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EFFECTIVENESS OF USING ROLLER-BIT BUCKETS TO MINIMIZE GROUND VIBRATION GENERATION IN BORED PILING

By

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Abstract

Ground vibration induced during the construction work becomes annoying for the neighboring community and eventually a great headache for the project management team due to continues complaints from the community. This study focused on the ground vibration generation during in-situ cast bored piling, since bored piling is becoming popular and mainly going on in highly urbanized areas. Effect of vibration to public can identify in two different ways as perception levels of vibration to human body and the effect of vibration to dwellings or any other structures, which cause public alert on vibration. The defined levels for either case is taken from the "Transportation and construction vibration guidance manual" released by California Department of Transportation in 2013 and ISO 4866:1990 (E) standards which also accepted by the Central Environmental Authority of Sri Lanka.

Generally, in bored piling, the ground vibration is generating when drilling through rock layers, especially in hard rock layers. A tool called core barrel is used to cut the perimeter of the rock. To cut the rock a special part is attached to the core barrels called a "Bullet teeth" which is consisted with tungsten carbide tip. Another option available for bullet teeth is called the "Roller bits" which consists of Tungsten carbide tips and use a different mechanism from bullet teeth. This study focused on the comparison of the effectiveness of tools with "Roller bits" and tools with "Bullet teeth" in terms of cost and time consumption and in terms of minimization of public nuisance. In this study a construction site was identified which adopted both types of tools in two different phases of the same project. It was observed that the other factors were same for both phases and the comparison was mainly on the two tool types used.

Based on the vibration levels obtained through site vibration measurements, it is found that the levels of vibration generated during piling operation has affected human perception levels which make them annoying according to "Transportation and construction vibration guidance manual" released by California Department of Transportation in 2013. And the level of vibration generated has exceeded the level stipulated by the Central Environmental Authority of Sri Lanka for Category 4 structures and Category 3 structures for certain occasions.

From the study it is found that the penetration rates are almost same for both cases but the difference in cost for pile shows apparently higher in the case 1, which was done with "Bullet teeth". The difference in cost is about 3.9% approximately. It is found during the cost analysis that the difference is mainly due to the cost of rectification work in the case which used "Bullet teeth" tools for pile boring. And the summary of field vibration monitoring also shows a reduction of about 20% in the average of maximum values, in the case which used "Roller bit" tools for boring work. Based on above findings it is beneficial to use "Roller bit" buckets for bored in-situ cast piling operations instead of "Bullet teeth" tools, especially in highly urbanized areas with sensitive buildings.

From the data obtained in this study based on the consumption and unit price, it is noted that the difference in the cost of Bullet teeth and the Roller bit is about 15.1% higher in using Roller bits. Hence it is important to monitor the performance of operation closely with the consumption of "Roller bits" since the consumption may vary with the operating skill of Rotary drilling machine.

Key words: Ground vibration, Piling, Bullet teeth, Roller bit, Public nuisance

Acknowledgement

This research is about the ground borne vibration during bored piling activities, which using most of the construction projects in urban areas with the boost in infrastructure development in the country in post war period. outcomes of the study will be helpful for the developers, contractors and specially the project management teams who engage in piling activities in construction projects.

Firstly, I express my sincere gratitude to Prof. Rangika Halwatura for his supervision and guidance provided during the research project. And also, for the motivation, confidence and enthusiasm given in the beginning when the topic was proposed.

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Last but not least I would like to thank my parents, brother, sisters and my wife for being the best support to hurdle all the obstacles throughout this research work.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CEA : Central Engineering Authority

ISO : International Standards Organization

BSI : British Standards Institute

UK : United Kingdom

ANSI : American National Standards Institute

US : United States of America

CECB : Central Engineering Consultancy Bureau

PPV : Peak Particle Velocity

RCD : Reverse Circulation Drilling

VdB : Velocity level in decibels

UCS : Unconfined compressive strength

Sec : Seconds

Rms : Root-mean-square

R-wave: Rayleigh wave

S-wave: Shear wave

Hz : Hertz

in/sec : inches per second

mm/sec: millimeters per second

MPa : Mega pascal

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List of Appendices

CHAPTER 1: INTRODUCTION

1.1 Background

Ground vibration induced during the construction work becomes annoying for the neighboring community and eventually a great headache for the project managers due to continues complaints from the community. Project managers have to face frequent inquiries from police, public protests, court cases, etc. due to continues vibration induced which also can cause the project costs to increase drastically and to reduce the performance of the project management teams. In some cases, the project might be stopped for some period of time due to public protests or court orders or might be abandoned.

The main activities which ground vibrations generates due to construction are pile driving, dynamic compaction, blasting, and operation of heavy construction equipment. These vibrations may harmfully affect surrounding properties, and their effect ranges from disturbance of residents to visible structural damage. Due to above facts frequent protests from public in surrounding is inevitable. Basically, in this research study the ground vibration generation due to bored and cast in-situ pile driving and the cost and time benefits are assessed for two different techniques used in pile boring work.

1.1.1 Reasons for public nuisance

Pile driving is an activity that is ill suited to the urban environment. The noise and the ground vibration created during the bored and cast insitu or installation of pre-formed piles by dynamic methods can lead to human disturbance and structural damage. The public nuisance due to ground vibration can be mainly due to two reasons as follows;

1. The level of vibration generates exceeds the tolerable levels for human perception
2. Damages to dwellings or buildings due to excessive vibration

The damages can be minor in nature, but it creates alarming situation in public creates resistance from the community which creates problems to the project management teams.

Block Wall cracks

Plaster falling off

Figure 1.1 Damages to buildings due to ground borne vibration

1.1.2 Bored and cast in situ piling

A cast in situ pile is constructed by drilling a hole into the ground with or without a casing and filling the hole with concrete after inserting a reinforcement cage. Currently the most common method using for drilling is the use hydraulic rotary drilling machines due to speed, accuracy or verticality and the possibility of identifying soil or rock layers easily with depth.

In the operation of bored piling, when drilling with short augers or buckets different types of tools such as soil auger, soil boring bucket, rock auger, rock boring bucket, core barrel, etc. are used depending on the soil or rock strata existing.

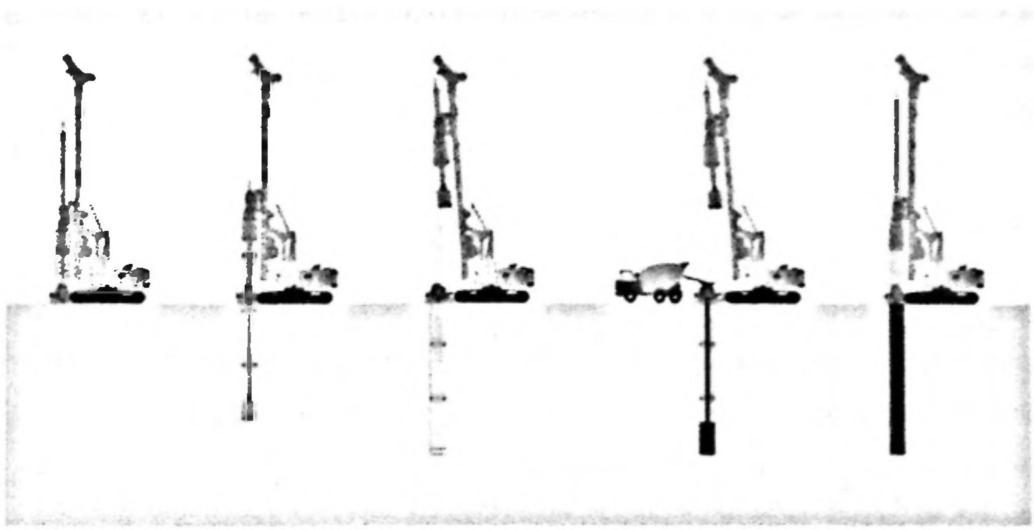
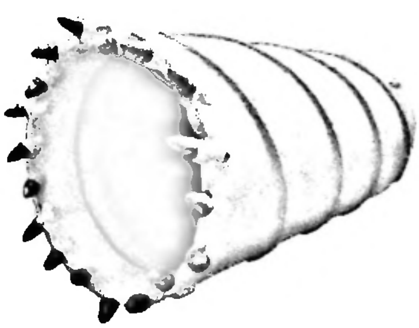
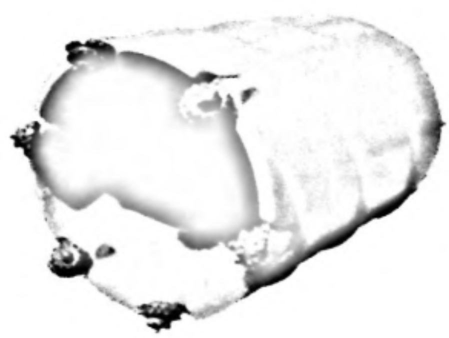


Figure 1.2 Different types of rock boring tools of comparison

Generally, the ground vibration is generating when drilling through rock layers, especially in hard rock layers. To penetrate the rock there are special types of buckets or augers used. Normally a tool called core barrel is used to cut the perimeter of the rock and a rock bucket or a rock auger is used to take out the drilled rock. In order to cut the rock a special part is attached to the core barrels, rock buckets or rock augers. Basically, it is called a "Bullet teeth" which is consisted with tungsten carbide tip. Another option available for bullet teeth is called the "Roller bits" which consists of Tungsten carbide tips and use a different mechanism from bullet teeth.



Core barrel bucket with "Bullet teeth"



Core barrel bucket with "Roller bit"

Figure 1.3 Different types of rock boring tools of comparison

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It is noticeable that the vibration generation during drilling in hard rock is less comparatively, when using Roller bits than in using Bullet teeth. Unfortunately, there are not many researches conducted in this area and less data or publications available both locally and internationally.

1.2 Research Problem

Ground borne vibration during bored and cast in-situ piling work can cause the cracks to form in neighboring buildings or dwellings due to either ground settlement with long term vibration or due to effect of vibration on the structure. This can become annoying for the neighboring community and eventually a great headache for the project management teams involve in piling work, due to continues complaints from the community and the additional cost for the rectification work of those third-party properties. Hence it is advisable to use the techniques which generates the less ground born vibration during bored piling. There are different techniques use in the industry but unfortunately less data available for comparison of techniques. But it is important to identify that the selected method or technique is financially feasible or will not increase the project cost drastically than the conventional method. And, it is important evaluate the time consumption of the new method in comparison of conventional method to identify that the new method will not affect the project duration unnecessarily.

1.3 Objectives

- To identify the effectiveness of using "Roller bit" buckets for bored piling operation to minimize ground vibration generation, instead of conventional use of "Bullet teeth" buckets, in Sri Lanka.
- To Identify the financial feasibility and effect on construction duration in using "Roller bit" buckets for bored piling operation instead of conventional use of "Bullet teeth" buckets.

1.4 Research Methodology

In order to achieve the above objective, the following research methodology has been adopted:

- A detail literature review has been carried out to investigate the data available for the ground vibration generation during bored piling operation with the rotary drilling machines worldwide. Further the data has been gathered on the details of both tools, "Bullet teeth" and "Roller bit" and their working principles. Also, the effect of vibration to the neighboring community, issues recorded, and the ways of the issues settled were studied.

- A field survey has been carried out to identify the situations that used "Roller bits" instead of "Bullet teeth" as ground vibration reduction measure in Sri Lanka. And a construction site was identified which adopted both types of tools (i.e. Bullet teeth & Roller bit) in two different phases of the same project.

- Geotechnical investigation report of the location was obtained and studied the soil or rock profile in the location. Also, the piling layouts were gathered in both phases of project and selected the same size of pile diameters for the study.

- Ground vibration monitoring data during bored piling operation, which was done by an "Independent testing agent" was obtained for the comparison of ground vibration generation in both cases.

- Operational data such as Rotary drilling machine types used, manpower usage, material usage, other items related to cost of the piling operation were gathered in both phases of project. Also, the cost of rectification work for third party properties or insurance claims were gathered to do a cost comparison of piling work in each phase.

- Operational data such as Rotary drilling machine types used, boring data records, bore log data was obtained to analyze the time consumption of pile boring operation when using each type of tool, either "Bullet teeth bucket" or "Roller bit bucket".

1.5 Main Findings

- Ground borne vibration when using Roller bits are slightly lower than when using Bullet teeth.
- Effectiveness of Roller bits is higher in comparison with Bullet teeth, in both cost involvement and minimizing public complaints because of ground vibration.

1.6 Research Organization

Structure of the research would be divided in to following chapters.

Chapter 1 – Introduction of the research problem, background of the problem, objective of research and the general methodology followed is presented in chapter 1.

Chapter 2 – A detailed literature review in related to research problem is included in this chapter. A detailed study in piling operation using rotary drilling machines, different types of tools & techniques used in bored piling operation, ground vibration generation and propagation, effects of ground borne vibration to human & structures and the levels of affect, etc. is included in this chapter.

Chapter 3 – Methodology adopted in the research program is described with the relevant data gathering procedures under this chapter. Further the selection procedure of piling site, processes of ground vibration monitoring, process of data gathering related to piling operation, process of cost and time calculation is described under this chapter.

Chapter 4 – Under the chapter 4, the cost and time consumption analysis for each phase based on per one-meter length of a pile is discussed. The assumptions made during data analysis process has been also summarized. Further the findings of the analysis process were also discussed under this chapter.

Chapter 5 – Conclusion of the research findings and the recommendations to adopt in related to the research problem has summarized here. Also, the possible areas for future studies in related to the same problem which were not covered under this study, has been summarized under this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 General

A considerable ground born vibration induces during the construction work. And becomes annoying for the neighboring communities. Hence the governments and the different engineering or policy making bodies of countries around world has introduce and certain limits for ground borne vibration and noise generates in construction works. International Standards Organization (ISO), British Standards Institute (BSI) UK are some of the organizations implementing standards or limits for vibration control in construction activities in the world and Central Engineering Authority (CEA) Sri Lanka is the local authority of implementing these limits or standards.

Ground vibration in construction activities basically occurs during excavation for foundations, piling work for foundations, sheet piling and other shoring works, blasting of rock, pile hacking or hacking of other concrete elements in ground level, backfilling or compaction work of soils, heavy machinery movement, etc.

This study is basically focus on the ground vibration generation during in-situ cast bored piling activities, since bored piling is becoming popular in the country and the bored piling operations mainly going on in highly urbanized areas.

In this chapter a detailed literature review has been done on the piling methods, bored and cast in situ piling operation, selection process of tools for pile boring work, ground borne vibration due to piling activities, propagation of vibration, vibration propagation variation with soil or rock strata available, field vibration measurement methods, limits of vibration level for human perception, limits of vibration level cause for structural damages and government or international standards or regulations on levels of vibration.

2.2 Ground Borne Vibration

Ground borne vibration is a technical term basically used to describe mostly man-made vibrations of the ground, in contrast to natural vibrations of the Earth studied by seismology. Vibrations caused by mining, blasting activities, construction works (in foundation work and heavy machinery movement), railway and road traffic, machinery and plants operating in industries, etc. are falling under this category.

It was recognized that, though the manmade ground vibrations can be severe and damaging, the levels of the ground strain involved usually much smaller than those associated with the strong motion of earthquakes. (Skipp, 1998)

Ground vibrations are in the form of different types of elastic waves, propagating through the ground, like in seismology. These can be categorized as surface waves, Rayleigh waves, bulk longitudinal waves and transverse waves (shear waves) propagating into the ground. Typical frequency range for environmental ground vibrations is 1 Hz – 200 Hz. Waves of lower frequencies (below 1 Hz) are usually called microseisms, like water waves in oceans. Ground vibrations generated by rail and road traffic may cause annoyance to residents of nearby buildings both directly and via generated structure borne interior noise. Very strong ground vibrations like vibrations generated by heavy machineries may even cause structural damage to very close and sensitive buildings. (Skipp, 1998)

Magnitudes of ground vibrations are usually described in terms of particle vibration velocity (in mm/s or m/s). Also they are described in decibels (relative to the reference particle velocity of 10^{-9} m/s). For example values of ground vibration (peak particle velocity) associated with vehicles passing over road humps are in the range of 0.1 mm/s – 2 mm/s. (Skipp, 1998). Magnitudes of ground vibrations that are considered to be able to cause structural damage to buildings are above 10 mm/s –20 mm/s and depend on the condition of building. If the frequency of horizontal soil vibrations to a building's natural frequency may generate the resonance in that building. And mostly vertical ground vibrations can cause foundation settlements (Richart, 1970).

2.3 Ground Vibration Due to Construction Activities

The main sources of ground vibrations in construction industry are pile driving, dynamic compaction, blasting, and operation of heavy construction equipment. These vibrations may harmfully affect surrounding buildings, and their effect ranges from disturbance of residents to visible structural damage.

Ground borne vibration from heavy construction works; specially piling works has the potential to adversely affect the nearby receivers. The potential impacts can be disturbance to human and animal occupants (between vibration levels 1 mm/s - 5 mm/s), or concern regarding building or infrastructure damage (between vibration levels 5 mm/s - 50 mm/s). (Kym burgemeister, Kai fisher & Kathey franklin, 2011). Construction vibration guidance (Construction noise strategy,2007) of Australia suggests appropriate distances of between 2m -25m are adequate to control vibration to prevent building damage, although they may not be sufficient to ensure to avoid disturbance to human perception. (Kym burgemeister, Kai fisher & Kathey franklin,2011).

Impact hammers are one of the common sources generating construction vibrations. Maximum rated energy of the commonly employed piling hammers varies from 5 kJ to 200 kJ per blow. Vibrations with high frequencies of about 300 Hz -700 Hz are generated by the hammer-cushion system. Frequencies of natural longitudinal pile oscillations are in the range of 7 Hz -50 Hz. Maximum pile velocity and displacement values range from 0.9 m/s - 4.6 m/s and 12 mm - 35 mm, respectively. Both parameters depend on pile type and hammer transferred energy. Displacement can be affected by soil conditions also (Svinkin, 1992).

In dynamic compaction of loose sands and granular fills, a large steel or concrete weight of 49.1 kN - 137.3 kN is used to dropped from a height of 15 m - 30 m. This dynamic impact can generate surface waves with a frequency of 3 Hz to 12 Hz. Dynamic deep compaction is also can consider as a source of intensive low frequency ground vibrations (Mayne, 1985).

The dominant frequency of propagating waves from quarry and construction blasting ranges mostly between 10 Hz - 60 Hz. In general, energy in rock blasting is much larger than energy of other sources of construction work related ground borne vibrations. For an example, energy released by 0.5 kg of TNT is about 5400 kJ. Such energy is 50 - 1000 times the energy transferred to piles during driving and 15 - 80 times the energy transferred to the ground during dynamic compaction of soils. (Mayne, 1985).

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2.4 Vibration Propagation

Vibration in soil can propagate in the form of various types of waves, propagating both on the surface of the soil and from deep trough the soil or rock. Generally, these different wave types travel at different speeds. Close to the source, it is expected that all forms of vibration will be important, but at larger distances, typically in hundreds of meters, the relative levels of these vibrations can vary depending on the soil type. This is mainly because of that the different types of waves attenuated at different rates due to their differences in speed and propagation methods.

Sources of construction vibrations generate compression waves, shear waves and Rayleigh waves. Rayleigh waves are the surface waves that contain roughly 70 % of the total vibration energy and become predominant over other wave types at comparatively small distances from the vibration source. For example, pile driving from depths between 4 and 10 m will generate Rayleigh waves within 0.4 m to 3 m of the pile, depending on the propagation velocities of Rayleigh and compression waves. (Richart et al, 1970).

Soil vibrations are mostly vertical near the source of vertical impact loads, but as distance increases, vertical and horizontal soil vibrations become similar in magnitudes and for some locations at the ground surface, the amplitude of horizontal vibrations might be up to3 times greater than that of vertical vibrations. Waves travel in all directions from the source of vibrations forming a series of harmonic waves with the frequency equal or close to the frequency of the source. In general, faster attenuation of high frequency components is the primary cause of changes of soil vibrations with distance from the source. However, it is not possible to explain all the cases by this mechanism and the effect can vary with the uncertainties of the geological profile (Sinking, 1996).

There are two mechanisms that attenuate vibration as it propagates through the soil. They are, “Geometric loss” (attenuation is modeled by geometric spreading to match empirical data) and “Material loss” (attenuation is modeled by frictional loss in the soil to match empirical data). Geometric loss is due to the spreading of waves as they propagate out from the source. The rate of loss depends on the type of wave. Material loss is due to viscous behavior of the soil and is a loss per unit distance travelled. Generally, the attenuation increases with increasing frequency (Woods & Jedele, 1985).

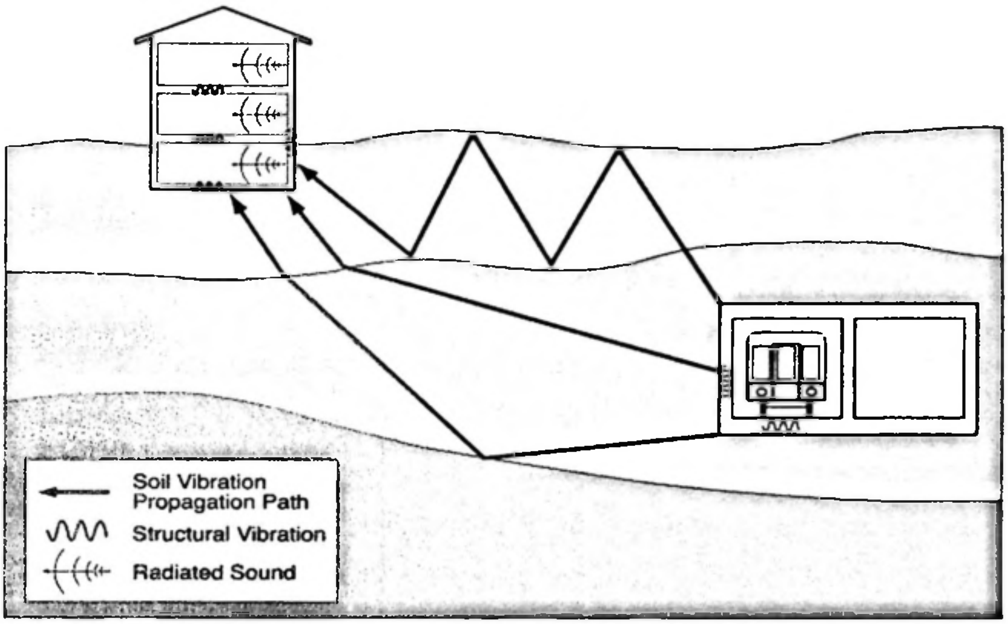

Figure 2.1 Propagation of ground borne vibration into buildings

Vibration levels are generally higher in stiff clay-type soils than in loose sandy soils. In rock layers, vibration levels are usually high near at-grade track when the depth to bedrock is 30 feet or less. Vibration level does not attenuate as rapidly in rock as it does in soil because of efficient propagation. Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics. The presence of the water table also might have an effect on ground-borne vibration propagation, but a definite relationship has not been established (Woods & Jedele, 1985).

2.5 Construction Vibration Site Measurements

The necessity for structures to sustain vibration is increasingly recognized and requires consideration both in the design for structural integrity, serviceability and environmental acceptability, and in the preservation of historic structures.

Method for vibration monitoring is described in ISO 4866. 1990 and in the second edition published in 2010.

As per mentioned in (ISO 4866,1990) measurement of vibration in or nearby a structure is carried out for a variety of purposes such as,

a) Problem recognition, where it is reported that a structure is vibrating at such a level as to cause concern to occupants and equipment, possibly making it necessary to establish whether the levels warrant concern for structural integrity.

b) Control monitoring, where maximum permitted vibration levels have been established by an agency and those vibrations must be measured and reported.

c) Documentation, where dynamic loading has been recognized in design, and measurements are made to verify the predictions of response and provide new design parameters (These may use ambient or imposed loading. Strong motion seismographs, for example, may be installed to indicate whether the responses to earthquake warrant changes on operating procedure in a structure).

d) Diagnosis, where it has been established that vibration levels require further investigation, measurements are made in order to provide information for mitigation procedures (another diagnostic procedure is to use structural response to ambient or imposed loading to establish structural condition, e.g. after a severe loading, such as an earthquake).

As per (ISO 4866,1990) classification of events according to their duration can be identified as follows;

a) Permanent - the source emission is permanent or quasi-permanent during the selected reference interval.

b) Intermittent - a succession of events, each of relatively short duration, is separated by irregular intervals during which the vibration amplitude is equivalent to the background level.

c) Single occurrence - sources generating vibration events, which are of short duration (a few seconds) and which can occur only once. Single occurrences do not exceed five per day.

Classification of events according to the variation of their amplitude with time can be done as follows;

a) Stable - the variation of the amplitude with time does not exceed 10 %.

b) Cyclic - repeated events with the same magnitude occur.

c) Other events - "Other" events cannot be classified as stable or cyclic.

Classification according to the category of signals emitted by the source can be identified as,

a) stationary (e.g. generators)

b) non-stationary (e.g. trains)

c) transient or impulsive vibrations with separated (e.g. blasting) or repeated impulses (e.g. forging hammers).

peak particle velocity (p.p.v.) the maximum instantaneous velocity of a particle at a point during a given time interval, and should be measured with the related frequency for p.p.v.

2.6 Effect of Ground Borne Vibration on Buildings

Generally, type of foundation, ground condition underlying, condition of the building affects the response of a building to ground borne vibration. Interaction between ground and the foundation of the building has a major effect on building response. The soil condition or the soil layers between the vibration source and the building also can affect the input frequency spectrum to the building. In general, higher input frequencies developed in hard ground conditions. stiffer foundations result in higher natural frequencies of the building-soil system. The strain imposed on a building at foundation level is proportional to the p.p.v. of the wave but is inversely proportional to the propagation velocity of the shear or compression waves in the ground (New B.M, 1986).

Building damage due to soil compaction Depending upon the type of ground. ground vibration can cause consolidation or densification of the soil, which can be led to differential settlement and building damage as a result. Loose and water saturated cohesionless soils are vulnerable to vibration which can cause liquefaction. (Dowding C.H., 1986).

For a building not exposed to major external disturbances such as vibration, there exists a time rate of cracking due to natural ageing. This natural cracking rate can be significantly increased by an external disturbance triggering cracks instantaneously, which can only be detected by a survey of building cracks immediately before and after the disturbance. A small increase in cracks or crack length however should not be taken as damage due to any imposed vibration. Buildings also expand and contract preferentially along existing weaknesses (cracks) between daytime and night-time and also seasonally. This continually varying expansion and contraction will return normal repair and repainting to the previous cracked state within several years or even months (Dowding C.H., 1986).

2.7 Building Classification

Before introducing the vibration standards for the operation of machinery blasting activities, construction activities & vehicle movements, it is necessary classify the building structure as the vibration affects in accordance with the nature of the nearby structure. Building that have been built-up in Sri Lanka could be categorized into the following categories in accordance with the ISO 4866:1990 (E) standards. Please note that the following categorization of buildings has been adopted in introducing the vibration standards for all cases. However, it is noteworthy to mention here that even though the classification of buildings given by the International Standards are almost the same, the same categories have been divided into subcategories to suit the Sri Lankan situation. The categorization is as same in the classification published by the

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Central Environmental Authority of Sri Lanka under "Amended ABOP standards,2008".

Table 2.0.1: Categorization of structures according to the type of building (from ISO-4966: 1990E)

Category of the structure	Description
Type 1	Multi story buildings of reinforced concrete or structural steel, with in filling panels of block work, brick work or precast units not designed to resist earthquakes
Type 2	Two-story domestic houses & buildings constructed of reinforced block work, precast units, and with reinforced floor & roof construction, or wholly of reinforced concepts or similar, not designed to resist earthquakes
Type 3	Single and two-story houses & buildings made of lighter construction, using lightweight materials such as bricks, cement blocks etc., not designed to resist earthquakes
Type 4	Structures that, because of their sensitivity to vibration, do not correspond to those listed above 1,2 & 3, & declared as archeologically preserved structures by the Department of Archaeology

Table 2.0.2: Tolerable limits of vibration

Category of the structure as given in Table 1.1	Type of Vibration	Frequency of Vibration (Hz)	Vibration in PPV (mm/Sec.)
Type 1	Continues	0 -10	5.0
		10 - 50	7.5
		Over 50	15.0
	Intermittent	0 -10	10.0
		10 - 50	15.0

		Over 50	30.0
Type 2	Continues	0 -10	2.0
		10 - 50	4.0
		Over 50	8.0
	Intermittent	0 -10	4.0
		10 - 50	8.0
		Over 50	16.0
Type 3	Continues	0 -10	1.0
		10 - 50	2.0
		Over 50	4.0
	Intermittent	0 -10	2.0
		10 - 50	4.0
		Over 50	8.0
Type 4	Continues	0 -10	0.25
		10 - 50	0.5
		Over 50	1.0
	Intermittent	0 -10	0.5
		10 - 50	1.0
		Over 50	2.0

Apart from that there are buildings that are more sensitive to vibration may not fallen into above categories. For example, laboratory buildings for Nano science, electronics lithography, or high magnification electron microscopy or imaging are significantly more sensitive to vibration than above mentioned categories. these types of buildings are commonly designed to achieve internal vibration levels between 3 µm/s - 25 µm/s. (Unger et al., 1990)

2.8 Public Nuisance

In contrast to airborne noise, ground-borne vibration is not a phenomenon that most people experience every day. The background vibration velocity level in residential areas is usually 50 VdB or lower, well below the threshold of perception for humans which is around 65 VdB. Most perceptible indoor vibration is caused by sources within buildings such as operation of mechanical equipment, movement of people or slamming of doors. The relationship between ground-borne vibration and ground-borne noise depends on the frequency content of the vibration and the acoustical absorption of the receiving room. Quantifying Human Response to Ground-Borne Vibration and Noise One of the major problems in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration, human annoyance with building vibration.

The American National Standards Institute (ANSI) developed criteria for evaluation of human exposure to vibration in buildings in 1983 and the International Organization for Standardization (ISO) adopted similar criteria in 1989 and revised them in 2003. The 2003 version of ISO 2361-2 acknowledges that "human response to vibration in buildings is very complex." It further indicates that the degree of annoyance cannot always be explained by the magnitude of the vibration alone. In some cases, the complaints are associated with measured vibration that is lower than the perception threshold. Other phenomena such as ground-borne noise, rattling, visual effects such as movement of hanging objects, and time of day (e.g. late at night) all play some role in the response of individuals. To understand and evaluate human response, which is often measured by complaints, all these related effects need to be considered.

According to (Transportation and construction vibration guidance manual,2013) released by California Department of Transportation, summary of numerous studies conducted to characterize the human response to vibration are presented in following tables.

Table 2.3: Human Response to Steady State Vibration

PPV (in/sec)	Human Response
3.6 (at 2 Hz)–0.4 (at 20 Hz)	Very disturbing
0.7 (at 2 Hz)–0.17 (at 20 Hz)	Disturbing
0.10	Strongly perceptible
0.035	Distinctly perceptible
0.012	Slightly perceptible

Table 2.4: Human Response to Continuous Vibration from Traffic

PPV (in/sec)	Human Response
0.4–0.6	Unpleasant
0.2	Annoying
0.1	Begins to annoy
0.08	Readily perceptible
0.006–0.019	Threshold of perception

Table 2.5: Human Response to Transient Vibration

PPV (in/sec)	Human Response
2.0	Severe
0.9	Strongly perceptible
0.24	Distinctly perceptible
0.035	Barely perceptible

The results in Tables 2.3 – 2.5 suggests that the thresholds for perception and annoyance are higher for transient vibration than for continuous vibration.

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2.9 Piling

Piles are the most used type of deep foundations where vertical distribution of the load takes place. There are different types of piles and they can be classified based on the type of the material of piles, method of installation or the amount of soil displaced during installation of the pile. As the geotechnical and structural performance of the piles largely depend on the method of installation, classification of the piles based on the method of installation is very common. (Thilakasiri, 2009)

Following the classification of the piles based on the method of installation, piles can be grouped into the following categories:

1. Bored and cast in situ piles
2. Driven and cast in situ piles
3. Driven piles
4. Jacked piles
5. Screw piles
6. Excavated cast in place piles
7. Continuous flight augured grout and concrete injected piles
8. Jetted piles

In this research it is focused on the bored and cast in situ piles. A bored and cast in situ pile is constructed by drilling a hole into the ground with or without a casing and filling the hole with concrete after inserting a reinforcement cage. Currently the most common method using for drilling is the use hydraulic rotary drilling machines due to speed, accuracy or verticality and the possibility of identifying soil or rock layers easily with depth. In the operation of bored piling, when drilling with short augers or buckets different types of tools such as soil auger, soil boring bucket, rock auger, rock boring bucket, core barrel, etc. are used depending on the soil or rock strata existing. (Thilakasiri, 2009)

2.10 Comparison of Tools

Installation of bored piles diameters, usually from 450mm to 3000mm into rock formations can be carried out using conventional rotary drill tools, air roller core

TH 4273

barrels or cluster drills. All methods can be used in dry conditions (dry boring) or under drilling fluid (usually bentonite or polymer). When drilling with cluster drills under fluids it is critical to apply a suitable backpressure to the cluster drill in order to prevent drilling fluid from entering the pistons of the individual hammers, which will cause increased wear and tear or unrepairable damage of the same. Removal or collection of rock cutting can be done using boring or cleaning buckets as required. For air roller core barrels or cluster drills calyx baskets (spoil baskets) will be utilized which are commonly placed on top of the drill barrel. Calyx baskets needs to be emptied from drill cuttings for every 1m to 3m of drilling. Alternatively, reverse-circulation-drilling (RCD) methods can be adopted which will enable the drill tool to penetrate the rock in one bite without lengthy extraction periods to empty the calyx baskets. Particularly for deep excavations RCD is an attractive option to optimize drilling times on site (Larisch, 2012).

2.11 Selection of Suitable Drill Tools for Bored Piles

In rock drilling, it can be noted that the higher the energy input into a unit volume of rock, the more penetration is expected of an appropriately selected sharp cutting tool. For conventional drill tools, it can be stated that with increasing pile diameters the number of required drill bits have to increase proportionally. As a result, the individual drill bit pressure decreases, if the vertical thrust of the piling rig remains constant. Thus, drilling with conventional tools is limited by the maximum vertical thrust and will rapidly become uneconomical in rock strengths exceeding 100 MPa However, in certain rocks with compressive strengths around 50MPa and more, alternative drilling techniques, generally beyond the capabilities of the conventional tools, can be used to achieve more economical production rates. Hard rock drilling using air roller core barrels and cluster drills to penetrate hard rock with UCS even greater than 100 MPa, which is beyond the capabilities of the conventional drill tools for rocks of the order of 50 to 100 MPa compressive strength. Not only the compressive rock strength (UCS), but also the degree of fractures and number of joints in the rock mass as well as the material's resistance to tensile, frictional, shear and abrasive forces are also factoring that influence both rock drilling ability and durability of the tool (Larisch, 2012).

In considering a typical core barrel with bullet teeth, there are three force components acting on a single bullet tooth bit, which are the vertical thrust force (V) normal to cutting direction, a cutting force (C) along the cutting direction, and a lateral force (M*) normal to the plane going through V and C. The torque (M) is normally proportional to the cutting force (C); M = C * lever arm length (drill tool radius). The process strongly relies on applying enough rotary torque M and pull-down force (thrust) V at a constant rotation of the drill tool. This is important to maintain an adequate bit pressure for effective cutting action. The ratio $V / M \approx 0.5$ for soil and low strength rock meaning that M has more impact than V when using conventional techniques with bullet teeth (drag picks). If the applied thrust (V) and rotary torque (M) are insufficient, the bullet teeth won't be able to bite and break the rock into cuttings or chips; instead it will produce fine grinding particles, resulting in low penetration rates and high bit wear. (Larisch, 2012)

If the rock strength is too high for conventional drill tools, the energy transferred from the drill bit into the ground won't be enough to produce an adequate fracturing stress field at the rock surface where the carbon tungsten tip of the bullet tooth is in contact with the rock. Instead of cutting and producing large chips, tool blunting and rock grinding will occur. Increasing the thrust (V) and torque (M) will only increase the risk of damaging the machine and breaking off the tungsten carbide bits. Hence alternative drill methods should be considered when encountering harder and tougher rocks. Roller bit core barrels are designed to operate on the principle of cutting by thrust indentation and shearing rotation, also called the "twisting and tearing" method resulting in a "rock crushing" mechanism depending on the rock strength and other rock characteristics. A roller bit core barrel consists of cone shaped roller bits at the bottom end in different angles and directions. Each roller bit is fitted with a series of tungsten carbide tips. The roller bit core barrels are used to cut an annulus into the rock mass by applying vertical thrust V and rotational torque M. The number of rollers must be matched with the barrel diameter and the rotational speed of the drilling operation. After cutting core can be removed using boring bucket or rock augers (Ale ossein and Hood, 1996).

Air roller core barrels work using the "twisting – tearing" principle in rock formations with compressive strength (UCS) ranging from about 50 to 100MPa. The roller is usually fitted with tungsten carbide drill buttons which will cut into the rock as it rolls along. It is important to apply enough thrust force V for biting or indentation as well as cutting force through the rotational torque M to produce sufficient damaging stress in the rock resulting in cracks and chips at the contact area between the drill button and the rock face. While entering the rock face, the material in front and below the button will be initially compressed by loading. However, on the way out of the ground the drill button will loosen the material and lift out the chip (Ale ossein and Hood, 1996).

2.12 Chapter Summary

In this chapter a detailed literature review has been done on the piling methods, bored and cast in situ piling operation, selection process of tools for pile boring work, ground borne vibration due to piling activities, propagation of vibration, vibration propagation variation with soil or rock strata available, field vibration measurement methods, limits of vibration level for human perception, limits of vibration level cause for structural damages.

Ground borne vibration is a technical term basically use to describe mostly man-made vibrations of the ground. It was recognized that, although man made ground vibrations can be severe but usually much smaller than those associated with the strong motion of earthquakes. Ground borne vibration from heavy construction works, specially piling works has the potential to adversely affect the nearby receivers.

Soil vibrations are mostly vertical near the source of vertical impact loads, but as distance increases, vertical and horizontal soil vibrations become similar in magnitudes, and, for some locations at the ground surface, the amplitude of horizontal vibrations might be up to three times greater than that of vertical vibrations.

the relative levels of these vibrations can vary depending on the soil type. This is because different types of waves are attenuated at different rates due to their differences in speed and propagation methods. Vibration levels are generally higher in stiff clay-type soils than in loose sandy soils.

The necessity for structures to sustain vibration is increasingly recognized and requires consideration both in the design for structural integrity, serviceability and environmental acceptability, and in the preservation of historic structures. Method for vibration monitoring is described in ISO 4866, 1990 and in the second edition published in 2010.

As per (ISO 4866,1990) classification of events can be identified as follows;

Classification according to the category of signals emitted by the source can be identified as,

a) stationary

b) non-stationary

c) transient or impulsive vibrations with separated or repeated impulses

And classification of events according to their duration as,

a) Permanent

b) Intermittent

c) Single

According to (Transportation and construction vibration guidance manual,2013) released by California Department of Transportation, the human response to vibration are presented in table 2.4 for steady state vibrations.

Building that have been built-up in Sri Lanka could be categorized into the following categories in accordance with the ISO 4866:1990 (E) standards. The categorization is as same in the classification published by Central Environmental Authority of Sri Lanka under "Amended ABOP standards,2008". The classification is presented in table 2.1 and table 2.2.

In this research it is focused on the bored and cast in situ piles and the ground borne vibration generates from it. A bored and cast in situ pile is constructed by drilling a hole into the ground with or without a casing and filling the hole with concrete after inserting a reinforcement cage. Currently the most common method using for drilling is the use hydraulic rotary drilling machines. In the operation of bored piling, when drilling through rock, different types of tools are used such as rock boring bucket, core barrel, cleaning bucket etc. Mostly the vibration generates in the process of cutting the rock using core barrels.

In the comparison of the two tools in consideration, it is important to identify the principle of rock drilling in each tool type. Generally, "Roller bit" core barrels are designed to operate on the principle of cutting by thrust indentation and shearing rotation, also called the "twisting and tearing" method which also can identify as a "grinding" method, resulting in a "rock crushing" mechanism depending on the rock strength and other rock characteristics. In consideration of a typical core barrel with bullet teeth, the principle of cutting is by thrust indentation, which can be called the "tearing" method. The process strongly relies on applying torque M and pull-down force (thrust) V at a constant rotation of the drill tool. It is important to maintain an adequate bit pressure for effective cutting action.

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CHAPTER 3: METHODOLOGY

3.1 General

The methodology adopted to achieve the following objectives is elaborated in this chapter.

- To identify the effectiveness of using "Roller bit" buckets for bored piling operation to minimize ground vibration generation, instead of conventional use of "Bullet teeth" buckets, in Sri Lanka.
- To Identify the financial feasibility and effect on construction duration in using "Roller bit" buckets for bored piling operation instead of conventional use of "Bullet teeth" buckets.

Basically, the research plan, data collecting procedures and data analyzing methods adopted is described under this chapter.

3.2 Research Plan

The followed methodology of the research work after doing the literature survey can be summarized as follows:

- A field survey has been carried out to identify the situations that used "Roller bits" instead of "Bullet teeth" as ground vibration reduction measure in Sri Lanka. And a construction site was identified which adopted both types of tools (i.e. Bullet teeth & Roller bit) in two different phases of the same project.

- Geotechnical investigation report of the location was obtained and studied the soil or rock profile in the location. Also, the piling layouts were gathered in both phases of project and selected the same size of pile diameters for the study.

- Ground vibration monitoring data during bored piling operation, which was done by an "Independent testing agent" was obtained for the comparison of ground vibration generation in both cases.

• Operational data such as Rotary drilling machine types used, manpower usage, material usage, other items related to cost of the piling operation were gathered in both phases of project. Also, the cost of rectification work for third party properties or insurance claims were gathered to do a cost comparison of piling work in each phase.

• Operational data such as Rotary drilling machine types used, boring data records, bore log data was obtained to analyze the time consumption of pile boring operation when using each type of tool, either "Bullet teeth bucket" or "Roller bit bucket".

3.3 Selection of Site

In the process of identifying the location or the piling construction site, few major piling contractors were contacted in Sri Lanka. And the following factors were considered during the process of selection of the location.

1. Ground borne vibration during bored piling and the propagation of vibration will be vary based on the ground soil or rock condition. Hence the comparison should be done in a condition where both tools should apply in locations where geotechnical condition is more similar.
2. Ground borne vibration can be changed based on the capacity and type of Rotary drilling machinery used. In a condition where similar machinery is used for both cases considered, the accuracy of the data is much higher.
3. The level of damages reported can be varied with the neighboring community of different site locations. The structures in the surrounding environment of the site location also affect the level of damages that can report due to effect of vibration. In a location where the conditions are similar for both cases, the third-party damage compensation can be more similar.

With the above considered factors, a piling construction site was found where both tool types considered under this study are used in the same project in two different phases of project. Location plan of site, location plan of the two different phases are attached in Annex A.

3.3.1 Diameter of piles selected

In the both phases the diameter of piles were 1000mm piles. In phase 3, the first phase where "Bullet teeth" tools were used there are a total of 185 piles were bored and casted in-situ. And in Phase 4, there were 181 number of piles with 1000mm diameter which was drilled by using "Roller bit" tools. Layouts of pile locations in each phase are annexed under Annex B.

3.3.2 Type of machinery used

Bauer BG25 type Rotary drilling rigs were used for the boring work of piles. And in both phases considered, four number of piling machines of type BG25, were used for boring of piles. The specification of the rotary drilling rig is attached in Annex D.

In phase 3, the boring tools were equipped with "Bullet teeth" and in phase 4, the tools were equipped with "Roller bit". The specification of the "Bullet teeth" & "Roller bit" are annexed in Annex D.

3.3.3 Geotechnical condition

Since the location of different phases considered for piling are in the same land are which is very close to each other, the geotechnical condition (i.e. the water level, different types of soils & depths, weathered or hard rock levels, types or hardness of rock) is considered same in both phases. Bore hole locations and the borehole data related to both locations are attached in Annex B.

3.3.4 Neighboring third party properties

The neighboring community or the properties can be considered as same for both phases considered since both the phases are in close proximity and belong to the same land or owner. The buildings or the community surrounded are varying from low cost houses to multi-story apartments. In the beginning of the project a pre-construction survey was carried out by the project management team for a perimeter of 50m approximately to cover the third-party properties in surrounding area. The surrounding property or building details & the layout of preconstruction survey done on third party properties are annexed under Annex C.

3.4 Collection of Data Related to Piling Work

In collection of data for the site operation of piling work in both phases, it was divided in to two categories as,

1. Operational data related to cost
2. Operational data related to time

3.4.1 Data related to cost

The data related to cost were further divided in four subcategories as follows;

1. Cost of materials/ machinery – Bentonite, Concrete, Bullet teeth or Roller bit, reinforcement, wearing and tearing cost for machinery or buckets, water, etc.
2. Cost of manpower
3. Cost for other utilities – Water, Electricity
4. Cost of rectification work for third party properties

Site store records, bill of quantities, utility bills, manpower records, machinery breakdown and repair work records and third-party property rectification reports in both phases were referred to collect the data related to above categories. When calculating the cost for comparison, average cost of a pile is considered.

3.4.2 Data related to time

In consideration of data related to time consumption, few factors were identified as follows;

1. Penetration rate in soil or rock boring
2. Machine capacity or the torque provided
3. Skill level of workers
4. Rate of bentonite supply
5. Time taken for tool changing process
6. Time taken for tool repairs
7. Rotary drilling machine breakdown time

From above factors soil or rock boring time can be considered as the varying factor since all the other parameters are same due to selection of same location for both cases.

Tool changing, bentonite or any other type of drilling fluid supply, operating skill is considered as similar in both cases since the working staff is basically same for both phases. Tool repairing was considered as similar for both cases, since the repairing work was done in outside workshops. The principle or the method of repairing both types of tools was more over similar which takes same time consumption basically. Machine capacities were same in both phases, as described in section 3.2.2

The detail sheet recording the summary of pile boring time, soil layers, rock layers and total boring depth called "Pile boring record sheet" for each pile were collected and summarized the details. The time taken for soil boring, weathered rock boring and hard rock boring was analyzed and obtained the average time taken for each case in both phases.

3.5 Calculation of Cost Variance

In calculation of cost variance, the following factors were omitted with the reasons or assumptions as noted.

Cost of "Bentonite drilling fluid" – it was noted that the average pile depths are more over similar in both phases with the boring record summary obtained. Since the selected pile diameter also same in both phases compared, the volume of bentonite supply can be considered as same for both phases. Hence the cost of "Bentonite supply" can be omitted from the comparison.

Cost for machinery including repair cost – Since the both phases considered were completed within recent years without much gap between the operations, the rental cost considering in pricing has taken as same for both phases. Machine breakdown time has taken from the site record and was noted that the breakdown time is slightly less when using "Roller bit" but more over similar in both cases. Since the nature of the breakdowns were similar when looking at the summary of breakdowns, it was assumed that the costs of breakdown repairs are similar in both phases.

Cost of manpower – Manpower records were compared in both phases and found that the quantity and quality of manpower used in both phases were similar. The reason for this was the nature of site, client or consultant's requirement, number of rotary drilling machines and other supporting machines such as cranes or excavators and number of piles were similar in both phases in consideration, the manpower requirement was remained same in both phases. It was assumed that the no increments in salary levels for the considered period of piling in both cases.

Cost of tool repair works – There were two different type of rock coring mechanisms used in two phases considered. But the basic tools which can be identified as soil boring bucket, rock boring bucket, core barrel and cleaning bucket as similar in both cases. Though the drilling mechanism is different, the tool repairing time and method were basically same and same capacity of labor, machinery or material is required. Based on above observations, it was assumed that the cost of tool repair works is same for both phases and omitted from the comparison.

Cost of other utilities – Cost of other utilities were identified more over similar in both cases and omitted from the comparison based on few observations. The summary of utility bills was compared in identifying the above factor. Basically, the duration of piling operation and quantity of work was same in both cases, hence the consumption of water or electricity were same.

With the omission of above factors affecting cost of work, below key factors were selected for the comparison of cost between two methods.

1. Cost of "Bullet teeth" & cost of "Roller bit" for each phase
2. Cost of rectification work for third party properties in each phase

In order to find out the cost of "Bullet teeth" of cost of "Roller bit", site consumption records and the material purchasing invoices were obtained. And for the rectification cost of each phase, payment records for rectification work were extracted from the interim payment certificates. For the comparison, cost for a pile is calculated based on above two parameters.

3.5.1 Cover on property damages due to vibration by the Insurance policy

The third-party damage rectification costs were not agreed to pay by the insurance company which provided the "Contractor's all risk policy" on behalf of the contractor, to the project. Under the clause, "Damage to any property or land or building caused by vibration or by the removal or weakening of support or injury or damage to any person or property occasioned by or resulting from any such damage" of special extrusions to "Third party liability" of "Contractors all risk policy" obtained for piling construction work, the damages occur due to the vibration was no covered by the insurance company. A comparison was done on several insurance policies provided by different insurance companies in Sri Lanka to identify the above fact and all the companies have included the above exclusion in their insurance policies under "Third party liability".

3.6 Calculation of Time Variance

In calculation of time variance, the following factors were omitted with the reasons or assumptions as noted.

Machine capacity – Since same type of rotary drilling machines were used in both phases, the capacity of torque provided for drilling can be considered same and were omitted from the comparison. In both phases "Bauer, BG 25" type rotary drilling machines were used.

Skill level of workers – The skill level of Boring rig operators & other staff was considered similar in both cases since the operation was done by the same team in both phases. And the quantity of labor used in each phase also were more over similar.

Rate of "Bentonite" drilling fluid supply – It was assumed a continues drilling fluid supply in both phases as per the drilling requirement at site. And no delays in pile boring work due to delay in bentonite supply. The assumption was based on few factors such as same number of bentonite silos were used, same manpower capacity was used for bentonite supply and continues supply of water for bentonite mixing work at site in both phases.

Time taken for tool changing process – The time taking for tools changing process in pile boring work is a considerable factor with time consumption. But since the same processes and procedures were used by the same team of workers in both phases, this can be omitted when comparing the time consumption in both phases.

Time taken for tool repairs – Tool repairing time has considered as same for both phases since the basic principles or methods were same in both phases, as described in section 3.5.

Rotary drilling machine breakdown time – Machine breakdown summary was obtained from site and made a comparison of the affected for piling operation due to machine breakdowns. And it was observed that the idling time due to machine breakdowns were slightly less in using Roller bits but almost similar in both cases. Hence this factor was omitted from the comparison of time consumption for piling operation. The summary of machine breakdown records is annexed in Annex C.

With above observations and assumptions made, it was decided to focus mainly on the penetration rate of rock which was obtained from the "pile boring records" of site. And the data was summarized in a tabular form for the comparison. The summary of boring records is annexed in Annex A.

3.7 Field Vibration Monitoring

Ground vibration monitoring data during bored piling operation, which was done by an "Independent testing agent" was obtained for the comparison of ground vibration generation in both cases. The monitoring locations were same in both phases and the locations were basically covered the total perimeter of the land. The piling locations were captured in the reports with each report produced. It was assumed that the location of piling of rotary drilling machines since the piling was done all over the land and the complaints were generally made all over the period of project duration.

3.7.1 Instruments used

Instantel Blastmate iii is the instrument used for the monitoring of ground vibration of the project. Method for vibration monitoring described in ISO 4866: 1990 has used for the recording of ground vibration during bored piling. Peak particle velocity (ppv) is measured and the minimum detection limit set was 0.07mm/s. Frequency of the vibration also measured and recorded by the same instrument.

3.7.2 Summary of vibration monitoring results

Vibration field monitoring data was obtained for a month which the works assumed to was in peak and summarized for each phase. In assuming the month of peak progress at site cashflow data or was analyzed during the period of project. The summery of vibration results is tabulated in section 4.6.

3.8 Complaint Registry

The registry maintained by the safety department of the project team to record the public complaints, complaints reported to police and the actions taken by the project team was obtained. The details were summarized for the identification of public response due to vibration generation or the property damages. The summary of complaint registry is annexed in Annex F.

3.9 Questionnaire Survey from The Client Project Management Team

A questionnaire was given to the project management team of the client or the developer of the project. The experience and the observations made by the client was analyzed based on the questionnaire sheet. This questionnaire basically in three sections. Section 1 focused on the experience of the client on the ground vibration levels and the complaints from the public. The section 2 questions on the third-party property rectification work. Section 3 mainly focused on the cost of rectification and the insurance policy provided. The questionnaire answered by the Project manager or the client is attached in Annex G.

3.10 Chapter Summary

followed methodology of the research work after doing the literature survey can be summarized as follows:

A field survey has been carried out and a construction site was identified which adopted both types of tools (i.e. Bullet teeth & Roller bit) in two different phases of the same project.

Geotechnical investigation report and piling layouts were gathered in both phases of project and selected the same size of pile diameters for the study.

Ground vibration monitoring was obtained for the comparison of ground vibration generation in both cases.

Operational data related to piling boring work were gathered in both phases of the project. In collection of data for the site operation of piling work in both phases, it was divided in to two categories as operational data related to cost and operational data related to time.

The registry maintained by the safety department of the project team to record the public complaints, complaints reported to police and the actions taken by the project team was obtained.

The experience and the observations made by the client was analyzed based on the questionnaire sheet.

CHAPTER 4: DATA ANALYSIS AND RESEARCH FINDINGS

4.1 General

In general, the analysis of data has been done in focusing to the two objectives stated in section 1.3. The selected site was in an urbanized area. And the effects of site location and the piling locations are described under section 4.2.

Basically, the ground vibration data obtained through third party ground vibration monitoring records were summarized and analyzed the levels of vibration in each case. The complaint registry data was analyzed get verified the effect of vibration on the neighboring community which gives a clue on reasons for third party property rectification.

A detail analysis has done on the data related to cost of the piling work. And mainly focused on the cost of "Bullet teeth" and the cost of "Roller bit" in both cases, after making assumptions that the following factors were not affected mainly on the cost of a pile.

1. Cost of Bentonite drilling fluid
2. Cost for machinery including repair cost
3. Cost of manpower
4. Cost of tool repair works
5. Cost of other utilities

In omission of the above factors a critical analysis was done and summarized under section 4.8.

Also, a detailed analysis has been done on the penetration rate of piling work to identify the effect on two methods used for pile boring work on the progress or the time duration of the piling operation. In analyzing the time duration of a pile following factors were omitted.

1. Machine capacity
2. Skill level of workers
3. Rate of "Bentonite" drilling fluid supply

4. Time taken for tool changing process
5. Time taken for tool repairs
6. Rotary drilling machine breakdown time
7. Time taken for soil boring work

In omission of the above factors an analysis was done and summarized in section 4.9.

As a summary the average cost of a pile in consideration of rock boring against the penetration rate was tabulated to analyze the effectiveness of the "Bullet teeth" and "Roller bit" tools used in both phases of project.

4.2 Location of Site

The selected site based on the methodology adopted in section 3.2, is located in Havelock town, Colombo 05. The site was surrounded by several types of buildings such as multistory apartment buildings, two or three-story houses with good structural rigidity, one or two-story houses with light construction and some old houses. And, the community around the selected site is having a large diversity. The Figure 4.1 shows the location of site and the neighboring building arrangement.

Figure 4.1: Site location

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4.2.1 Location of each phase of piling

The location of Phase 3 and Phase 4 of piling work is marked in the Figure 4.2 below. Both locations were located close by and the soil and rock profile are mostly same in both phases. The surrounding buildings in both phases are similar in nature and the quantity. And the community surrounded also same for the two phases considered. In north side of the site, multi-story apartment buildings were situated. And all the other three sides are covered by the residential buildings of two to three stories.

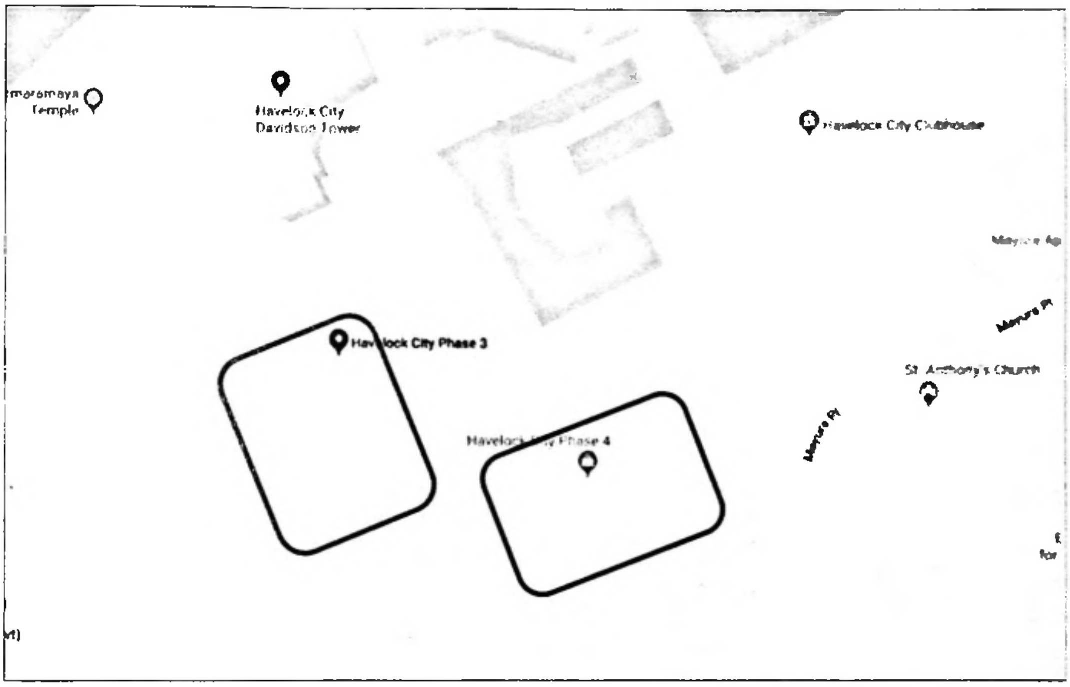

Figure 4.2: Location of Phase 3 and Phase 4 of piling work

4.3 Piling Layouts in Each Phase

4.1.1 Piling layout of Phase 3 piling work

Phase 3 consisted of 185 numbers of piles in total with the diameter of 1000mm. The basic arrangement of the piles is shown in Figure below. Layout of piles in phase 3 is annexed in Annexure A.

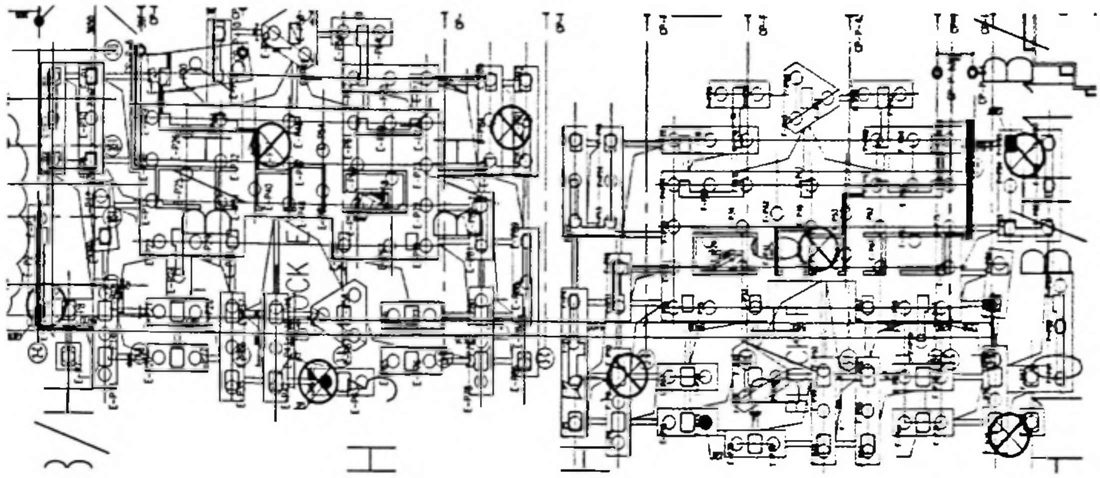

Figure 4.3: Phase 3 piling layout

4.1.2 Piling layout of Phase 4 piling work

Phase 4 consisted of 180 numbers of piles in total with the diameter of 1000mm. The basic arrangement of the piles is shown in Figure below. Layout of piles in phase 4 is annexed in Annexure A.

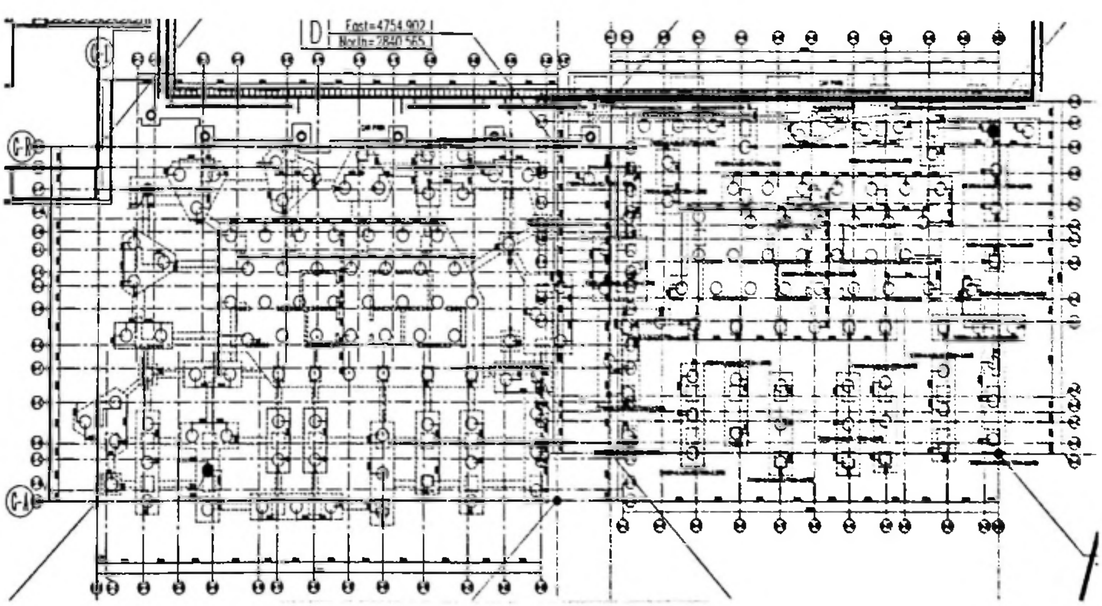

Figure 4.4: Phase 4 piling layout

4.3 Affected Neighborhood

4.1.3 Pre-construction survey on third party properties

A preconstruction survey on third party properties has been carried out by the project management team through an independent agency for a perimeter of 80m approximately. The apartment buildings or the common buildings under the developer was not covered by the survey by the project management team since the management and maintenance of those buildings were by the developer himself. The Figure below shows the layout of the area covered by the third-party properties' preconstruction survey.

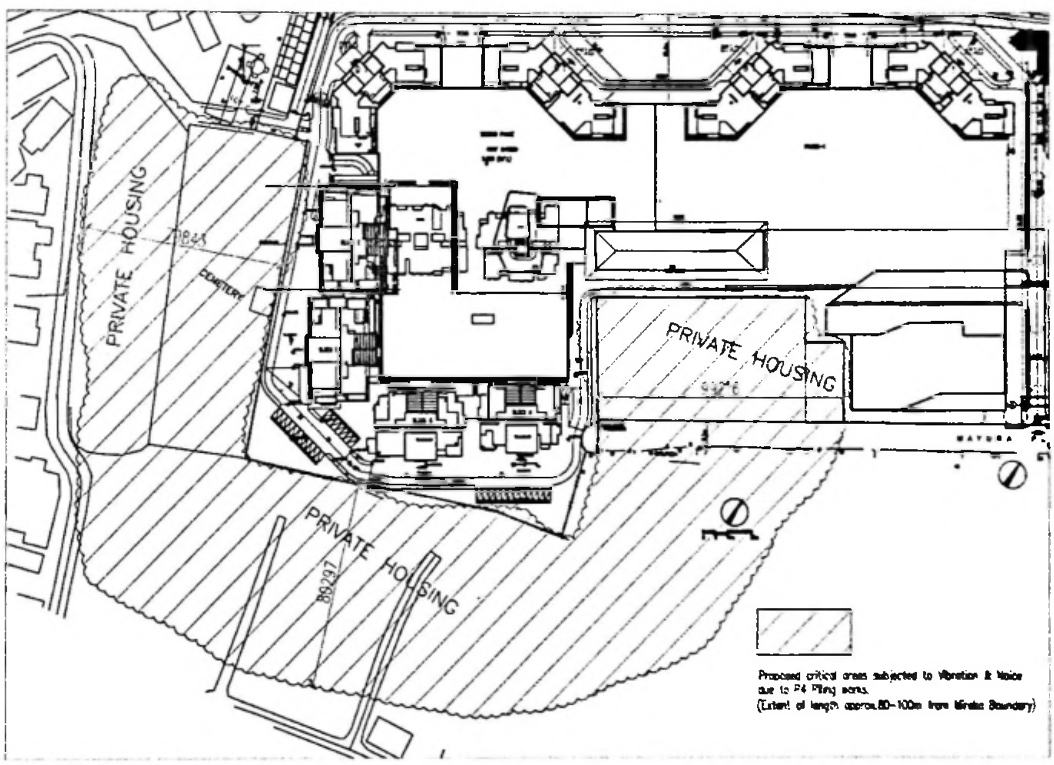

Figure 4.5: Area of pre-construction survey

the pre-construction survey report has been used by the project management team in determination of the damages caused due to piling work. A post-construction survey has been carried out by the same independent agency to verify the condition after piling work.

4.4 Analysis of Geotechnical Parameters

Bore hole data obtain from the geotechnical investigation report of the project is analyzed to understand the soil and rock strata underneath. A sample soil and rock profile at the location is shown in below figure and the full profile is annexed in Annex A. Basically, the two phases are in very close locations and there were not much difference in the soil or rock profiles encountered.

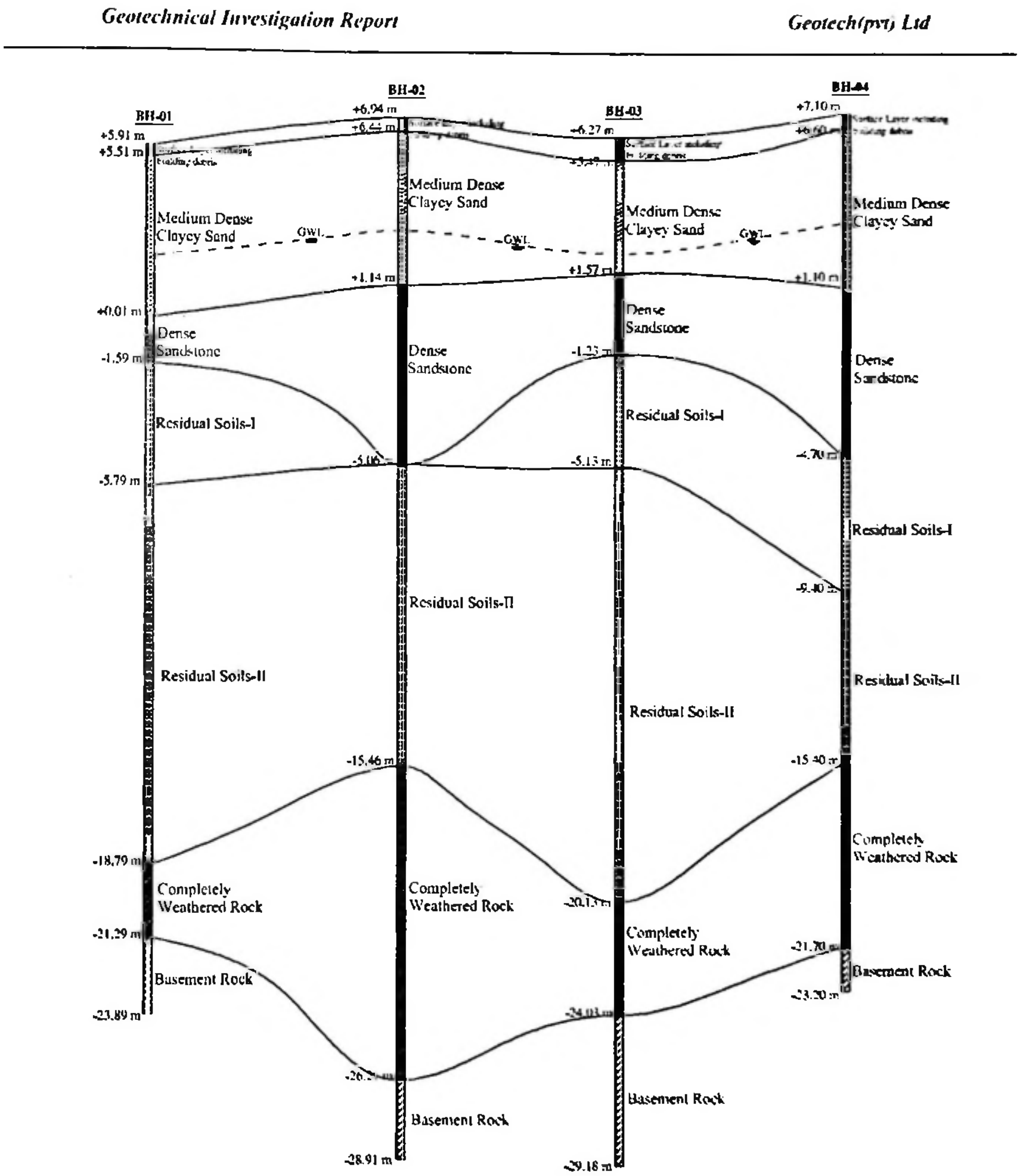

Figure 4.6: Sample sub surface layering (across BH01, BH02, BH03, BH04)

Basically, as per soil profile mapping data, a thick layer of medium dense clayey sand layer is present in everywhere of the site. Hence it can be assumed that the propagation of vibration is same in both phase 3 and phase 4. And also, the ground water level also similar for both phase 3 and phase 4.

The Unconfined compressive strength test results of hard rock samples obtained from bore holes are presented in the figure 4.7 and figure 4.8.

Basically, the UCS value is around 20 MN/m2 to 40 MN/m2. From the borehole layout attached it can be distinguished that figure 4.7 relates the rock strength in phase 3 where figure 4.8 relates to strength of rock in phase 4.

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UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS OF ROCK

TEST METHOD : ASTM : D 2938 - 86

PROJECT :	Proposed 3rd Stage-Havelock City Apartment Complex at Havelock Road, Colombo 05	Sheet 01 of 02
CLIENT :	M/S Geotech (Pvt) Ltd.	JOB NO : GL/1239/001

BH No.	BH-01	BH-03	BH-04	BH-06	BH-07	BH-08	BH-09	BH-10
Depth (m)	27.20-28.80	30.30-31.80	28.80-30.30	31.15-32.15	28.80-30.00	22.80-24.30	22.80-23.80	37.80-39.15
Diameter of Core (mm)	54	54	54	54	54	54	54	54
Length of Core (mm)	108	108	108	72	87	108	59	94
Load at Failure (kN)	45.5	116.0	82.3	78.4	31.4	90.3	21.0	100.7
Unconfined Compressive Strength (MN/m^2)	19.87	50.65	35.94	32.29	13.32	39.43	8.34	43.20
Failure Sketch								

TESTED BY	CHECKED BY	
M.D.D.S.Wijekoon.	Eng. K.V.S.D. Jayamali	

Figure 4.7 Compressive strength properties of rock, BH01 – BH10

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UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS OF ROCK

TEST METHOD : ASTM : D 2938 - 86

PROJECT :	Proposed 3rd Stage-Havelock City Apartment Complex at Havelock Road, Colombo 05	Sheet 02 of 02
CLIENT :	M/S Geotech (Pvt) Ltd.	**JOB NO :** GL/1239/001

BH No.	**BH-11**	**BH-12**	**BH-13**	**BH-14**	**BH-15**	**BH-16**	**BH-18**	**BH-20**
Depth (m)	30.40-31.55	29.90-31.10	27.10-28.20	27.30-28.80	28.90-30.00	29.70-30.90	33.90-35.00	41.90-43.40
Diameter of Core (mm)	54	54	54	54	54	54	54	54
Length of Core (mm)	98	80	83	75	108	79	92	86
Load at Failure (kN)	35.5	55.2	125.0	12.2	31.4	53.3	37.5	35.5
Unconfined Compressive Strength (MN/m^2)	15.31	23.13	52.68	5.06	13.71	22.29	16.04	15.04
Failure Sketch								

TESTED BY M.D.D.S.Wijekoon.	**CHECKED BY** Eng. K.V.S.D. Jayamali	

Figure 4.8 Compressive strength properties of rock, BH11 – BH20

From The above results of UCS tests conducted on bore hole samples, it is noticeable that the quality of hard rock encountered is more over similar in both phase 3 and phase 4 piling work. Hence it has assumed that the rate of penetration in rock has not affected by the rock quality in different phases.

4.5 Field Vibration Data Analysis

Filed vibration monitoring locations are shown in the location map below. Basically, the locations selected were covered the total perimeter of the land which consisted both Phase 3 and phase 4 of piling work. And the monitoring locations were same in both phase 3 and phase 4.

The field vibration monitoring data obtained for a period of one month was summarized in for each phase. The maximum vibration value recorded in a day has taken as the reading for the day in tabulation. The average value of maximum vibration recorded in PPV, in each phase has been calculated.

Table 4.1: Field Vibration Monitoring Data - Phase 3

Field Vibration Monitoring Data - Phase 3		
Monitoring Date	**Maximum Vibration recorded in PPV (mm/s)**	**Frequency of vibration (Hz)**
Thursday, October 1, 2015	1.93	61
Friday, October 2, 2015	1.66	68
Saturday, October 3, 2015	1.87	73
Sunday, October 4, 2015	-	-
Monday, October 5, 2015	2.10	>100
Tuesday, October 6, 2015	2.15	88
Wednesday, October 7, 2015	1.99	76
Thursday, October 8, 2015	1.80	67
Friday, October 9, 2015	2.10	54
Saturday, October 10, 2015	1.70	95
Sunday, October 11, 2015	-	-
Monday, October 12, 2015	1.98	52
Tuesday, October 13, 2015	2.31	69
Wednesday, October 14, 2015	2.01	56
Thursday, October 15, 2015	1.68	87
Friday, October 16, 2015	1.94	79
Saturday, October 17, 2015	1.59	61
Sunday, October 18, 2015	-	-
Monday, October 19, 2015	1.64	34
Tuesday, October 20, 2015	1.68	68
Wednesday, October 21, 2015	1.41	45
Thursday, October 22, 2015	1.83	59
Friday, October 23, 2015	1.68	97
Saturday, October 24, 2015	1.88	82
Sunday, October 25, 2015	-	-
Monday, October 26, 2015	2.31	87
Tuesday, October 27, 2015	2.01	58
Wednesday, October 28, 2015	1.95	78
Thursday, October 29, 2015	1.91	98
Friday, October 30, 2015	1.48	45
Average maximum	**1.87**	-

Source: Vibration monitoring reports provided by Central Engineering Consultancy Bureau (CECB) for Phase 3.

Table 4.2: Field Vibration Monitoring Data - Phase 4

Field Vibration Monitoring Data - Phase 4		
Monitoring Date	**Maximum Vibration recorded in PPV (mm/s)**	**Frequency of vibration (Hz)**
Tuesday, November 1, 2016	1.37	43
Wednesday, November 2, 2016	1.80	87
Thursday, November 3, 2016	1.71	64
Friday, November 4, 2016	1.50	45
Saturday, November 5, 2016	1.12	26
Sunday, November 6, 2016	-	-
Monday, November 7, 2016	0.89	35
Tuesday, November 8, 2016	1.80	48
Wednesday, November 9, 2016	1.06	64
Thursday, November 10, 2016	1.70	32
Friday, November 11, 2016	1.65	87
Saturday, November 12, 2016	1.36	35
Sunday, November 13, 2016	-	-
Monday, November 14, 2016	1.54	43
Tuesday, November 15, 2016	1.64	56
Wednesday, November 16, 2016	1.50	39
Thursday, November 17, 2016	1.78	87
Friday, November 18, 2016	1.90	68
Saturday, November 19, 2016	1.07	55
Sunday, November 20, 2016	-	-
Monday, November 21, 2016	0.97	22
Tuesday, November 22, 2016	1.90	73
Wednesday, November 23, 2016	1.86	47
Thursday, November 24, 2016	1.54	68
Friday, November 25, 2016	1.77	74
Saturday, November 26, 2016	0.97	38
Sunday, November 27, 2016	-	-
Monday, November 28, 2016	1.05	42
Tuesday, November 29, 2016	1.55	56
Wednesday, November 30, 2016	1.68	68
Average maximum	**1.49**	-

Source: Vibration monitoring reports provided by Central Engineering Consultancy Bureau (CECB) for Phase 4.

In comparison of vibration monitoring data for two cases, it can be observed minor reduction in average of maximum values of ground vibration generation during piling operation of phase 4 which used "Roller bit" buckets for piling than in Phase 3.

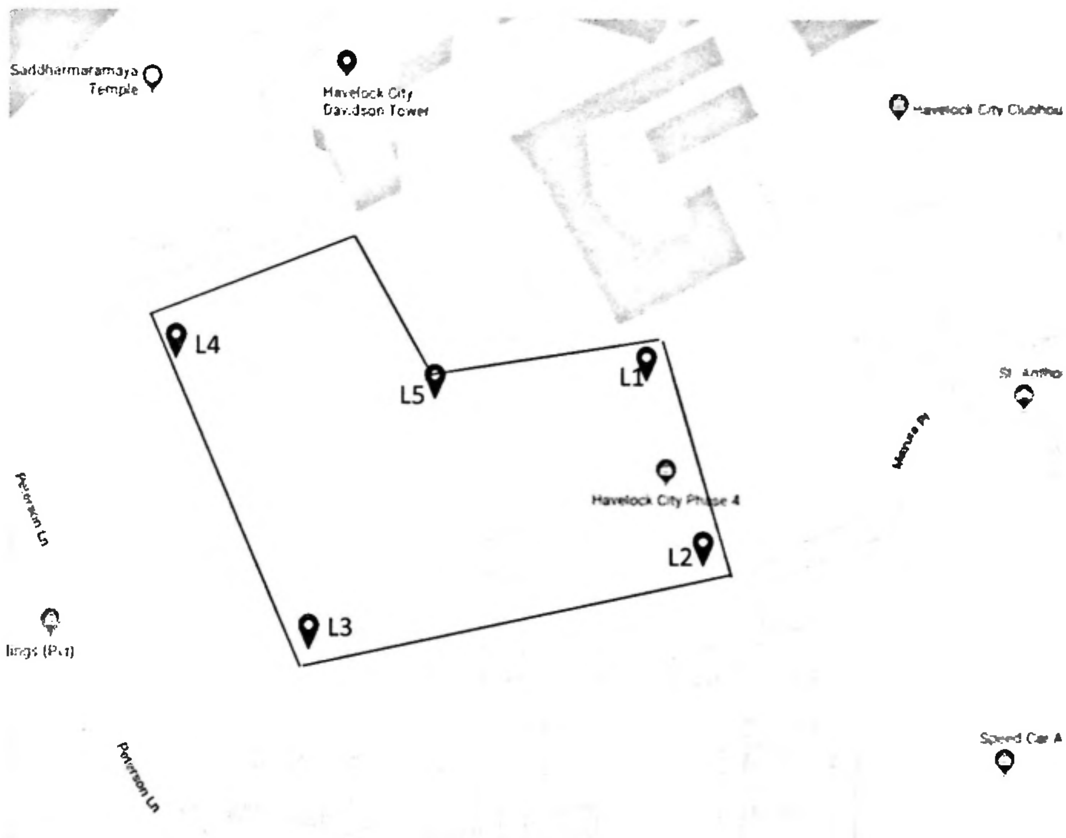

Figure 4.9: Vibration monitoring locations at site

In the process of identification of effect on the community, two major factors were considered.

1. Effect of vibration level on human perception
2. Effect of vibration level on nearby buildings

For the comparison of the levels of vibration on human perception, the levels released by California Department of Transportation (Transportation and construction vibration guidance manual,2013) is considered.

Since the ground vibration generation is due to a force exerting continuously by a machine, the steady state vibration condition was selected for the comparison. For the steady state transmission of vibration, the levels stipulated in the Transportation and construction vibration guidance manual,2013 is in given table below.

Table 4.3: Human Response to Steady State Vibration (California Department of Transportation, Transportation and construction vibration guidance manual,2013)

PPV (in/sec)	Human Response
3.6 (at 2 Hz)–0.4 (at 20 Hz)	Very disturbing
0.7 (at 2 Hz)–0.17 (at 20 Hz)	Disturbing
0.10	Strongly perceptible
0.035	Distinctly perceptible
0.012	Slightly perceptible

The average maximum vibration values in each phase is falling into the category of "Very disturbing" to the human according to the levels given in above table.

And, according to the levels and types given in table 4.4 and table 4.5, the vibration level exceeds the levels for the type 4 category buildings given by Central environment authority, Sri Lanka and the levels are closer to the maximum level of category 3 buildings in some cases. The levels stipulated by the CEA of Sri Lanka is tabulated below.

Table 4.4: Categorization of structures according to the type of building (Central Environmental Authority of Sri Lanka under Amended ABOP standards,2008)

Category of the structure	Description
Type 1	Multi story buildings of reinforced concrete or structural steel, with in filling panels of block work, brick work or precast units not designed to resist earthquakes

Type 2	Two-story domestic houses & buildings constructed of reinforced block work, precast units, and with reinforced floor & roof construction, or wholly of reinforced concepts or similar, not designed to resist earthquakes
Type 3	Single and two-story houses & buildings made of lighter construction, using lightweight materials such as bricks, cement blocks etc., not designed to resist earthquakes
Type 4	Structures that, because of their sensitivity to vibration, do not correspond to those listed above 1,2 & 3, & declared as archeologically preserved structures by the Department of Archaeology

Table 4.5: Tolerable limits of vibration

Category of the structure as given in Table 1.1	Type of Vibration	Frequency of Vibration (Hz)	Vibration in PPV (mm/Sec.)
Type 1	Continues	0 -10	5.0
		10 - 50	7.5
		Over 50	15.0
	Intermittent	0 -10	10.0
		10 - 50	15.0
		Over 50	30.0
Type 2	Continues	0 -10	2.0
		10 - 50	4.0
		Over 50	8.0
	Intermittent	0 -10	4.0
		10 - 50	8.0
		Over 50	16.0

Type 3	Continues	0 -10	1.0
		10 - 50	2.0
		Over 50	4.0
	Intermittent	0 -10	2.0
		10 - 50	4.0
		Over 50	8.0
Type 4	Continues	0 -10	0.25
		10 - 50	0.5
		Over 50	1.0
	Intermittent	0 -10	0.5
		10 - 50	1.0
		Over 50	2.0

This clearly depicts that there was an effect to the neighboring community due to the ground vibration, when comparing levels of vibration. Also, it can affect some building structures which basically falling into categories 3 and 4, as per categorization by the Central Environmental Authority of Sri Lanka under Amended ABOP standards.2008.

4.6 Comparison of Complaints Registries

The summary of the complaint registry is shown in the table below. The complaints basically received from the project team, but certain complaints received as a police inquiry to the project team. All the complaints made were not related to the damages or cracks in houses or buildings. Majority of the complaints are basically due to the public nuisance arise due to vibration and noise.

The number of complaints made due to cracks or other damages due to ground vibration shows the effect to the neighboring community purely due to ground vibration generation.

Table 4.6: Summary of complaints by neighboring community

Summary of complaints by neighboring community					
Phase	**Number of complaints to project management team**	**Number of Police complaints**	**Total Number of complaints**	**Number of complaints related to cracks or damages**	**Attended for Rectification**
3	34	24	58	17	9
4	26	21	47	12	8

4.7 Analysis of Cost Factor

Following factors were omitted with the reasons or assumptions as described in section 3.4, in the calculation of cost variance.

1. Cost of Bentonite drilling fluid
2. Cost for machinery including repair cost
3. Cost of manpower
4. Cost of tool repair works
5. Cost of other utilities

With the omission of above factors affecting cost of work, below two key factors were selected for the comparison of cost between two methods.

6. Cost of "Bullet teeth" & cost of "Roller bit" for each phase
7. Cost of rectification work for third party properties in each phase

For the comparison, cost for a pile is calculated based on above two parameters.

4.7.1 Cost of Bullet teeth and Roller bit

The rate of "Bullet teeth" and "Roller bit" has taken from the purchase orders obtained from the contractor. The purchase order copies are shown in the figure 4.10 with related rates for "Bullet teeth" and "Roller bit".

Vendor Address	Information	
	Purchase Order No.	2000000551
Shandong,,China	Date	14.11.2015
China	Vendor No.	200476
	Currency.	USD
	Purchasing Group.	MAT
Billing Address:	Purchasing org.	2000
	Project / Plant	Pilling Unit
	Attention.	
Sri Lanka	Fax No.	
	Your reference.	20010328 on 14.11.2015
	Special instructions.	

Material/Desc.		Quantity	UM	Unit Price	Net Amount
BULBKH85 Bullet B.K.H 85	14.11.2015	3,000.00	NO	9.900	29,700.00
ROCPILORP4 Rock Pilot Rp 4 W/O Rsc	14.11.2015	40.00	NO	53.450	2,138.00
					31,838.00
FOB					31,838.00
Freight					90.00
Insurance					70.00
Total CIF					31,998.00

Vendor Address	Information	
	Purchase Order No.	2000000552
Hebei,,China.	Date	03.05.2016
Switzerland	Vendor No.	200604
	Currency.	USD
	Purchasing Group.	MAT
Billing Address:	Purchasing org.	2000
	Project / Plant	Pilling Unit
	Attention.	
Sri Lanka	Fax No.	
	Your reference.	M590401B on 03.05.2016
	Special instructions.	

Material/Desc.		Quantity	UM	Unit Price	Net Amount
ROLBIT8-1-2 Roller Bit -8 1/2	03.05.2016	150.00	NO	307.800	46,170.00
					46,170.00
FOB					46,170.00
Freight					103.00
Insurance					30.00
Total CIF					46,303.00

Figure 4.10: Unit cost of Bullet teeth & Roller bit

4.7.2 Cost of rectification work

Rectification work has done based on the pre-construction and the post construction survey evaluation. Sample photos of rectification work shown in below Figures 4.12 to 4.14, which were extracted from the report on third party property damages rectification work prepared by the project management team.

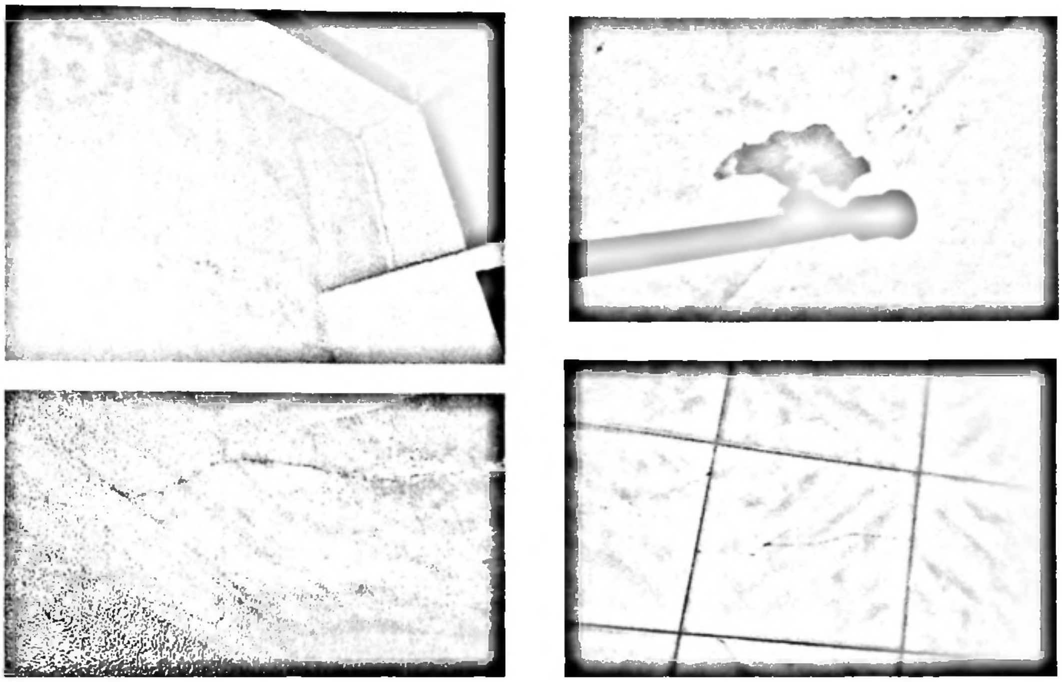

Figure 4.11: Common damages inspected

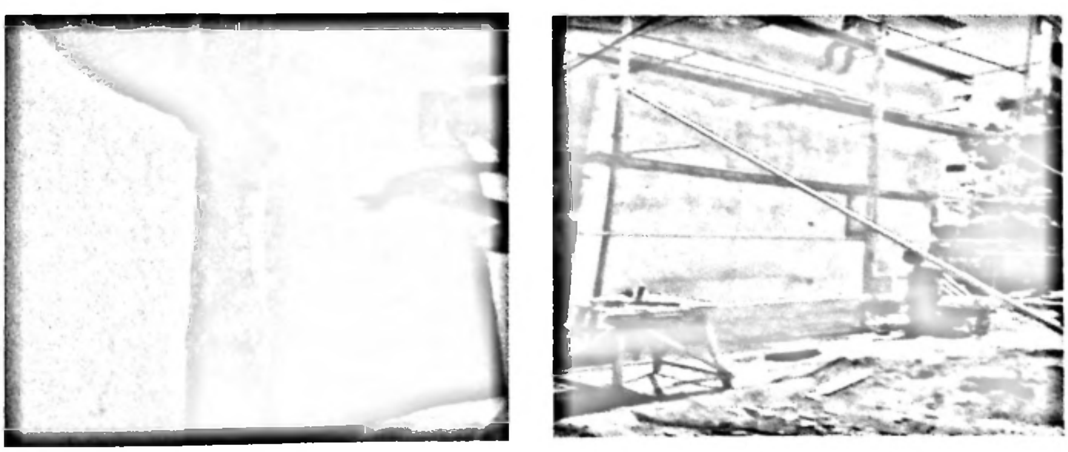

Figure 4.12: Rectification work

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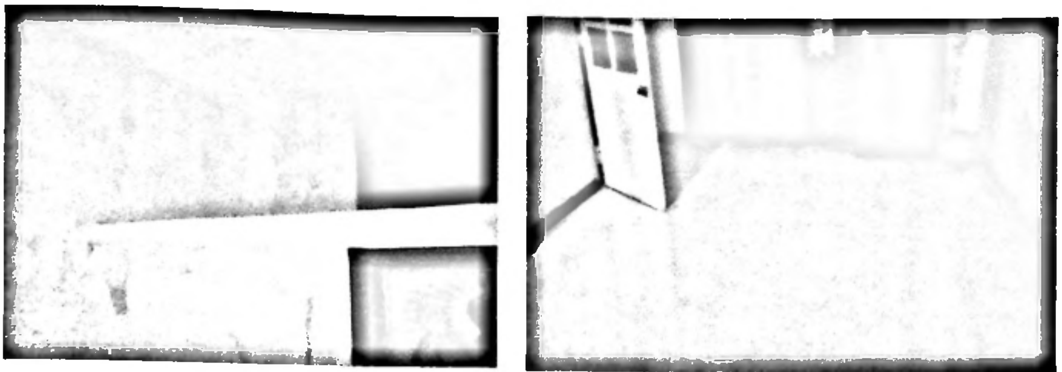

Figure 4.13: After rectification work completed

4.7.3 Cover on property damages due to vibration by the Insurance policy

The third-party damage rectification costs were not agreed to pay by the insurance company which provided the "Contractor's all risk policy" on behalf of the contractor, to the project. Under the clause, "Damage to any property or land or building caused by vibration or by the removal or weakening of support or injury or damage to any person or property occasioned by or resulting from any such damage" of special extrusions to "Third party liability" of "Contractors all risk policy" obtained for piling construction work, the damages occur due to the vibration was no covered by the insurance company. A comparison was done on several insurance policies provided by different insurance companies in Sri Lanka to identify the above fact and all the companies have included the above exclusion in their insurance policies under "Third party liability".

The summary of the cost comparison is tabulated in Table 4.7.

Table 4.7: Cost Comparison of piling work in phase 3 and phase 4

Cost Comparison of Phase 3 and Phase 4 (Bullet Teeth & Roller Bits)				
No	**Item**	**Unit**	**Project/ Phase**	
			Phase 3 (Bullet teeth)	**Phase 4 (Roller Bit)**
1.0	**Number of piles**	Nos	185	180
2.0	**Cost for pile boring work (Soil boring)**	$	389793.10	379258.15

3.0	**Cost for pile boring work (Weathered rock boring)**	$	124733.79	121362.61
4.0	**Cost for pile boring work (Hard rock boring, except cost of Bullet teeth/ Roller bit)**	$	434749.97	414543.57
5.0	**Cost of Bullet teeth/ Roller bit**			
5.1	Consumption of Bullet teeth/ Roller bit (Site store record annexed in Annex B)	Nos	4810	178
5.2	Cost of Bullet teeth/ Roller bit (Figure 4.10)	$	47619.00	54788.40
6.0	**Cost of reinforcement work**	$	294656.97	286693.26
7.0	**Cost of concreting**	$	574132.76	558615.66
8.0	**Cost for Third Party Property Damage**			
8.1	Number of houses rectified	Nos	9	8
8.2	Total Cost of house rectification work (Summary annexed in Annex I)	$	27246.37	9935.87
8.3	Amount claimed from the insurance	$	0.00	0.00
9.0	**Total Cost**	$	1892931.95	1770409.12
10.0	**Cost per pile**	$	10232.06	9835.61
11.0	**Cost per meter length (Avg. length of a pile = 30m)**	**$**	**341.07**	**327.85**

Assumptions & Notes

1	Assumed the rates for soil boring, weathered boring and rock boring are same for both phase 3 and phase 4.
2	Assumed a total pile length of 30m for both phase 3 and phase 4 based on BOQ annexed and summary of rock boring.
3	Assumed the rate of reinforcement work are same for both Phase 3 and phase 4
4	Assumed the rate of concreting work are same for both Phase 3 and phase 4

5	Assumed the conversion rate of Sri Lankan Rupees to USD as 1 USD = Rs. 145 with reference to conversion rates published by Central bank of Sri Lanka in January 2016
6	Insurance policy (CAR policy) did not cover the cracks generation in buildings. Cracks due to vibration was excluded under special extrusions to "Third party liability" of "Contractors all risk policy" obtained for piling construction work.

From the above cost comparison, it is observed that the total cost for a pile in average is less in phase 4 which used "Roller bit" bucket for rock drilling. Also, it shows that there is a reduction in costs of rectification work of third-party property damages.

4.8 Analysis of Time Factor

In analyzing the time duration of a pile with the two methods considered, following factors were omitted.

1. Machine capacity
2. Skill level of workers
3. Rate of "Bentonite" drilling fluid supply
4. Time taken for tool changing process
5. Time taken for tool repairs
6. Rotary drilling machine breakdown time
7. Time taken for soil boring work

The omission of the above factors one to six was critically analyzed in section 3.6 of chapter 3. Basically, the tools considered above used for the rock boring work. Hence the effect on time of boring work was analyzed for rock boring in piling process. Thus, the time taken for soil boring was not considered for the analysis.

As per the summary of boring records, the average penetration rate in case 1 which used "Bullet teeth" is 280 mm/hr and for case 2 which used "Roller bit" is 282 mm/hr. The difference is only 0.7% which is even less than 1%. This difference can be neglected and that the time consumption for both phases is almost same. Hence it can be concluded that no major effect to the duration of project either using buckets with "Bullet teeth" or with "Roller bit".

Table 4.8: Comparison of Rock Boring work

Comparison of Rock Boring work					
Phase	Description	Bored length (m)			Rate at toe (mm/hr)
		Weathered rock	Fresh rock	Total	
3	Average per pile	1.799	3.226	5.025	280
	Total	334.601	599.987	934.588	
4	Average per pile	1.783	3.220	5.003	282
	Total	321.008	579.548	900.556	

The total summary of boring records is annexed in Annex E.

4.4 Comparison of Cost and Time consumption

The summary of the time consumption and the cost involved can be seen in the table 4.9. The tabulation has been done with the rock penetration rate in two method against the cost per pile as calculated in section 4.3.

Table 4.9: Comparison of Cost & Penetration rate of rock

Phase	**Phase3 (Bullet teeth)**	**Phase 4 (Roller Bit)**
Cost per pile ($)	341.07	327.85
Rate of penetration in Hard rock (mm/hr)	280	282

From the above table it is visible that the penetration rates are almost same for both cases but the difference in cost for pile shows apparently higher in the case 1, which was done with "Bullet teeth". The difference in cost is about 3.9% approximately, where the difference in hard rock penetration rates remain in 0.7%.

4.8 Chapter Summary

- Ground vibration generation due to bored piling operation is falling into the category of "unpleasant" or "very disturbing" based on the levels given by Transportation and construction vibration guidance manual,2013) released by California Department of Transportation which tabulated under literature review.
- Levels of ground vibration exceeds the level for "Category 4 buildings" types and closer to the level of "Category 3 buildings", according to the levels published by the Central Environmental Authority of Sri Lanka.
- Ground borne vibration when using Roller bits are slightly lower than the use of Bullet teeth. The difference of the average of maximum PPV values is about 20%.
- The penetration rates are almost same for both cases in hard rock, where the difference is only about 0.7%.
- The cost for a pile shows apparently higher value in the case 1, which was done with "Bullet teeth". The difference in cost is about 3.9% approximately.
- The difference in the cost of Bullet teeth and the Roller bit is about 15.1% higher in phase 4 which used Roller bits.
- The difference in the cost of rectification work is higher in Phase 3 which used Bullet teeth, by about 63.5%.

CHAPTER 5: CONCLUSION & RECOMMENDATION

5.1 Conclusion

- Based on the vibration levels obtained through site vibration measurements, it is found that the levels of vibration generated during piling operation has affected human perception levels which make them annoying according to "Transportation and construction vibration guidance manual' released by California Department of Transportation in 2013.
- And the level of vibration generated has exceeded the level stipulated by the Central Environmental Authority of Sri Lanka for Category 4 structures and Category 3 structures for certain occasions.
- The summary of complains registry shows that the impact on the neighboring community, with the number of complains made and with the number of police complains lodged. There was a considerable amount spent by the project management team for the rectification of third-party property damages.
- A considerable ground born vibration induces during bored insitu-cast pile construction work and becomes annoying for the neighboring communities. This cause public nuisance and increase in project cost and reduce project progress.

- From the summary of analysis results, it can be concluded that the penetration rates are almost same for both cases but the difference in cost for pile shows apparently a higher value in using the "Bullet teeth" tools than in using the "Roller bit" tools for pile boring work, The difference in cost is about 3.9% approximately, where the difference in hard rock penetration rates remain in 0.7%.
- Also, when considering the difference in the cost of Bullet teeth and the Roller bit for the project, is about 15.1% higher in phase 4 which used Roller bits. And the difference in the cost of rectification work is higher in Phase 3 which used Bullet teeth, by about 63.5%.
- It is found during the cost analysis that the difference is mainly due to the cost of rectification work in the case which used "Bullet teeth" tools for pile boring.
- The reason behind the increase in rectification work of third-party properties can be identified from the summary of complaints register maintained by the project

management team. The number of complaints made due to cracks or other damages due to ground vibration shows the effect to the neighboring community purely due to ground vibration generation.

- And the summary of field vibration monitoring also shows a reduction in the case which used "Roller bit" tools for boring work which is about 20.3% in the average maximum values compared to phase 3 which used "Bullet teeth".
- Based on above observations it can be decided that the effectiveness of Roller bits is higher in comparison with Bullet teeth, in both cost involvement and minimizing public complaints because of ground vibration.

5.2 Recommendations

Based on above conclusion it is recommended to use "Roller bit" buckets instead of using buckets with "Bullet teeth" for bored in-situ cast piling operations, especially in highly urbanized areas with sensitive buildings.

Since the drilling method is different in "Roller bit" buckets than "Bullet teeth" buckets, it is recommended to monitor the consumption of "Roller bits" during operation, since the consumption can increase with the poor performance of drilling machine operators, which may lead in increase of project cost.

5.3 Limitations

- The contractor was same in both phases which selected for comparison in the project and the data can be vary with the performance of the contractor`s staff.
- The performance of the tools with either "Bullet teeth" or "Roller bit" can be vary with the different rock types with impurities, due to different mechanisms in both tool types. This was not evaluated in this study.
- Noise monitoring data was not available hence noise levels were not considered when evaluating the effect on human response.
- Benefit on lifetime of Rotary drilling machine due to less vibration generation was not evaluated in cost calculating process.

5.4 Future research

- Efficiency of using Roller bit buckets in drilling different rock types with comparison of rock penetration rate and the consumption of Roller bits.
- Effectiveness of using roller bit buckets to minimize noise generation during bored piling.
- Effect of vibration generates to Rotary drilling machine lifetime and the effectiveness of using Roller bits to increase machine lifetime.
- The perimeter of vibration propagation for a single rotary drilling rig with Roller bit buckets, in different soil conditions.

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