5 m Barrier	8	0	1	5	10	11	3	3	4	5	2	0	1	2	4	5	9
10 m Barrier	14	0	1	5	13	20	5	3	11	12	2	0	1	2	5	5	10
EE + 3 m Barrier	12	0	1	5	13	16	12	4	10	11	2	0	2	3	9	6	11
EE + 5 m Barrier	14	0	1	5	15	20	13	4	11	12	2	0	2	4	10	6	11
EE + 10 m Barrier	15	0	1	5	16	23	15	4	12	13	2	0	2	4	10	6	11

Table 21 LSA 3 noise attenuation by mitigation measures (ΔdBA)

	R 1	R 2	R 3	R 4	R 5	R 6	R 7	R 8	R 9	R10	R11	R12	R13	R14	R15	R16	R17
Equipment Enclosure (EE)	9	0	1	4	10	10	10	3	8	9	1	0	2	3	8	5	8
3 m Barrier	2	0	1	4	7	6	3	3	0	2	1	0	1	1	1	4	7
5 m Barrier	3	0	1	5	10	11	3	3	4	3	1	0	1	2	2	5	9
10 m Barrier	5	0	1	5	13	20	5	3	11	4	1	0	1	2	3	5	10
EE + 3 m Barrier	12	0	1	5	13	16	12	4	10	11	1	0	2	3	9	6	11
EE + 5 m Barrier	11	0	1	5	15	20	13	4	11	11	1	0	2	4	9	6	11

EE + 10 m Barrier	13	0	1	5	15	23	15	4	12	11	1	0	2	4	10	6	11

In addition, as expected, noise reduction for the buildings close to the construction site was higher than for the building situated far from the construction site or for the building shielded by another building.

Figure 32 illustrates the neigbourhood baseline noise, construction noise, and the most effective mitigation strategy (Equipment Enclosure and 5 m high barrier) of LSA 1. The results for LSA 2 and LSA 3 are similar.

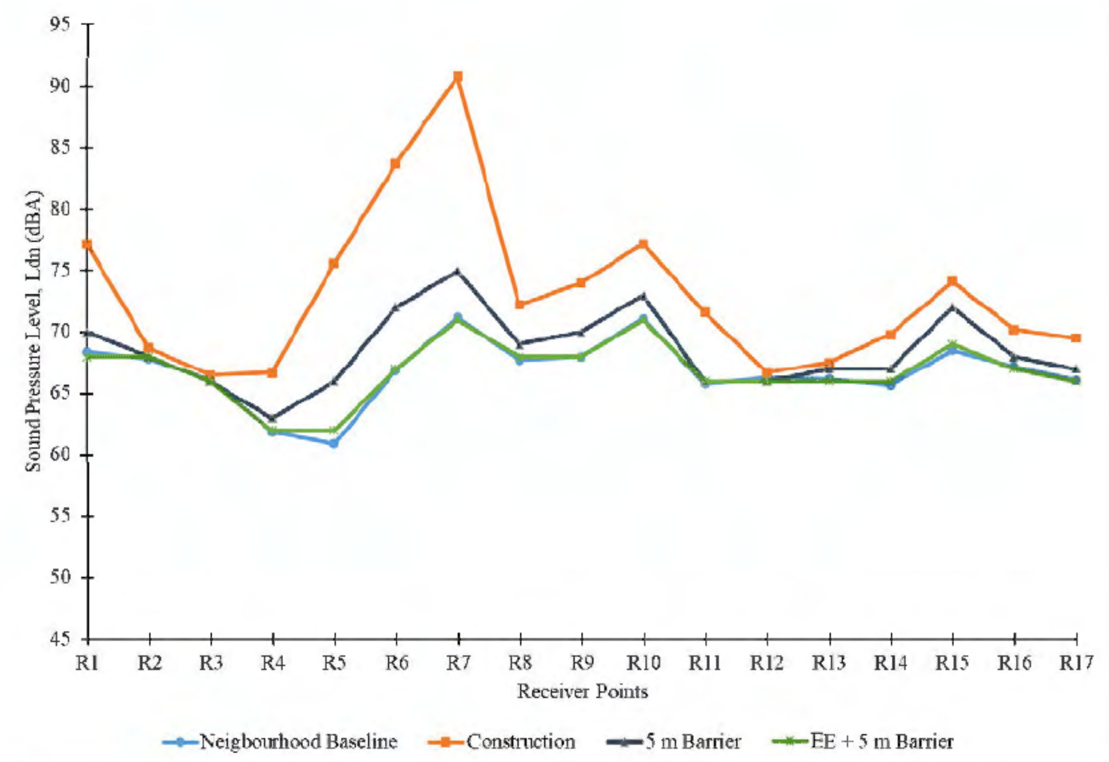


Figure 32 LSA 1 most effective mitigation strategy (Refer to Figure 15 Section 4.2)

Re-evaluation of community annoyance (%HA):

As discussed in the section 5.3, %HA for LSA 1, LSA 2 and LSA 3, without employing any noise mitigation was found to exceed the Health Canada recommended level. Therefore, a reassessment of %HA is required to impact due to the noise mitigation measures. A comparison of the pre-mitigation and post-mitigation change in %HA between baseline and construction noise is presented in Table 22, Table 23, and Table 24.

Table 22 LSA 1 Pre- and post-mitigation %HA between baseline and construction noise

Change in %HA between baseline and construction								
		After noise control measures						
Receivers	**Before noise control measures**	**Equipment Enclosure (EE)**	**3 m Barrier**	**5 m Barrier**	**10 m Barrier**	**EE + 3 m Barrier**	**EE + 5 m Barrier**	**EE + 10 m Barrier**
R1	27.0	11.0	13.7	9.9	8.3	8.3	7.0	7.0
R2	7.9	6.8	7.0	7.0	7.0	7.0	7.0	7.0
R3	6.5	**6.1**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
R4	9.5	**4.8**	**5.0**	**5.0**	**3.4**	**4.1**	**4.1**	**4.1**
R5	31.4	10.1	16.4	9.1	**6.5**	**5.4**	**4.5**	**3.7**
R6	48.4	20.7	22.3	14.9	12.8	**6.5**	**6.5**	**6.5**
R7	56.7	32.5	26.4	16.0	11.8	8.4	8.4	8.4
R8	14.1	7.5	9.9	8.3	7.0	7.0	7.0	7.0
R9	18.2	8.9	11.7	9.9	8.3	8.3	7.0	7.0
R10	21.5	10.5	13.8	11.8	10.0	10.0	8.4	8.4
R11	15.2	**6.4**	7.2	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
R12	6.8	**6.4**	6.8	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
R13	7.8	**6.3**	7.2	7.2	**6.0**	**6.0**	**6.0**	**6.0**
R14	11.5	**6.4**	8.6	7.2	**6.0**	**6.0**	**6.0**	**6.0**
R15	17.0	8.3	14.5	12.4	12.4	7.5	7.5	7.5
R16	11.3	6.8	9.2	7.8	7.8	**6.5**	**6.5**	**6.5**
R17	11.0	6.7	7.2	7.2	**6.0**	**6.0**	**6.0**	**6.0**

Table 23 LSA 2 Pre- and post-mitigation %HA between baseline and construction noise

Change in %HA between baseline and construction								
		After noise control measures						
Receivers	**Before noise control measures**	**Equipment Enclosure (EE)**	**3 m Barrier**	**5 m Barrier**	**10 m Barrier**	**EE + 3 m Barrier**	**EE + 5 m Barrier**	**EE + 10 m Barrier**
R1	45.3	12.4	33.5	21.9	8.9	12.4	8.9	7.5
R2	7.0	6.8	7.0	7.0	7.0	7.0	7.0	7.0
R3	6.5	**6.1**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
R4	9.1	**5.2**	**4.5**	**3.7**	**3.7**	**3.7**	**3.7**	**3.7**
R5	29.5	7.7	12.4	7.7	**4.5**	**4.5**	**3.1**	**2.5**
R6	64.0	22.3	46.4	34.1	10.9	19.7	10.9	**6.5**
R7	56.1	24.3	50.5	50.5	46.0	27.0	24.3	19.0
R8	12.8	8.3	7.8	7.8	7.8	**6.5**	**6.5**	**6.5**
R9	39.5	12.4	33.5	27.5	10.6	12.4	10.6	8.9
R10	43.5	13.8	37.9	29.3	11.8	13.8	11.8	10.0
R11	9.2	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**
R12	**6.0**	**6.4**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
R13	9.2	**6.5**	7.8	7.8	7.8	**6.5**	**6.5**	**6.5**
R14	12.8	7.8	10.9	9.2	9.2	7.8	**6.5**	**6.5**
R15	30.5	8.3	21.9	19.2	16.8	8.9	7.5	7.5
R16	16.1	7.6	8.6	7.2	7.2	**6.0**	**6.0**	**6.0**
R17	28.0	7.9	11.0	7.9	6.6	**5.5**	**5.5**	**5.5**

Table 24 LSA 3 Pre- and post-mitigation %HA between baseline and construction noise

Change in %HA between baseline and construction								
		After noise control measures applied						
Receivers	**Before noise control measures**	**Equipment Enclosure (EE)**	**3 m Barrier**	**5 m Barrier**	**10 m Barrier**	**EE + 3 m Barrier**	**EE + 5 m Barrier**	**EE + 10 m Barrier**
R1	47.4	20.8	41.5	38.5	32.3	13.7	15.9	11.7
R2	7.0	6.8	6.8	6.8	6.8	7.0	7.0	7.0
R3	7.2	**6.1**	**6.1**	**6.1**	**6.1**	**6.0**	**6.0**	**6.0**
R4	9.1	**4.5**	**4.5**	**3.7**	**3.7**	**3.7**	**3.7**	**3.7**
R5	31.2	8.7	13.7	8.7	**5.3**	**5.3**	**3.7**	**3.7**
R6	64.0	37.2	49.3	34.1	10.9	19.7	10.9	**6.5**
R7	56.1	32.7	50.5	50.5	46.0	27.0	24.3	19.0
R8	12.8	8.3	8.3	8.3	8.3	**6.5**	**6.5**	**6.5**
R9	39.5	16.8	39.5	27.5	10.6	12.4	10.6	8.9
R10	43.5	18.4	37.9	35.1	32.2	13.8	13.8	13.8
R11	7.8	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**
R12	**6.0**	**6.4**	**6.4**	**6.4**	**6.4**	**6.0**	**6.0**	**6.0**
R13	9.2	**6.5**	7.8	7.8	7.8	**6.5**	**6.5**	**6.5**
R14	12.8	7.8	10.9	9.2	9.2	7.8	**6.5**	**6.5**
R15	33.5	12.4	30.5	27.5	24.6	10.6	10.6	8.9
R16	16.1	7.6	8.6	7.2	7.2	**6.0**	**6.0**	**6.0**
R17	28.0	9.4	11.0	7.9	6.6	**5.5**	**5.5**	**5.5**

The pre-mitigation change in %HA is exceeded recommend level for all receiver points in all three LSA except R12 in LSA 2 and LSA 3. The reassessed value of change in %HA between baseline and construction shows application of noise control measures reduces noise levels to level that keeps the change in %HA below 6.5%, showed in blue in Table 22, Table 23, and Table 24. When equipment enclosure and 3 m high noise barrier is put in place, more than half of receiver points in LSA 1, LSA 2 and LSA3 shows change in %HA fell below 6.5%. However, receiver points such as R1, R7, R10 and R15 still has the change in %HA above 6.5%. Unlike the other receiver points, the construction noise level and change in %HA at R1, R7, R10 and R15 is high, because noise generated from construction site propagated directly to these receiver points without any shielding.

6. Modelling Limitation

The noise propagation from the actual site was modelled based on the noise sources (construction equipment) identified in drone captured images. Drone images was captured every two weeks for a one-year period. Drone images may not capture all aspects of the site noise levels. Noise level for construction equipment identified in the drone images was only used to model the construction noise which might be different from measured by field data.

Construction equipment not seen on the drone images were not accounted for. It is expected that construction noise propagation modelled in this research to be less than the actual construction noise measured by the field measurement.

The typology of the buildings in three LSAs was adopted and standardised from the actual neigbourhood. Neighbourhood baseline noise was modelled based on the vehicular traffic data in the vicinity. The latest available vehicular traffic count data in the database was ten years old. An average of 4% annual increase of the traffic was estimated to calculated baseline noise which might be different from the current year vehicular traffic.

There is an inherent limitation with the %HA algorithm based on Ldn. However, construction noise is typically experienced during the daytime hours given the City noise by-laws.

7. Discussion

The findings can inform municipality in formulating more detail noise bylaws and the noise mitigation measures taken by the construction management. Overall, the construction noise estimation in CadnaA software found the excavation stages have relatively higher noise level (99 dBA) than other stages in construction. This finding was similar with other research results (A. Gilchrist et al., 2003; Ng, 2000; Xiao et al., 2016) where researchers used field measurement method.

In analyzing the modelled neighbourhood noise estimation, it can be concluded that there is no significant difference between baseline noise levels in three neighbourhood LSA1, LS2 and LSA 3. Neighbourhood baseline noise levels are modelled based on the road vehicle count. The traffic count was kept constants for all three neighbourhoods in this research. The LSA 1 baseline noise levels did not exceeded the CoV noise bylaw limit. However, two receivers point in LSA 2 and one receiver points in LSA 3 exceeded the bylaw limit. This could be due to the result of street canyon effect in LSA 2 and LSA 3. On the other hand, the baseline noise level for all but two receiver points in LSA 1, LSA 2 and LSA 3 were found higher than the Health Canada recommended baseline noise limit.

The findings of neighbourhood construction noise exposure suggests that buildings close to and open to the construction site received higher noise than the noise in the building that are away from the site and shielded by another building. In LSA 2, 4-storey and 6-storey buildings along the Cambie St and W King Edward St with the remainder community modelled as 1 storey single family housing. Construction noise level difference between ground, middle and top floors was not significant, differs by 1~2 dB between upper and lower floor. However, for LSA 3, 24-storey towers modelled around the three side of the junction between Cambie St and W Kind Edward St. Construction noise, recorded as high as 84 dBA, found to be dominant for the middle and upper floors on the façade exposing to the construction project.

The most effective noise mitigation was modelled to be a combined control, using noise barrier and equipment enclosure together. In this combination, equipment enclosure with a 5 m high noise barrier gives almost same attenuation achieved by a equipment enclosure and a 10 m high barrier.

The %HA calculation result suggest that if the BCIT SHS construction project were to build in the modelled neighbourhoods without any noise mitigation measures, residents would experience widespread annoyance. The change in %HA value was found higher than the Health Canada recommended limit (6.5%) for all the receiver points for all three neighbourhoods. After the noise control measure applied, the change is %HA was slightly improved.

This research estimates the total population over-exposed to the construction noise and summarized in Table 25. If construction works continue without any noise mitigation measures 12% of resident in LSA 2 and 25% of resident in LSA3 have been overexposed according to the City of Vancouver (CoV) guidelines. According to the Health Canada guidelines, almost everyone in LSAs would have been over-exposed.

Table 25 Estimation of overexposed population in LSAs

	Total populations	Overexposed populations			
		Pre-mitigation		Post-mitigation	
		SPL	**%HA**	**SPL**	**%HA**
LSA 1	408	6	408	0	21
LSA 2	1687	203	1615	0	306
LSA 3	2213	549	2141	0	839

When the noise mitigations were applied, the CoV guidelines, 85 dBA noise limits at the site perimeter, are met. What is striking in the Table 25 is that even after applying construction noise controls, 1 in every 6 peoples in LSA 2 and more than one third of populations in LSA 3 would have been overexpose if no further noise mitigations are not applied in an attempt to reduce the noise level. This happened because of two reasons; the high neighbourhood baseline noise, and high construction noise. Due to the non-linear relationship between noise level and %HA, the %HA increased when there is a small increase due to construction in an already high baseline noise level neighbourhood.

8. Conclusion

Due to the ongoing rapid urbanization, construction projects are taking place everywhere in the urban and non-urban communities and increasing environmental noise. Existing research evidenced that environmental noise exposure is associated with adverse human health effects such as hearing loss, interference with communication, performance and behaviour, mental health, sleep disturbance, annoyance, and cardiovascular diseases. Therefore, this research investigates construction noise from the community perspective in designing residential neighbourhoods and considers compliance with municipality and Health Canada guidelines.

Construction noise was modelled on CadnaA software for an actual construction site. The noise estimation of an actual construction site from drone images was analyzed to identify the construction equipment as inputs into CadnaA software. The construction noise trend for the researched construction site was found to be aligned with the construction noise level published in the literature. Construction noise during the excavation stage and until the grade level construction was found to be the loudest among other construction stages.

The actual construction project was modelled into three idealized community neighbourhoods at the same location in Vancouver. Sound pressure levels and the community annoyance were modelled. For the neighbourhood baseline noise modelling, findings illustrate that Ldn baselines are similar across LSA and they meet the CoV by-laws. However, the neighbourhood baseline noise is significantly more than the Health Canada guidelines.

The neigbourhood construction noise can reach as high as 93 dBA if no noise control measures are employed. Ldn Construction can be similar or Δ6+ across the LSA. Construction noise can be mitigated by employing different noise mitigation strategies. The most effective noise mitigation was modelled to be a combined control, using noise barrier and equipment enclosure together.

If construction works continue without any noise mitigation measures, 12% of residents in LSA 2 and 25% of residents in LSA 3 have been overexposed according to the City of Vancouver (CoV) guidelines. According to the Health Canada guidelines, almost everyone in LSAs would have been over-exposed. Even after noise mitigation was in place, 5% in LSA1, 18% in LSA2, and 38% in LSA3 residents would experience widespread annoyance according to the Health Canada recommendations. These residual noises continue to remain and impact residents if further mitigation is not achieved.

9. Future Work

The modelled neighbourhood in the research excludes some of the noise sensitive receivers such as hospitals, schools, children, and senior care facilities. These receiver points have more stringent noise levels as recommended by World Health Organization. Future modelling could consider including these noise sensitive receivers into the model.

Besides auditory and non-auditory health effects, communities around construction sites also experience negative impacts such as economic losses. It would be an extension of this research to investigate how much social cost would the neighbourhood bear due to the impact of construction project noise.

This study investigated airborne noise from construction sites and did not address low frequency ground vibration. Further studies are required to evaluate the impact of ground-borne vibration which may cause disturbance on people and structures during the pile driving activities in foundation stage.

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11. Appendices

Appendix A Guideline values for community noise in specific environments.

Specific environment	Critical health effect(s)	L_{Aeq} [dB(A)]	Time base [hours]	L_{Amax} fast [dB]
Outdoor living area	Serious annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16	- -
Dwelling, indoors Inside bedrooms	Speech intelligibility & moderate annoyance, daytime & evening Sleep disturbance, night-time	35 30	16 8	 45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School class rooms & pre-schools, indoors	Speech intelligibility, disturbance of information extraction, message communication	35	during class	-
Pre-school bedrooms, indoor	Sleep disturbance	30	sleeping-time	45
School, playground outdoor	Annoyance (external source)	55	during play	-
Hospital, ward rooms, indoors	Sleep disturbance, night-time Sleep disturbance, daytime and evenings	30 30	8 16	40 -
Hospitals, treatment rooms, indoors	Interference with rest and recovery	#1		
Industrial, commercial shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment (patrons:<5 times/year)	100	4	110
Public addresses, indoors and outdoors	Hearing impairment	85	1	110
Music and other sounds through headphones/ earphones	Hearing impairment (free-field value)	85 #4	1	110
Impulse sounds from toys, fireworks and firearms	Hearing impairment (adults) Hearing impairment (children)	- -	- -	140 #2 120 #2
Outdoors in parkland and conservations areas	Disruption of tranquillity	#3		

#1: As low as possible.

[redacted]

Metric	Description
L_{eq}	L_{eq} is the equivalent continuous sound level measured over a specified period of time. The averaging period is often reported as a subscript. For example, a 16 hour averaging period would typically be reported as $L_{eq,16h}$
L_{max}	L_{max} is the maximum sound level, typically measured over a 1 second averaging period.
$L_{90\%}$ or L90	$L_{90\%}$ or L90 is the sound level that is exceeded 90% of the time. $L_{90\%}$ is often used to measure and report background noise because it removes occasional noise peaks and events from the measure.
L_d or L_{day}	L_d or L_{day} is the equivalent continuous sound level measured during daytime hours from 7 am to 10 pm.
L_n or L_{night}	L_n or L_{night} is the equivalent continuous sound level measured during nighttime hours from 10 pm to 7 am.
L_{DN} or DNL	L_{DN} or DNL (day-night level) is the equivalent continuous sound level measured over 24 hours with a 10 dB penalty assigned for nighttime noise between 10 pm and 7 am. This metric was introduced to account for increased annoyance experienced during the night.
L_{den}	L_{den} is the equivalent continuous sound level measured over 24 hours with a 5 dB penalty assigned for the evening noise between 7 pm and 10 pm, and a 10 dB penalty for nighttime noise between 10 pm and 7 am.

[redacted]

Appendix C

CadnaA noise model input configuration

Parameters	Model Setting	Notes
Software	CadnaA Version 2021 MR 1	Developed by DataKustik GmbH.
Standards	ISO 9613-2	This standard treats all sources and attenuation effects.
Ground absorption	0.1	1 represents porous ground, 0 represent hard ground, and between 0 to 1 represents mixed ground.
Reflection	2nd order	Consistent with ISO 9613-2.
Temperature/Humidity	10ºC / 70% RH	Representative summer condition.
Wind conditions	1 to 5 m/s	Consistent with ISO 9613-2.
Terrain	Contour lines	Contour line imported from Open Street Map as .OSM file to represent ground elevation.

Appendix D

LSA Baseline noise model input parameters

Road	Speed Limit [km/hr]	Traffic Count [per day]	% Heavy Vehicle	Day/Night Traffic [%]
W King Edward Ave EB	50	10,976	5.0	90/10
W King Edward Ave WB	50	10,530	5.0	90/10
Cambie St NB	50	11,334	5.0	90/10
Cambie St SB	50	8,948	5.0	90/10
West 26th Ave	50	5,287	2.5	90/10
Ash St	50	7,521	2.5	90/10
Yukon St	50	2,478	2.0	90/10
West 23rd Ave	50	5,965	2.5	90/10
West 24th Ave	50	6,732	2.5	90/10
Tupper St	50	2,220	1.5	90/10

Appendix E

Drone images is presented chronologically below-

Image# 1 - Oct 29 2019

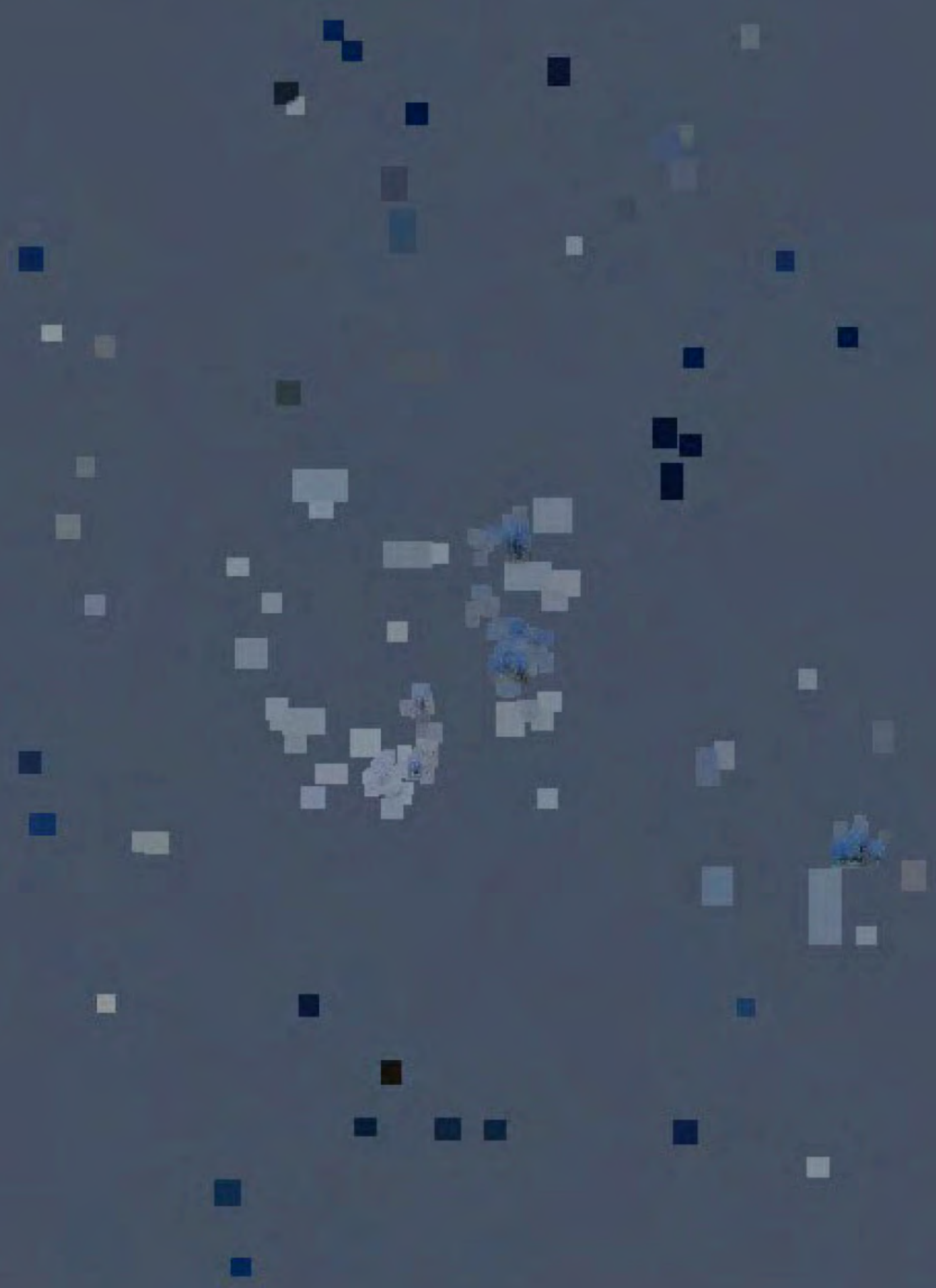
Image# 2 - Nov 13 2019

Image# 3 - Nov 25 2019

Image# 4 - Dec 8 2019

Image# 5 - Dec 28 2019

Image ## - Jan 16 2020. No ID assigned for this image. This image was excluded from the analysis since no noise source was visible in this image.



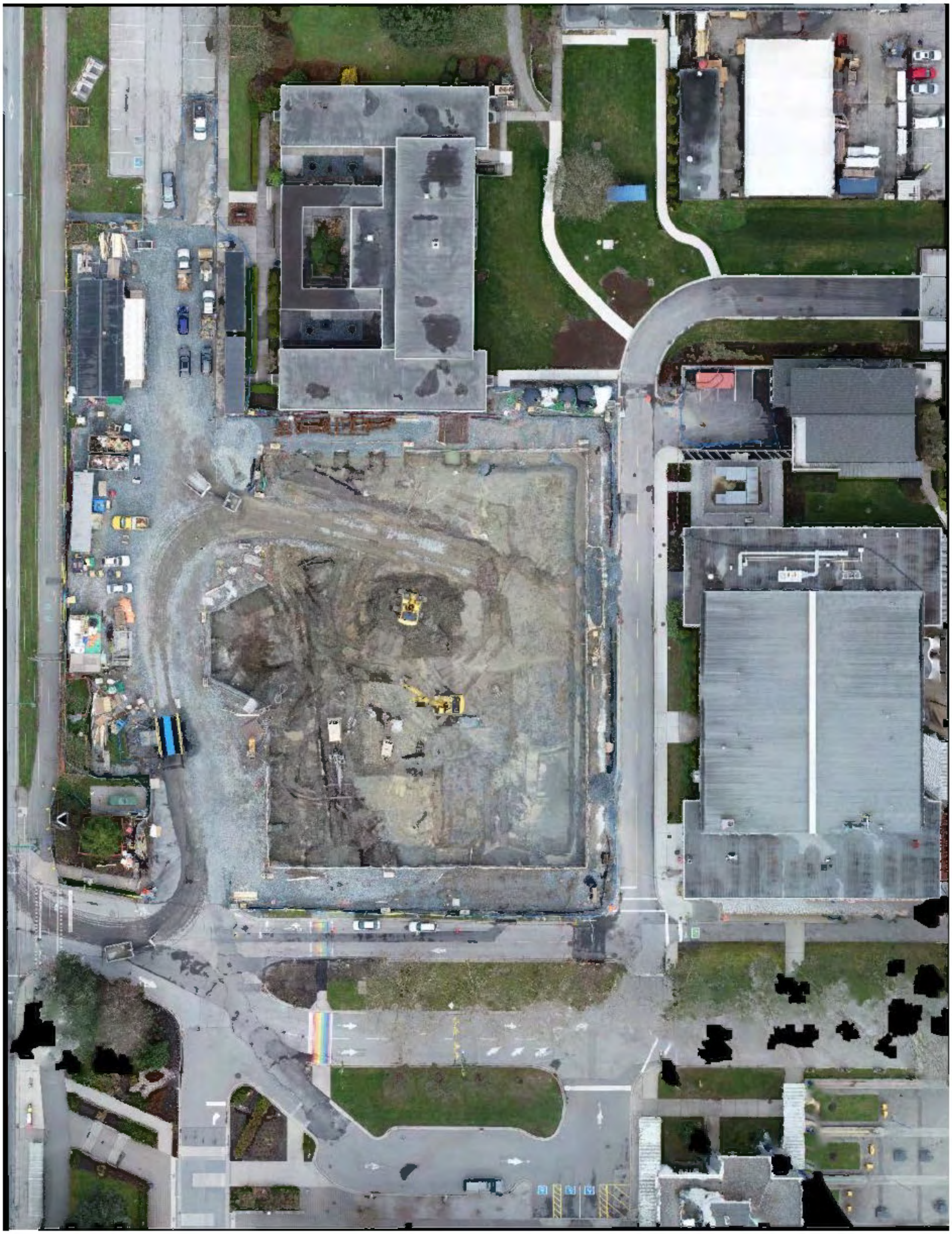
Image# 6 - Jan 26 2020

Image# 7 - Feb 13 2020

Image# 8 - Feb 29 2020

Image# 9 - Mar 17 2020

Image# 10 - Mar 31 2020



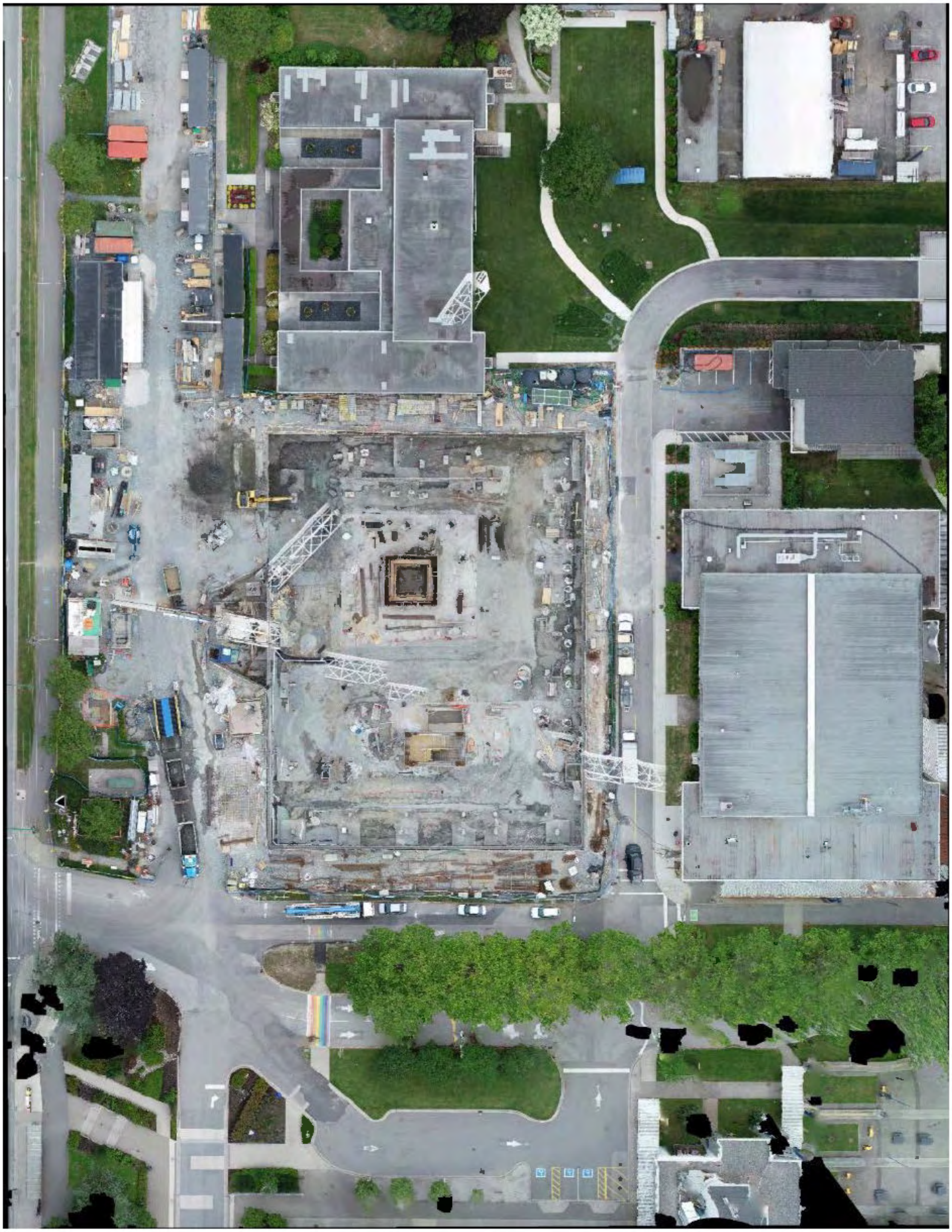
Image# 11 - Apr 18 2020

Image# 12 - May 3 2020

Image# 13 - May 18 2020

Image# 14 - May 31 2020

Image# 15 - Jun 18 2020



Image# 16 - Jun 28 2020

Image# 17 - Jul 12 2020

Image# 18 - Jul 30 2020

Appendix F

LSA 1 Baseline:																	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
Ld	68	67	65	61	60	66	70	67	67	70	65	65	65	65	68	66	65
Ln	60	59	57	53	52	58	62	59	59	62	57	57	57	57	60	58	57
Ldn	68	68	66	62	61	67	71	68	68	71	66	66	66	66	69	67	66
LSA 1 Construction:																	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
Ld	79	69	66	68	78	86	93	74	76	79	74	66	68	71	76	71	71
Ln	60	59	57	53	53	58	62	59	59	62	57	57	57	57	60	59	57
Ldn	77	69	67	67	76	84	91	72	74	77	72	67	68	70	74	70	70
LSA 2 Baseline:																	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
Ld	68	67	65	60	58	66	71	66	69	71	66	65	66	66	68	65	64
Ln	60	59	57	53	51	58	63	59	61	63	58	57	58	58	60	57	56
Ldn	69	68	66	61	60	67	72	67	69	71	67	66	67	67	69	66	65
LSA 2 Construction:																	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
Ld	86	68	65	67	77	91	94	73	85	87	68	66	69	72	81	74	78
Ln	60	59	57	52	51	58	63	58	61	63	58	57	58	58	60	57	56
Ldn	84	68	67	66	75	90	92	71	82	85	69	66	69	71	79	72	76
LSA 3 Baseline:																	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
Ld	68	67	65	60	58	66	71	66	69	71	66	65	66	66	68	65	64
Ln	60	59	57	53	51	58	63	59	61	63	58	57	58	58	60	57	56
Ldn	69	68	66	61	60	67	72	67	69	71	67	66	67	67	69	66	65
LSA 3 Construction:																	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
Ld	86	68	65	67	77	92	94	73	85	87	68	66	69	72	82	74	78
Ln	60	59	57	52	51	58	63	58	61	63	58	57	58	58	60	57	56
Ldn	84	68	67	66	75	90	92	71	82	85	68	66	69	71	80	72	76

12. Glossary and Abbreviation

dBA is A-weighted decibel levels tailored to human sensitivity, discounting low frequency sounds.

dBC is C-weighted netwrok used in measuring impulse or peak noise.

Sound pressure level is the ratio of the absolute Sound Pressure and a reference level which is the threshold of hearing. SPL is presented in a logarithmic value of decibels (dB).