IDENTIFYING THE TECHNIQUES AND CHALLENGES OF GPS SURVEYING FOR VERTICAL ALIGNMENTS IN HIGH-RISE BUILDINGS

Abdul Wahid Mohamed Safith

(138424U)

Degree of Master of Science

Department of Building Economics

University of Moratuwa
Sri Lanka

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Abdul Wahid Mohamed Safith

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Dissertation submitted in partial fulfillment of the requirements for the degree of
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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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DEDICATION

This is dedicated to

My Parents

&

beloved wife M.L. Fathima Mafaisa

for their love, support and encouragement

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ABSTRACT

Identifying the Techniques and Challenges of GPS Surveying for Vertical Alignments in High-Rise Buildings

Vertical alignment in high-rise building is a very important aspect. In order to manage the growing demand for spaces in urban cities, the people are now interested in construction of super high-rise buildings. The architects are nowadays interested in improvising untypical complicated morphology in building designs which increase the difficulties in surveying for vertical alignments. Consequently the surveyors are themselves forced to find alternative survey techniques to manage the difficulties. Though the GPS survey techniques are applicable like in other constructions, the majority of the construction society is still depended on the traditional survey methods.

As per the existing data sources, operational and spaces related challenges of GPS surveying are common for any kind of GPS applications; and though the GPS survey techniques are applicable for vertical alignment in high-rise buildings, there is lack of data sources to explicitly expose the applicability of different GPS survey techniques and the challenges to be considered in such applications. This study has been oriented to find out the best suitable GPS survey technique for the vertical alignments in high-rise buildings by checking the applicability of all five basic GPS techniques with their accuracy, efficiency, time consuming and cost implications while focusing on identifying further practical challenges apart from the already identified operational and space related problems.

The findings prove that the GPS techniques can be used for vertical alignments in high-rise buildings and the best technique among them is Static GPS with the combination of traditional survey methods; and there are some practical challenges to be considered in such GPS applications for vertical alignments in high-rise buildings. The findings have been attained by analyzing the reliable data gained through experts' comments, case studies and experiments.

Keywords: *High-Rise Building, Vertical Alignment, GPS Techniques, CORS, CWCSS*

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LIST OF ABBREVIATIONS

Abbreviation	Description
AR	Ambiguity Resolution
BIM	Building Information Modeling
CAD	Computer Aided Design
CORS	Continuous Operating Reference Stations
CWCSS	Core Wall Control Survey System
DGPS	Differential Global Positioning System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
KSA	Kingdom of Saudi Arabia
MSS	Mobile Satellite Service
RF	Radio Frequency
RII	Relative Importance Index
RTK	Real Time Kinematic
SA	Selective Availability
UAE	United Arab Emirates
UHF	Ultra High Frequency
US	United States
UWB	Ultra-Wideband
VHF	Very High Frequency
VRS	Virtual Reference Station

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CHAPTER ONE

1 INTRODUCTION

1.1 Background

"Surveying is basic to engineering" (Roy, 2006). For an efficient accomplishment in construction projects, it is a must to do the necessary survey activities accurately. In recent past, the traditional surveying techniques were the only option to perform any survey activities in construction; but nowadays there are many modern digital surveying equipment and techniques available in the industry such as GPS to perform surveying tasks with better accuracy and many advantages.

"The GPS is a space-based satellite navigation system that provides location and time information in all weather conditions, anywhere on or near the earth where there is an unobstructed line of sight to four or more GPS satellites" (Sassan Ahmadi, 2013). GPS positioning is now an indispensable tool for a wide range of precise applications in navigation, surveying and geodesy (Chris Rizos, 2001).

Because of the modern technological advancement and infrastructure development, most of the dense urban cities are now engaging in construction of high-rise buildings in order to accommodate the growing demand for spaces (Milind and Sumedh, 2004).

In high-rise buildings, the vertical alignment is a very important aspect. Vertical structures are subject to strong external tilt effects caused, for instance, by wind pressures, unilateral thermal effects by exposure to sunlight, and unilateral loads. Because of the varying loads of the structures due to differential raft settlement, differential concrete shortening, and construction tolerances, achieving the exact verticality or vertical alignment during the construction is a challenge. (Douglas Hayes, Ian Sparks, Joël van Cranenbroeck, 2006).

“Surveying techniques are used for dimensional control or setting out of designed constructional elements and also for monitoring deformation movements” (Schofield and Breach, 2007, p1). Because of above such challenges, once the construction has attained a certain height or a certain ratio of height to cross section, the surveyors need to have a proper survey control system at each level of the building so that it is accurately matching with the same control system at other levels for proper controlling of horizontal and vertical alignments (Douglas Hayes et al. 2006).

“As on most construction sites, surveyors typically work around steel structures and obstructions and beneath or beside materials being lowered by crane. The working areas are congested with materials, equipment, and people, and of course working at height requires a special regard for safety. Under these conditions, surveying becomes difficult” (Joël van Cranenbroeck, 2010). If the construction site is in urban cities congested with many towers, the situation becomes more critical.

The precision of surveying depends on the reliability of the reference stations. Up to now, surveying on high-rise buildings is done by geodetic electro-optical total stations, and these instruments periodically being referenced to fixed external reference points with known coordinates. Because of the above explained external tilt effects and varying loads of the structures of building, it is not recommended to use the reference stations fixed on the building itself. The usage of ground based external fixed stations which are not subject to shifts is also limited up to the certain height or level of the buildings due to the congested built-up surroundings and excessive distance between the Total Station at upper level and reference stations while the relative distances between the fixed reference points become too small (Douglas Hayes et al. 2006). And according to Milind and Sumedh (2004) there are glaring common disadvantages in all traditional survey methods such as Plumb bob, Construction laser, Total Station etc. due to lack of accuracy.

In order to overcome the above such challenges in applying the traditional surveying techniques including Total Station in high-rise buildings, modern GPS applications with different field procedures such as Core Wall Control Survey System (CWCSS) of Leica Geosystems are now applied to provide reliable reference points at the upper level of the buildings for reliable horizontal and vertical alignments (Joël van Cranenbroeck, 2010).

According to Milind and Sumedh (2004), and Douglas Hayes et al. (2006), the GPS survey applications for controlling verticality in high-rise building construction are successful. Building construction is one of the main applications of RTK GPS (Rizos and Han, 1998) and Speed (2011) has mentioned that the layout using GPS is highly effective and accurate in building construction. Even though the GPS application has the advantages of greater efficiency, around-the-clock operation, weather independency, speediness, need only less manpower and reduction in cost for survey crews etc., it is not widely applied; and the majority of the construction societies are still depended on the traditional survey method because of their lack of knowledge on modern GPS techniques.

Although such GPS applications are found successful in high-rise buildings such as amazing Burj Khalifa Tower in Dubai, Al-Hamra Tower in Kuwait etc. according to David (1999), GPS is not simply an alternative to existing surveying techniques but has advantages and disadvantages which need to be evaluated, and Hanh et al. (2009) states that “In the world, we have some applications using GPS technology for measuring the movement of construction but the procedure is unclear or not unity”. Rizos and Han (1998) stated that there are several shortcomings with GPS and it is not the ideal system for all users; and it is necessary to consider the factors influencing the choice of positioning. The quotations emphasize that still there are challenges in GPS surveying also on which the techniques have to be further improved or replaced with alternatives.

1.2 Research Problem

According to the above facts, it is obvious that the GPS surveying techniques are applicable in high-rise building construction, whereas, there are several shortcomings or challenging factors to be considered in such applications. But, there is a lack of useful data sources to clearly prove whether which techniques among different GPS techniques are well suited and what kind of shortcomings or challenging factors are there so that the construction society can evidently take a decision on choosing a suitable GPS technique and to be vigilant on the challenges may occur to face. Hence, identifying the GPS techniques suitable for building construction, and the challenges faced while applying the techniques in the industry, is vital and most beneficial to the construction society.

Further, modern techniques and applications are actually introduced in order to mitigate the challenges or ease the tasks for which it is applied. Modern GPS applications in high-rise buildings have actually been introduced since the developers came to know about the problems or challenges faced by the surveyors in fulfilling their requirements in surveying with traditional survey methods. According to Rizos and Han (1998), one of the main objectives of "real-time kinematic" (RTK) products is to make GPS more competitive with traditional surveying technologies; and building construction is one of the main applications of RTK. Hence, in order to further improve the techniques or field procedures; it is necessary to analyze their strengths, weaknesses, opportunities and threats in the industry.

In order to fill this gap in the literature and contribute to the technological advancement in construction surveying, there is a need to concentrate on the subject to identify the GPS surveying techniques suitable for controlling verticality in high-rise buildings and the constrains, issues or challenges to be considered in such applications in the industry.

1.3 Research Questions

The research problems mentioned above present the following questions to be answered.

- Is it beneficial to apply GPS surveys in building construction?

- What are the GPS techniques applicable for vertical alignments in high-rise buildings and which is the best among them?

- What are the problems or challenges to be considered in GPS surveys for vertical alignments in high-rise buildings?

1.4 Aim

The research is mainly aimed on studying the suitability of GPS survey techniques for vertical alignments in high-rise buildings and the challenges over traditional survey methods.

1.5 Objectives

To achieve the main aim of the task, the research will focus on the following specific objectives.

- Identifying the different GPS surveying techniques applicable for controlling verticality in high-rise buildings.

- Comparing GPS with traditional survey methods on vertical alignment in high-rise buildings.

- Identifying the factors of challenges to be considered in GPS applications for controlling verticality in building construction.

- Recommending the best suitable GPS survey technique for vertical alignments in high-rise building construction.

1.6 Significance of the Research

Since this research concludes with the reliable findings of modern GPS surveying techniques applicable for vertical alignments in high-rise buildings and the challenging factors to be considered while applying such techniques, it will be a fruitful solution or guide for those who are seeking for an alternative to traditional surveying methods applied in high-rise buildings; and the challenges, as weaknesses, will be useful for further development of GPS techniques. In addition to that since it gives detail knowledge on the followings, the necessity of this research is further emphasized.

- Accuracy and efficiency of GPS of surveying so that one can take a decision on the applicability of the GPS surveying in high-rise buildings with the level of accuracy required.
- Different GPS surveying techniques and the best techniques applicable for horizontal and vertical alignments in high-rise buildings.
- Field procedures whether how the techniques are applied.
- The factors of challenges to be considered in GPS surveying for building construction and their significance.
- Advantages and disadvantages in using GPS instead of traditional surveying methods for vertical alignment in high-rise buildings.

1.7 Limitations of the Research

The study was carried under the limitations listed below.

- The study never considered the absolute GPS positioning and it just dealt with only the relative positioning.
- In high-rise buildings, GPS surveying can be carried out for many purposes such as horizontal and vertical alignments, vertical or height control,

monitoring etc. this particular research study has dealt with such GPS applications for vertical alignment only.

- The GPS surveys and processing were based on the Continuously Operating Reference Stations (CORS) and Virtual Reference Station (VRS) network of a DGPS data and correction service provider.

- There was no geographical limitation for the data collection. The questionnaire surveys/interviews were carried out among those who were available to reach in different parts of the world.

- The challenges in GPS surveying for vertical alignments in high-rise building have not been identified for each and every GPS technique separately, and it was focused in a common view.

- The GPS techniques applicable for vertical alignment in high-rise buildings have been identified by considering their accuracy, efficiency, time consuming and cost implication only.

1.8 Overview of the Research Methodology

This research study has been designed to answer the questions of "what are the GPS techniques applicable for controlling verticality in high-rise building during construction, which is the best among those techniques, and what constraints, issues or challenges, are there in such applications?" The report of this research will expose and emphasize the identified GPS surveying techniques applicable, and constraints, issues and other factors of challenges by which the construction society is discouraged so that they are still depended on the traditional survey methods.

The problem was approached by analyzing both primary and secondary data collected through in-depth literature survey on the existing documents, questionnaire survey, case studies, experiments and conducting semi-structured interviews with related experts and professionals who are having knowledge and experience in such kind of GPS applications in the industry.

At first, the existing documents such as books, journals, research papers and other scholarly articles were studied, and some professionals having academic background and field experience were interviewed to have a general idea on the GPS techniques applicable for controlling verticality in high-rise buildings, and possible constraints, issues and other factors by which the applications are challenged. Then those were presented to the selected experts and professionals via structured questionnaire for improving the validity, reliability and accuracy of the findings while searching for further applicable techniques, constraints, issues and other factors of challenges through extended questions.

Since, there was no clear idea about the actual population from which the sample was selected for analysis; it was approached by selecting a non-probability sampling. The sample includes seventy-eight experts or professionals who responded to the above structured questionnaire which gives place for sharing freely their own ideas; and there was no any geographical limitation for selecting the respondents so that a respondent could respond from any country or part of the world.

The data gained through both primary and secondary data sources were quantitatively and when necessary qualitatively analyzed. Then the findings, specially the GPS techniques were checked by case studies and experiments by comparing their accuracy, efficiency, time consuming and cost implication for better conclusions and recommendations. The results of the analysis have been presented with tables, charts, graph and statistical measures. The research approach can be illustrated as shown in the Figure 1.1 below.

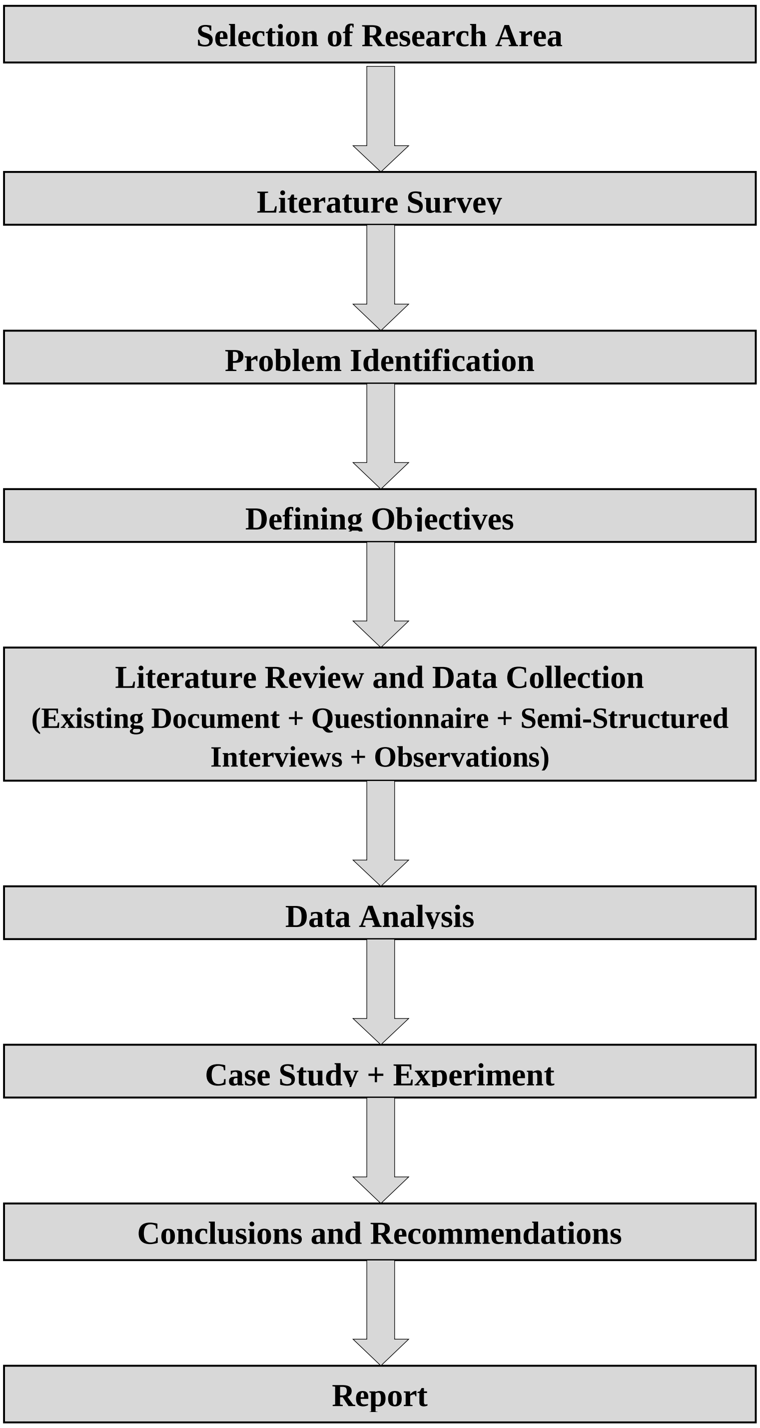


Figure 1.1: Research Approach

1.9 Outline of the Dissertation

According to the structure of the dissertation, the latter parts of the dissertation are presented in another five appropriate chapters. Chapter Two presents the literature review in detail with previous works done on the subject and findings. It further addresses the relationship of the topic with those previous research approaches and findings.

The methodology of the study is presented in Chapter Three. It contains a detail discussion on the research approach applied to achieve the objectives. It further explains the research activities, method of selecting an appropriate sample from the population, methods of data collection, analysis, overview on the case studies and experiments etc.

Chapter Four carries the data analysis which is oriented to achieve the aim and objectives of the study. This chapter presents the results of data analysis and detail discussion which scientifically and critically justifies the reliability of the approach.

Chapter Five of the dissertation presents the complete details of the case studies and experiments carried out. It further discusses comparatively on the results gained through the preliminary data analysis, case studies and experiments towards the conclusions.

Finally, the conclusions and recommendations towards further development of the techniques and future researches are presented in Chapter Six followed by the references and appendices.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the background of GPS surveying and previous works on the research area under investigation. It further addresses the findings of different previous research studies which are touching the present approach and intended findings. The related facts were reviewed on books, journals, research papers, academic publications, and other scholarly articles available in any format such as hard copies, digital, audio and visual formats. GPS application in high-rise building construction, principle of GPS positioning, different GPS techniques and their applications in building construction, concepts of Differential GPS, CORS, and VRS, the application of Core Wall Control Survey System (CWCSS) and some of the identified GPS survey challenges are further discussed.

2.2 GPS in High-Rise Building Construction

Because of the growing demand for spaces, most of the crowded urban cities are now engaged in construction of super high-rise buildings. In a surveying perspective, high-rise buildings present many challenges for construction society while being constructed (Milind and Sumedh, 2004).

It is theoretically essential that a straight element being constructed should have exact vertical alignment when all biasing conditions are neutralized. In high-rise buildings, the vertical alignment is a very important aspect. High-rise buildings are subject to strong external tilt effects due to the various influencing factors, for instance, wind pressures, unilateral thermal effects by exposure to sunlight, and unilateral loads. Because of the varying loads of the structures due to differential raft settlement, differential concrete shortening, and construction tolerances, achieving the exact verticality or vertical alignment during the construction is a challenge. (Hayes, Sparks, Cranenbroeck, 2006).

“As on most construction sites, surveyors typically work around steel structures and obstructions and beneath or beside materials being lowered by crane. The working areas are congested with materials, equipment, and people, and of course working at height requires a special regard for safety. Under these conditions, surveying becomes difficult” (Cranenbroeck, 2010). If the construction site is in urban cities congested with many towers, the situation becomes more critical.

“Precise location plays a critical role in the construction sector” (ACIL, 2013). The precision of surveying depends on the reliability of the reference stations. Up to now, surveying on high-rise buildings is done by geodetic electro-optical total stations, and these instruments periodically being referenced to fixed external reference points with known coordinates. Because of the above explained different settlement and tilt effects of the building structures, it is not recommended to use the reference stations fixed on the building itself. The usage of ground based external fixed stations which are not subject to shifts is also limited up to the certain height or level of the buildings due to the congested built-up surroundings and excessive distance between the Total Station at upper level and reference stations while the relative distances between the fixed reference points become too small (Hayes et al. 2006).

Because of such challenges, once the construction has attained a certain height or a certain ratio of height to cross section, the surveyors need to have a proper survey control system at each level of the building so that it is accurately matching with the same control system at other levels for proper controlling of horizontal and vertical alignments (Hayes et al. 2006).

According to Milind and Sumedh (2004), although different survey techniques such as plumb bob, construction laser, geodetic electro-optical total stations etc. are applied for surveying during the phase of construction, there are glaring common disadvantages in all such methods.

In order to overcome the above such challenges in applying the traditional surveying techniques including Total Station in high-rise buildings, modern GPS applications are now found indispensable to provide reliable reference points at the upper level of the buildings for reliable horizontal and vertical controls (Cranenbroeck, 2010). Milind and Sumedh (2004) stated that development of differential GPS offers solutions to mitigate the most of problems. According to Mekik and Can, (2010), any engineering project relying on fast and accurate positions now finds its economical and productive solution in GPS, especially Real Time Kinematic GPS (RTK GPS).

The development in the Global Navigation Satellite Systems (GNSS) and its range of accuracy expands the use of Real Time Kinematic (RTK) GPS positioning techniques in building construction when rapid survey is needed. RTK GPS and the traditional techniques employing total stations give statistically compatible results; and the reduction in expenses for surveying, reduction in survey crew members, and eliminating the needs of accurate traverses and multiple control stations are further emphasizing the effectiveness and efficiency of GPS surveying in construction (El-Mowafy, 2004).

According to ACIL ALLEN (2013), Output from the Construction Industry in Australia is estimated to be between $448 million and $723 million higher in 2012 as a result of the use and application of augmented GNSS in activities such as site surveying and machine guidance. This could rise to between $1430 million and $2,507 million by 2020 with further adoption of augmented GNSS supported applications and expansion of GNSS services.

2.3 Overview on Global Positioning System (GPS)

"The Global Positioning System (GPS) is an all-weather, global, satellite-based, round-the-clock positioning system developed by the U.S. Department of Defense, that became available to the civilian surveying and navigation community in the early 1980s" (Rizos, 2001). The GPS system can be divided in to three main segments known as the *space* segment, the *control* segment and the *user* segment (Schofield & Breach, 2007, p321).

According to Schofield and Breach (2007), the space segment is composed of satellites. The constellation of satellites which are in almost circular orbits is at a height of 20200 km above the earth; and they are equally spaced in six orbital planes as in the Figure 2.1. The satellites broadcast ranging codes and navigation data on two frequencies, called L1 (1575.42 MHz) and L2 (1227.60 MHz); furthermore, U.S. government has announced in January 1999 to add two more civil signals denoted as L2C and L5 to new GPS satellites under the GPS modernization program. The L2C signals will be available for the application of non-safety of life at the L2 frequency, and L5 (1176.45 MHz) is intended to be used for safety-of-life use applications (Kaplan & Hegarty, 2006).

The control segment tracks and maintains the satellites in space. The segment monitors the satellites' health and signal integrity and maintains the orbital configuration. Further, it updates the satellite clock corrections and ephemerides as well as numerous other parameters essential for determining user requirements. Finally, the user receiver called user segment performs the navigation, positioning, timing, or other related functions (Kaplan & Hegarty, 2006).

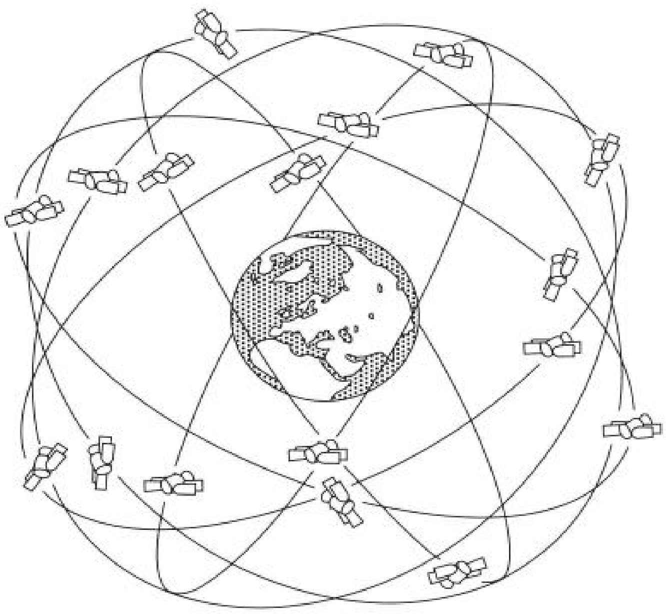


Figure 2.1: Satellite Constellation

Source: Kaplan & Hegarty (2006)

2.3.1 Principle of GPS positioning

Three dimensional positioning of a user's GPS receiver involve the measurement of distance (or range) from the receiver to at least three satellites whose *X*, *Y* and *Z* position is known. The satellite transmits a signal on which the time of its departure (t_D) from satellite is modulated. The receiver notes the time of signal's arrival (t_A). Then the time took by the signal to reach the user receiver from the satellite is (t_A- t_D) = Δ*t* called delay time. Then the distance or range *R* is obtained by equation 2.1 below (Schofield & Breach, 2007).

$$R = (t_A - t_D)\, c = \Delta t\, c \tag{2.1}$$

where *c* = velocity of light

In order to obtain the range measurement accurately, the receiver is required to have a clock as accurate as in the satellite, and has to be perfectly synchronized with it. When there is any difference between the times of two clocks, the difference termed as "clock bias" results in an incorrect assessment of Δ*t.* Consequently the computed distance or range also becomes incorrect called "pseudo-range". The effect of clock bias can be eliminated by the use of four satellites rather than three as shown below (Schofield & Breach, 2007).

Range *R* defined by the difference of coordinates in an *X*, *Y* and *Z* system is,

$$\mathrm{R} = (\Delta \mathrm{X}^2 + \Delta \mathrm{Y}^2 + \Delta \mathrm{Z}^2)^{1/2} \tag{2.2}$$

Assume *δR* is the error in *R* due to clock bias. It is constant throughout, then:

$$R_1 + \delta R = [(X_1 - X_P)^2 + (Y_1 - Y_P)^2 + (Z_1 - Z_P)^2]^{1/2} \tag{2.3}$$

$$R_2 + \delta R = [(X_2 - X_P)^2 + (Y_2 - Y_P)^2 + (Z_2 - Z_P)^2]^{1/2} \tag{2.4}$$

$$R_3 + \delta R = [(X_3 - X_P)^2 + (Y_3 - Y_P)^2 + (Z_3 - Z_P)^2]^{1/2} \tag{2.5}$$

$$R_4 + \delta R = [(X_4 - X_P)^2 + (Y_4 - Y_P)^2 + (Z_4 - Z_P)^2]^{1/2} \tag{2.6}$$

where, X_n, Y_n, Z_n = coordinates of satellites 1, 2, 3 and 4 (n = 1 to 4)

X_P, Y_P, Z_P = coordinates of user point/receiver P

R_n = measured ranges to the satellites

By solving the four equations for the unknowns X_P, Y_P, Z_P and δR, the position of the user point/receiver can be determined.

2.3.2 Differential GPS (DGPS)

"Differential GPS (DGPS) is a technique for reducing the error in GPS-derived positions by using additional data from a reference GPS receiver at a known position" (Grewal, Weill & Andrews, 2002). The principle of this technique is to install a GPS receiver at a known point, to compute the difference in observed pseudo range from the computed range for each measurement cycle and transmit these time lagged pseudo range corrections (Figure 2.2) over a fast and reliable data link to the receiver (Prothero & McKenzie, 1998). According to Schofield and Breach (2007), the fundamental assumption in DGPS is that the errors within the area of survey would be identical. This assumption is acceptable for most engineering surveying where the areas involved are small compared with the distance to the satellites.

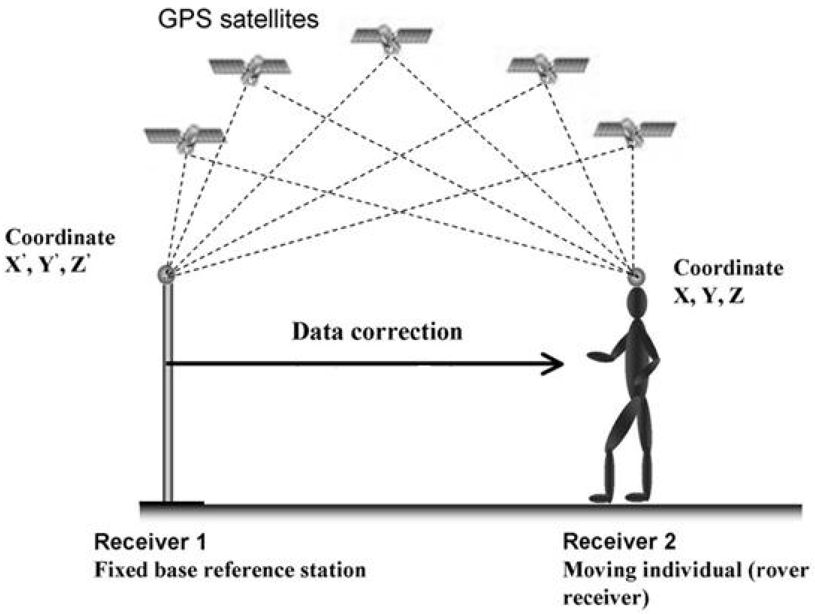


Figure 2.2: Differential GPS
Source: Terrier & Schutz, 2005

2.3.3 GPS Survey techniques in high-rise buildings

Schofield and Breach (2007) stated that according to different degree of accuracy required, the method of GPS positioning is ranging from dynamic (kinematic) to static with different kinds of field procedures. Generally pseudo-range measurements are used for navigation, while carrier frequency phase measurements (basis of differential GPS) are used for the higher precision necessary in engineering surveys. The following methods are used for relative positioning based on the use of carrier phase measurements.

2.3.3.1 Static positioning

This method is used where high precision is required like geodetic control surveys. One receiver is set up over a known station while the other receiver occupies where the coordinates are required. The observations on both stations are carried out simultaneously from 45 minutes to several hours in order to calculate the initial integer ambiguity. Then by post processing the data observed, the relative coordinates of unknown station can be determined accurately. Apart from control networks, this method is used for control densification, measuring plate movement in crustal dynamics and oil rig monitoring etc. (Schofield and Breach, 2007).

GPS static positioning is widely used for establishing survey controls and staking out at upper levels of the high-rise buildings or vertical towers (Hayes et al., 2006) and (Milind and Sumedh, 2004). Milind and Sumedh (2004) have further concluded in their study with an experiment with static GPS technique for verticality in tall buildings that “GPS was firstly used for only navigational purpose, but with the advancement in technique, now it is possible to use it for tower verticality”. Hayes et al. (2006) concluded after the Core Wall Control Survey System (CWCSS) applied in Burj Khalifa that “a combination of GPS survey techniques, Automatic Total Station, clinometers readings and mathematical modeling will provide a means to drive the construction of the world’s tallest building as a straight structural element and provided a wealth of data on building movement”.

2.3.3.2 Rapid Static

A receiver is set up on a reference point as 'master' receiver and it continuously tracks all visible satellites until the survey task is completed. The receiver termed 'rover' is taken to the points to be surveyed, and the observations on the rover stations are carried out for just a few minutes, typically 2-10 minutes. While travelling from one station to another, the rover can be switched off. Rapid static or fast static is accurate, economic and ideal for many engineering survey tasks. This method is applied for short baselines where systematic errors such as atmospheric, orbital, etc. are regarded as equal at all points to be surveyed (Schofield and Breach, 2007). With the development of DGPS and fast ambiguity resolution techniques, the rapid static method allows positioning of points with accuracy comparable to that of the GPS traditional static method; and it is widely used for rapid positioning in construction industry including building constructions (Santos, Souza & Freitas, 2000).

2.3.3.3 Reoccupation

This method which is also known as pseudo-kinematic procedure is regarded as a kind of static method. The survey is carried out as in the rapid static, but it is repeated after a time gap of one or two hours in order to make use of the change in receiver/satellites geometry to resolve the integer ambiguities. Here also the master is tracking throughout the duration of survey while rover visits the unknown points and repeats. Changing the receiver/satellite geometry is useful in positioning with cheaper single-frequency receivers and a poorer satellite constellation (Schofield and Breach, 2007). According to Remondi (1991), Reoccupation method is very useful where there are tall buildings and trees since the use of geometry change eliminates the effect of cycle slips in signals; further reoccupying a point verifies the accuracy of previous observations on the same point. Its rapidness and accuracy emphasizes its applications in high-rise buildings even in crowded cities.

2.3.3.4 Kinematic positioning

This method is applied for relative positioning from a moving platform like navigation. In this method, the integer ambiguity is to be resolved prior to the survey. Resolving the integer ambiguity, called initialization can be done by setting up the receivers at each end of a known baseline. In subsequent data processing, the coordinates are held fixed and the integer is determined; and by keeping one end of the baseline as the master, surveying can be carried out.

If there is no initial baseline with known coordinates, it can be established by static positioning prior to the survey. Alternatively ‘antenna swap’ method can also be used for initialization. An antenna is placed at each end of a short baseline of 5 to 10 m, and after observation for a short period of time the antennae are interchanged with lock and observation is continued. By the use of big change in the relative receiver/satellite geometry due to the interchange of antennae, the integer may rapidly be determined. Then antennae are returned to their original position prior to the survey. Reconnaissance prior to the survey is very important; otherwise the whole survey will be invalid if a cycle slip occurs in the signal.

According to the requirement, the movement of the rover may be ‘*continuous*’ or it will occupy at each unknown detail point for a very short time (less than two minutes); hence it is termed as ‘*Stop and Go*’. Traditional Kinematic Method and Real Time Kinematic (RTK) are the basic two observation methods in kinematic positioning (Schofield and Breach, 2007). The application of Kinematic GPS with Core Wall Control Survey System in Al-Hamrah Tower in Kuwait is emphasizing its applicability in high-rise buildings (Oh, 2012). The RTK positioning method is widely applied for precise setting out works in construction including high-rise buildings. RTK-GNSS observations at the highest story could provide a splendid alternative to traditional surveying techniques (Wunderlich, 2014).

2.3.3.5 Real Time Kinematic (RTK)

RTK is a recent innovative GPS technique that provides position accuracy close to that achievable with conventional carrier-phase positioning, but in real time. This technique can provide positional accuracy in millimeter level for wide range of applications including navigation, machine control, engineering, construction and hydrographic surveying (Langley, 1998). Unlike in previous methods, the relative position is determined instantaneously as the rover occupies the point to be surveyed while a master receiver is in position over a known point (Schofield and Breach, 2007).

One of the main objectives of "real-time kinematic" (RTK) products is to make GPS more competitive with traditional surveying technologies; and building construction is one of the main applications of RTK (Rizos and Han, 1998). In general, the layout using RTK GPS proved highly effective and accurate in building construction (Speed, 2011). With the use of Continuously Operating Reference Station (CORS), the application of RTK is vast for fast and accurate positioning. When comparing its results with static and conventional surveys, the findings are encouraging the use of RTK GPS (Shu, 2005), (Speed, 2011) & (Mekik & Arslanoglu, 2009).

2.3.4 CORS and VRS

Continuous Operating Reference Stations (CORS) are an important enhancement to a wide range of GPS surveying, mapping, and positioning activities. Most applications of GPS technology in surveying, mapping, and related disciplines have accuracy requirements that necessitate the use of a relative positioning technique. Relative positioning is performed by DGPS in either real time or static mode. In order to simplify the process of relative GPS positioning, government departments and many other organizations are establishing automated reference station facilities consist of a well-established and networked reference stations (Stone, 2006) and (Snay & ASCE, 2008). These stations are operating continuously and send the data to the server known as master control station which is continuously processing and estimating the corrections. With the concept of Virtual Reference Station (VRS), the use of CORS is vast (Wanninger, 2002).

When a rover is tracking the GPS signals, it approximates its position and sends it to the server via an effective communication link, and then the master control station estimates the correction to the approximated position and treats it as the virtual reference for following observations of the rover, see Figure 2.3. One primary benefit of VRS is that there is no need for a separate GPS base station and someone to guard it in order to perform RTK positioning (Landau, Vollath, & Chen, 2002).

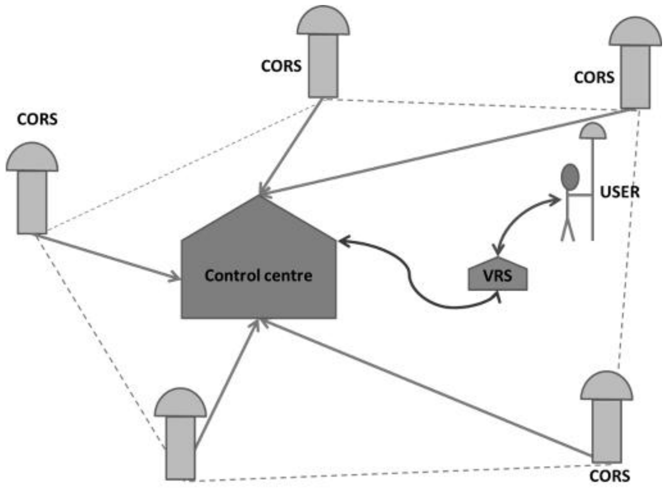


Figure 2.3: CORS and VRS

Source: Cina, Dabove, Manzino & Piras, 2015

2.4 Site Selection for GPS Surveys

According to Boal (1992), field reconnaissance is a must for the selection of specific locations or sites to ensure that the selected stations are suitable for GPS observations. GPS observations require direct line of sight to the broadcasting satellites. Since the signal transmitted could be absorbed, reflected or refracted by objects near the antenna or between the antenna and the signal source, it is desirable that, at normal antenna height, the sky be unobstructed from 15° above the horizon as illustrated in the Figure 2.4.

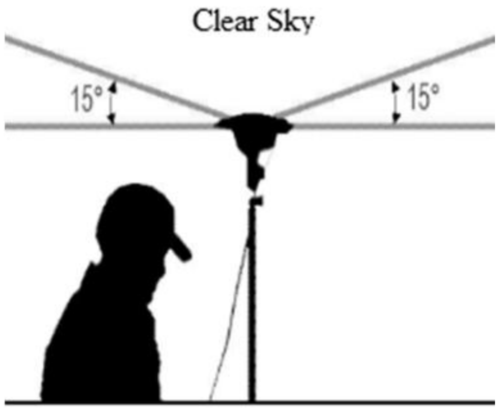


Figure 2.4 : Cut-off Angle
Source: www.spatial-ed.com

GPS signal reception is one of the major limitations in GPS survey applications (Kleusberg and Largley, 1990). Because of the nature of environment such as areas with tall trees or buildings and urban canyons, the efficiency and positional accuracy of GPS applications are highly affected. These kinds of surroundings are usually prone to birth of a source of “multipath error” (Xia, 2004 and Mekik and Can, 2010). In order to minimize the effects of multipath error sources, the area within at least 50 meters of the station should be free of artificial structures, particularly metal walls or fences, or natural reflective surfaces. As the radar or microwave transmitting stations, radio repeaters and high voltage power lines interfere the microwave GPS signals, the proximity of such sources should be avoided. An extended tracking period can sometimes reduce the effects of these biasing factors. It should be considered whenever the proximity of reflective surfaces and electromagnetic sources cannot be avoided in the project area. Thus the basic environmental requirements of unobstructed view of the sky in all directions, and free from multipath error sources and electromagnetic signal interferences to be fulfilled for precise GPS observations (James, 2015).

2.5 Challenges in Applying GPS Surveying for Verticality

Although the existing data sources do not show the same topic of this study to identify the challenges, the data sources express that the construction society is facing many challenges while applying GPS for surveying in building construction. "Implementing DGPS or RTK in real-time is a significant engineering challenge" (Rizos and Han, 1998). Some of the already identified challenges issues or constrains, and other possible challenges which have been hinted in different scholarly articles are discussed below.

2.5.1 Building movement

First and for most challenges in construction of tall buildings is ensuring verticality (Milind and Sumedh, 2004). From a surveying perspective, super high-rise and iconic buildings present many challenges (Cranenbroeck, 2010). Vertical structures are subject to strong external tilt effects caused, for instance, by wind pressures, unilateral thermal effects by exposure to sunlight, and unilateral loads. Because of the varying loads of the structures due to differential raft settlement, differential concrete shortening, and construction tolerances, achieving the exact verticality or vertical alignment during the construction is a challenge (Hayes et al., 2006; Cranenbroeck, 2010 and Wunderlich, 2014).

Under these conditions, surveying becomes difficult with any survey method including GPS. "The movement of the structure creates several problems for precise surveys. Theoretically, at any particular instant in time you need to know exactly how much the design center line of the building is offset from the actual vertical axis and at that same instant you need to know the precise coordinates of the instrument" (Zeiner, 2007). In order to overcome this challenge of movement effects, a specialized GPS surveying procedure called "Core Wall Control Survey System (CWCSS)" of Leica GeoSystems is used with the use of Precise Clinometer to measure the inclination and correct accordingly the positioning (Hayes et al., 2006, Cranenbroeck, 2010; and Speed, 2011).

2.5.2 Safety

"As on most construction sites, surveyors typically work around steel structures and obstructions and beneath or beside materials being lowered by crane. The working areas are congested with materials, equipment, and people, and of course working at height requires a special regard for safety. Under these conditions, surveying becomes difficult" (Cranenbroeck, 2010).

2.5.3 Shape of the structure

During the construction of a skyscraper with complex shape or design, the structure temporarily loses its exact verticality and the building tilts, contracts and expands (Speed, 2011). Because of the complex or different shape of the buildings, it becomes necessary to develop a survey system that can efficiently provide the large number of control points and can be used when the building is moving (Hayes et al., 2006 and Zeiner, 2007).

Kägi (as cited in Wunderlich, 2014) has reported that in contrast to a few low-rise buildings with exceptional oblique design, high-rise buildings have to strictly obey verticality according to the CAD or BIM models. Hence, it is the surveyor's prior task to ensure rigorous verticality of the structure from the very beginning of construction until completion. Though it is now possible to overcome this challenge with the different application of GPS, according to David (1999), it should be emphasized that GPS is not simply an alternative to all kinds of surveying activities, but has advantages and disadvantages which need to be evaluated".

2.5.4 Nature of environment

"As on most construction sites, surveyors typically work around steel structures and obstructions and beneath or beside materials being lowered by crane. The working areas are congested with materials, equipment, and people, and of course working at height requires a special regard for safety. Under these conditions, surveying becomes difficult" (Joël van Cranenbroeck, 2010).

Because of the nature of environment such as areas with tall trees or buildings and urban canyons, the efficiency and positional accuracy of RTK GPS application are highly affected. These kinds of surroundings are usually prone to birth of a source of error known as “multipath error”. A multipath error occurs when receiving GPS signals reflected from surfaces of ground or other objects around a receiver, and leads to a positional error resulting from the computation of the range between the satellite and receiver. No matter how carefully one tries to avoid this type of error, as the source of this error is the reflection of the GPS signals, high rise buildings in urban areas and industrial survey settings will still contribute to this owing to the nature of the surrounding (Xia, 2004 and Mekik and Can, 2010).

2.5.5 Quality control

Quality control is a very important aspect in construction of high-rise buildings. According to Rizos and Han (1998), Rizos (2001) and Stone (2006), in GPS positioning, the quality and reliability of data collection, data processing and data transmission should be ensured. But Quality control of the GPS kinematic positioning results is a critical issue. Although quality control procedures are applied, the quality control or validation criterion for Ambiguity Resolution (AR) is still a significant challenge. While using CORS and VRS, the reliability of the way of data collection, processing and data transmitted by the provider are still to be considered to ensure the quality. According to Higgins (1999), quality of ephemeris and starting coordinates is one of the main issues to be considered in designing a GPS deformation surveys.

2.5.6 Operation of reference receivers

Operation of reference receivers is an important constraint to be considered in taking steps for precise GPS positioning (Han & Rizos, 1996a). In order to achieve higher positioning accuracy, DGPS techniques must be applied. The major objective of DGPS is to cancel or reduce the error sources in the GPS measurements due to inaccurate GPS satellite clock and orbit data, atmospheric effects as well as GPS satellite and receiver related biases (Gao & Liu, 2001).

The principle of this technique is to install a GPS receiver at a known point to compute the difference and disseminate the correction (Prothero & McKenzie, 1998 and Schofield and Breach, 2007). In construction of high-rise buildings, surveying or setting out of structures may be needed at any time, hence there should be reference receivers operating continuously so that it can be used when necessary. In order to overcome this challenge CORS is established in many countries, cities and construction sites as well (Rizos, 2001; Hayes et al., 2006; Rizos and Han, 1998, Speed, 2011, Zeiner, 2007, KHOO, TOR & ONG, 2010 and Rizos, Han, Chen, & Chai, 2003). According to Dabove and Manzino (2015); Rizos and Han (1998) and Rizos (2001), when the separation between the reference receiver and rover increases the problems of accounting for distance-dependent biases grow. Hence the reference receivers should be within a certain range from the user receiver.

2.5.7 Distance from reference receivers

The distance from the user receiver to the nearest reference receiver may range from a few kilometers to hundreds of kilometers. As the receiver separation increases, the problems of accounting for distance-dependent biases grow. For medium-range or long-range precise GPS kinematic positioning, the distance dependent biases, such as orbit bias, ionospheric delay and tropospheric delay, will become significant problems. Because of these biases, the precision or accuracy of GPS observations become unreliable and reliable ambiguity resolution becomes an even greater challenge (Dabove and Manzino, 2015, Rizos and Han, 1998 and Rizos, 2001). According to Milind and Sumedh (2004), it constrains the overall accuracy of DGPS to about 2 mm for every kilometer of separation between the two receivers (i.e. 2 parts per million), up to the point where the two receivers can no longer see the same satellites.

2.5.8 Data latency

According to Brunner (1997), Rizos and Han (1998) and Rizos (2001), data latency is a challenge for many time-critical applications. The data latency is normally caused by the data transmission and the data processing, both of which cannot be avoided. Even if the data latency is only of the order of a few tenths of seconds, it may restrict many applications.

2.5.9 Ambiguity Resolution (AR)

According to the findings of Rizos and Han (1998) and Rizos (2001) in their studies on the topics of Precise Kinematic Applications of GPS - Prospects and Challenges and Precise GPS Positioning - Prospects and Challenges respectively, AR is a greater challenge in building construction in dense cities. Kim and Langley (2000) state in their research report that resolving the GPS carrier-phase ambiguities has been a continuing challenge for sub-centimeter-level high precision GPS positioning.

The GPS satellite signals are occasionally shaded or momentarily blocked in urban canyon due to buildings and other environmental conditions, and in these circumstances the integer ambiguity values are lost and must be re-determined or re-initialized. This process can take from a few tens of seconds up to several minutes with present commercial GPS systems for short range applications. During this "re-initialization" period the GPS carrier-range data cannot be obtained, and hence there is "dead" time until sufficient data has been collected to resolve the ambiguities. If interruptions to the GPS signals occur repeatedly, ambiguity "re-initialization" is, at the very least, an irritation, and at worse a significant weakness of commercial GPS-RTK positioning systems. When such interruptions occur repeatedly, the construction progress will be highly influenced (Rizos and Han, 1998 and Rizos, 2001).

2.5.10 Difficult to determine the observation span for AR

One of the main purposes of applying GPS surveying in high-rise buildings is to minimize the time spent for surveying activities. According to Rizos and Han (1998) and Rizos (2001), determining how long the observation span should be for reliable AR is a challenge for real-time GPS kinematic positioning. The longer the observation span is required the longer the "dead" time during which precise positioning is not possible. This can happen at the ambiguity initialization step if the GPS survey is just starting, or at the ambiguity re-initialization step if the GPS signals are blocked causing cycle slips or data interruptions. Consequently, there will be unexpected delays in the construction progress.

2.5.11 Need of powerful communication link

Real-time applications require a communication link between a service provider or reference station and the user. Currently, there are two main modes of communication that can be used in network RTK; either a duplex (bi-directional) communication or one-direction communication (El-Mowafy, 2011). Communication link is one of the greatest considerations in DGPS/RTK positioning. For an effective and reliable data transmission towards precise positioning, the communication link used should be powerful. Hence designing a local DGPS/CORS system or selecting an appropriate service provider for positioning is a big challenge with following technical aspects to be considered (Rizos and Han, 1998; Rizos, 2001 and El-Mowafy, 2011).

- Coverage
- Type of Service (whether it is a subscriber service or an open broadcast service)
- Functionality (whether one way or two way)
- Reliability
- Integrity
- Cost
- Data rate etc.

2.5.12 Expensiveness

One of the main objectives of GPS applications in construction industry is to reduce the cost (Rizos and Han, 1998). Though the GPS application in construction gives many advantages including the reduction of cost of laborers and surveying processes, the requirement of newer technology for precise DGPS positioning with better accuracy increases the cost of its capital, and maintenance

(Rizos and Han, 1998 and El-Mowafy, 2011). According to El-Mowafy (2011), the main disadvantage of facilitating a powerful communication link is the high cost of the infrastructure needed to build. Rizos and Han (1998) reported that precise positioning requires relative positioning, hence a minimum of two GPS receivers are required, and consequently the hardware cost is doubled with increased complexity. Furthermore, the kinematic positioning mode is more challenging than static positioning, and there is a "universal truth" that higher positioning accuracy implies higher costs.

2.5.13 Cycle slip

A cycle slip is a discontinuity in a receiver's continuous phase lock on a satellite signal. When lock is lost, a cycle slip occurs. A power loss, an obstruction, a very low signal-to-noise ratio, or other blocks to the satellite signals causes a cycle slip (Sickle, 2008). Trees, buildings, bridges, mountains and other tall structures are the causes of obstructions leading to the cycle slip (Kim and Langley, 2000).

2.5.14 Electromagnetic signal interferences

"GPS receivers are vulnerable to unintentional radiation from nearby radio transmitters and to intentional radiation such as jamming, meaconing and spoofing" (van Leeuwen, 2008). The primary source of unintentional interference of GPS signals, include ionospheric interference and radio frequency (RF) interference from the likes of broadcast television, VHF transmitters, personal electronic devices, Mobile Satellite Service (MSS) communications systems, and ultra-wideband (UWB) radar and com systems. There are also intentional disruptions to both the satellite and ground station segments of the GPS system (Burrell, 2003).

Electromagnetic signal interference can cause lower carrier-to-noise-density ratio (C/No) values and less reliable observations. Areas with very high wireless communication traffic or nearby high voltage power lines should be avoided.

Longer sessions could overcome some of the effect of the interference (SNJ, 2007).

2.5.15 Number of visible satellites and selective availability

Selective availability (SA) is a method of denying unauthorized GPS users of high real time position accuracy (Georgiadou and Doucet, 1990; Kremer et al. 1990). Because of the SA and obstructions in having clear sky for proper signaling, the GPS receivers in sub-canopy environments and urban canyons are facing difficulties in having sufficient number of visible satellites. Consequently, the satellite geometry becomes poor and position accuracy also becomes poor accordingly (Liu, 2002). Rizos (2001) reported that number of visible satellites is one the main issues in satellite positioning; and Roseblatt and Shimada (1992) pointed out that Selective Availability reduces real time positioning accuracy.

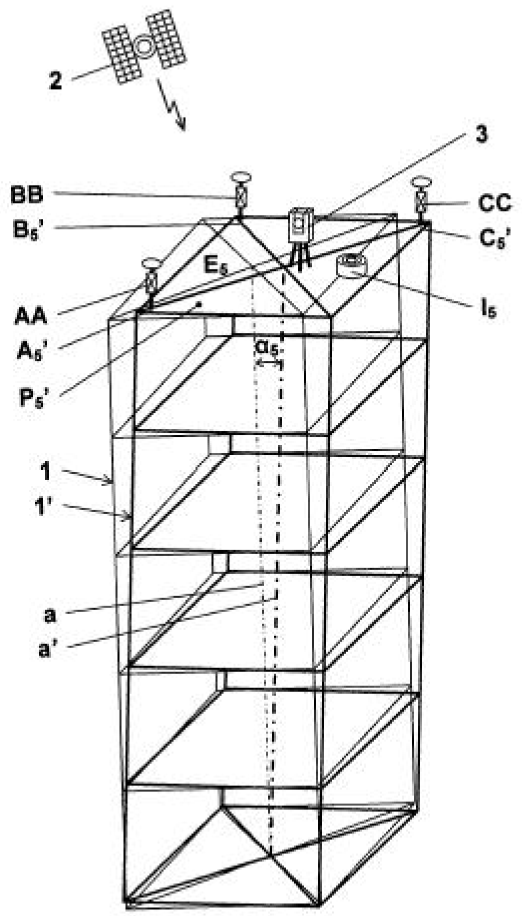
2.6 GPS against Traditional Surveying

Though the existing data sources do not explicitly expose the pros and cons of GPS surveying over traditional survey methods in the context of vertical alignments in high-rise buildings, generally there are greater advantages in GPS surveying over traditional surveying. Better level of accuracy, economical advantages from greater efficiency and speed of survey, reliability due to redundancy, around-the-clock operation, weather independency, no need for inter-visibility, estimation of 3D coordinates, reference can be taken from farther range etc. emphasize the applicability of GPS surveying in different fields in the industry including building constructions (Rao, 2010, p.328).

Although the GPS surveying provides greater advantages over conventional or traditional survey methods, GPS does have its share of=] disadvantages such as being depended on environmental conditions or nature of surroundings, need of clear sky for the visibility to satellites, need of trained labour force, high capital cost for instrumentation, not an alternative for all survey tasks etc. (Rao, 2010, p.328 and William, 2016).

2.7 Core Wall Control Survey System (CWCSS)

Since the movement of the vertical structure creates several problems in precise surveying; at particular instant in time, theoretically, there should be a system to determine exactly how much the design centre line of the building is offset from the vertical axis and at the same time the exact coordinates of the instrument used. When these two elements are determinable, the mean position taken over a short period for both elements can provide a suitable solution for the survey (Hayes et al., 2006). In order to determine these two elements, GPS reference station, GPS receivers with circular prisms, Total Station and precise Clinometers are combined as a complete data fusion system as shown in the Figure 2.4 and Figure 2.5.



Where,

AA, BB, CC -	GPS Receivers with Circular Prisms
A_5', B_5', C_5' -	Reference Points
a -	Ideal Axis
a' -	Actual Axis /Real Line
E_5 -	Uppermost Construction Level
I_5 -	Clinometer /Tilt Sensor
P_5' -	Reference Point on the floor
α_5 -	Tilt
1 -	Designed Structure
1' -	Tilted Structure
2 -	Satellite
3 -	Total Station

Figure 2.5: CWCSS Data Fusion System – Straight Real Line

Source: Joel, 2007

The data fusion system illustrates the surveying procedure called Core Wall Control Survey System (CWCSS) to provide a precise survey controls on the upper most construction level (E_5) of a high-rise building where its ideal axis (a) tended to real line (a') with a tilt (α_5). The reference points (A_5', B_5', C_5') are defined by satellite based positioning with GPS receivers (AA, BB, CC). The position of the geodesic Total Station (3) is determined relative to these reference points and to a singular point (P_5'); and the tilt (α_5) is acquired with a gravimetric tilt sensor (I_5). By considering the above positional and tilt measurements, a static coordinate system tied to ideal axis (a) is transformed to a coordinate system tied to the real line (a'), which is dynamically depends on the tilt. By periodically determining the tilt (α_5), the geodesic Total Station can be referenced and matched to the dynamically tilt-dependent coordinate system so that it can provide a precise and reliable surveying procedure (Joel, 2007).

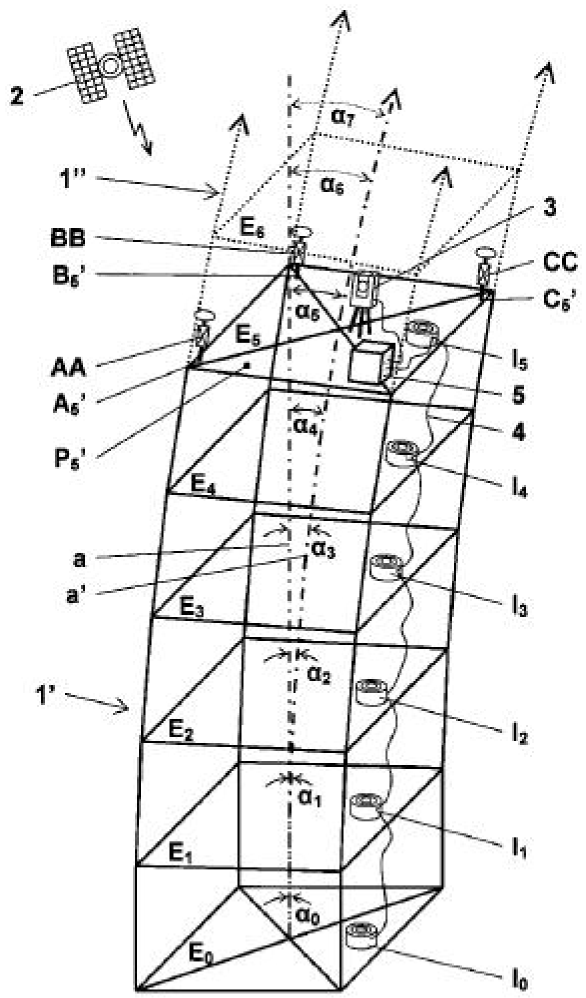


Figure 2.6: CWCSS Data Fusion System – Curved Real Line

Source: Joel, 2007

When the real line is curved as shown in the Figure 2.5, the values of tilt (α_0), (α_1), (α_2), (α_3), (α_4), (α_5), are acquired at closely spaced times on a number of construction levels (E_0), (E_1), (E_2), (E_3), (E_4), (E_5) and the curved real line (a') is modeled. By using the model, the values of (α_6), (α_7) or the pattern of the tilt beyond the current uppermost construction level (E_5) can also predicted (Joel, 2007).

2.8 Summary

In a surveying perspective, high-rise buildings present many challenges for construction society while being constructed. Even though the application of DGPS surveying in building construction is more advantageous than the traditional survey methods against these challenges, still there are some challenges or problems to be considered in such applications also. Building movements, safety, shape of the structure, nature of environment, quality control and necessity of CORS are some of the identified challenges to be considered in GPS applications for high-rise buildings. Though the existing data sources do not directly expose the particular challenges, it is expressed that there are many constraints, issues and challenges which are common for any kinds of GPS survey applications.

The general advantages and flexibility of GPS surveying over the traditional survey methods emphasize the applicability of GPS surveying in different fields in the industry including building constructions. The literature expresses that Static, Kinematic and RTK GPS techniques have been applied in building constructions with different field procedures. It should be noted that the techniques have been used with the combination of traditional survey methods; and the data sources to prove the standalone applications of the techniques in high-rise buildings is lacking. Static GPS technique has been used in several high-rise building construction projects for establishing precise control stations, and though the applications of other GPS survey techniques are hinted, there is a lack in the existing data sources to explicitly prove their applications in high-rise buildings. Though the data sources report the usage of different GPS survey techniques, the question of “what is the best suitable GPS survey technique for vertical alignments in high-rise buildings?” is still to be answered evidently. Core Wall Control Survey System (CWCSS) is a turning point in construction surveying for buildings. It emphasizes that the combination of GPS techniques, Total Station and other necessary items like precise Clinometers can provide a reliable survey procedure for vertical alignments in high-rise building construction.

CHAPTER THREE

3 METHODOLOGY

3.1 Introduction

Research methodology is a systematic way to solve a problem, and it is the main element in a research, which expresses the procedures how it is approached towards the indented findings. This chapter explains in detail the research design, population, sample selection, methods of data collection and analysis. It further presents an overview on the case studies and experiments conducted to check and verify the findings of preliminary data analysis. The concept of Relative Importance Index and the theories used for data analysis, such as 2D similarity coordinate transformation, least square adjustment and Total RMS Error are further discussed.

3.2 Research Design

According to the research problems mentioned in Chapter 1, this research study has been designed to achieve the aim of "studying the suitability of GPS survey techniques for vertical alignments in high-rise buildings and the challenges over traditional survey methods." In order to accomplish the aim and objectives, the study has been oriented to find answers for the questions of "What GPS techniques are applicable for vertical alignment in high-rise buildings, which is the best among those different GPS techniques, and what constrains, issues or challenges are there in such applications?"

In order to conclude with accurate and reliable answers for the questions, the problems were approached by analyzing both primary and secondary data collected through literature survey on the existing documents, interviews, questionnaire survey, case studies and experiments. The research approach is briefly illustrated in the Figure 3.1.

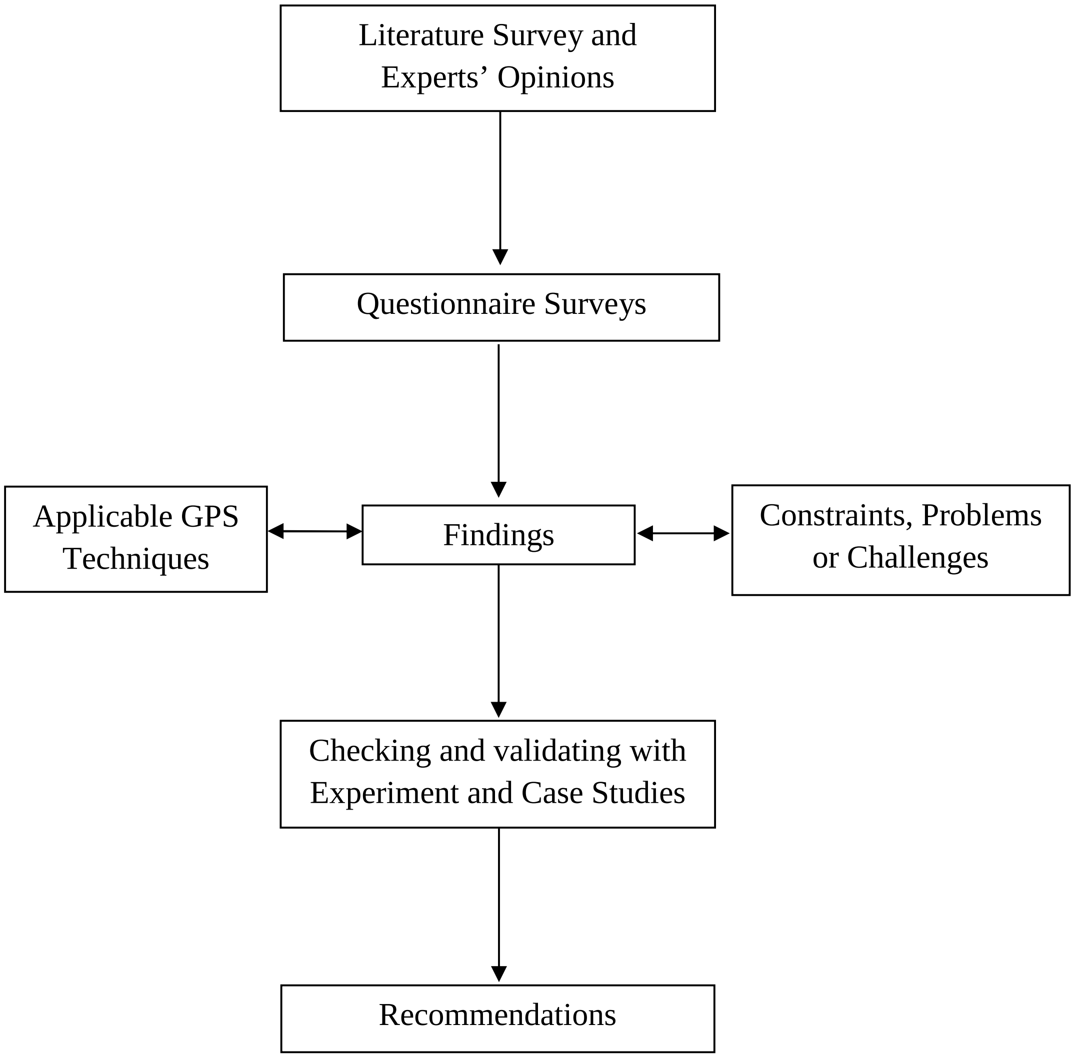


Figure 3.1: Body of Knowledge

At first, a general idea on GPS techniques applicable for controlling verticality in high-rise buildings and possible challenges were gained through an in-depth literature survey and interviews with related professionals and experts having enough knowledge and experience in the field. Then a structured questionnaire was prepared with the knowledge gained and presented to the selected experts and professionals for improving the validity, reliability and accuracy of the findings while searching for further knowledge on the techniques, constraints, issues and other factors of challenges through extended questions.

Then by quantitatively analyzing the data gained through the expert comments and the questionnaire survey, the findings, specially the GPS techniques were checked and validated by conducting case studies and experiments for better conclusions and recommendations by comparing their accuracy, efficiency, time consuming and cost implication.

3.3 Data Collection

Primary and secondary data for the study were collected through literature survey, structured questionnaire survey which allows the respondents to share their ideas freely, semi structured interviews, case studies, experiments or direct observations and conversations through emails and social media etc. The process of data collection was carried out in three phases.

3.3.1 Phase 1 – Literature survey and unstructured interviews

At first the existing documents such as books, journals, research papers and other scholarly articles were reviewed; and then three academically qualified professionals and four field practitioners having enough background knowledge and experience in the relevant fields were interviewed to have a general idea on the GPS techniques applicable for controlling verticality in high-rise buildings, and possible constraints, issues and other factors by which the applications are challenged. As per the information gained in the literature and unstructured interviews as above, a pilot questionnaire was prepared and issued to some selected academically qualified professionals and field experts including the above in order to improve the validity and accuracy of the questionnaire and information included. Then it was amended as per the comments given by the professionals and finalized as a structured questionnaire (annexed as Annexure – A) so that the professionals who are responding to it can share their own ideas freely. The professionals who were included in the above sample were first asked to confirm whether they have enough background knowledge and experience in GPS surveys and high-rise building constructions. It was confirmed that they were really proficient enough with more than ten years of experience in related fields so that they can provide reliable information for the study.

3.3.2 Phase 2 – Questionnaire survey and semi-structured interviews

In order collect reliable data for preliminary analysis, questionnaire surveys and semi-structured interviews were conducted among the selected field experts and academically qualified professionals with the questionnaire prepared as above. The surveys and interviews were designed so that to improve the validity, reliability and accuracy of the findings from the literature and preliminary interviews and find further information on the GPS techniques and the constraints, issues and other factors of challenges through extended questions.

Actually it was a very tricky task to identify the actual population and sample for the study. Thus the high-rise building construction projects where GPS survey techniques applied were first identified. Then the field experts who were involving with the GPS surveys in those projects were included in the questionnaire surveys and interviews. Further the academically qualified professionals and field experts who have enough experience in the related fields were identified and included in the sample. Since the GPS applications in high-rise buildings are limited in Sri Lanka, the survey was conducted out of Sri Lanka also to include the qualified professionals from different parts of the world.

3.3.3 Phase 3 – Case studies and experiments

After a preliminary analysis of the data gained through the above process, case studies and experiments were carried out to check and validate the findings for better conclusions and recommendations. Further details on the case studies and experiments have been given in section 3.4 of this chapter and Chapter 5.

3.3.4 Population and sample

The population of the study was the entire society having enough knowledge and experience on GPS applications and construction of high-rise buildings. Since the GPS applications in high-rise buildings are limited in Sri Lanka, no geographical limitations were applied on data collection process so that the competent professionals from any part of the world can be included in the survey. Since the actual population from which the sample was selected for analysis was not known, **Non-Probability Sampling** technique was selected to collect the data for study. The number of professionals or experts who are interested in the fields is not much and they are not available everywhere. Thus the professionals or experts who were included in the sample were first identified from wherever they were available to reach in different parts of the world. Although the surveying tasks in most of the building construction sites are done by professional surveyors, sometimes it is also done by engineers, architects or other practitioners who were specially trained for the tasks. Thus the sampling frame includes surveyors, engineers, architects and other specially trained field practitioners who have enough knowledge and skills in related fields.

When considering the information included in the questionnaire, some facts cannot be responded by the field experts without having thorough background knowledge on GPS and its applications. Thus the academically qualified professionals who were serving in both academic and industrial sectors were also included in the sampling frame to have unambiguous response for the above facts. Although around 100 professionals were available to include in the sample, some of them were omitted because of their insufficient level of expertise and experiences as such the finalized sample size was with only 78 members. Surveyors were the majority in the sample with 56 participants and as per the availability of participants in other categories, 11 structural engineers, 10 academically specialized professionals and an architect were also included so that to have reliable answers for the questions.

3.3.5 Questionnaire

The questionnaire was prepared towards achieving the objectives oriented to the main aim (refer Appendix–A). It was divided into five parts to make the questionnaire simple to the respondents; and each part was carrying different information needed for analysis. Part-I was looking for personal information of the respondents; and it was used for analyzing the different backgrounds of the respondents. Part II consists of six questions was asking about their working experience in the related fields, and the methods of surveying and techniques used for vertical alignment in their projects of high-rise buildings.

In order to expose that generally there are challenges in surveying for high-rise buildings, Part III of the questionnaire was carrying the problems faced while applying the traditional surveying techniques for controlling verticality in high-rise buildings. The respondents were expected to cast their level of acceptance by choosing a level from typical five-level Likert items ranged as "Strongly Disagree, Disagree, Slightly Agree, Agree and Strongly Agree". Further it was comparing the level of accuracy, efficiency, quality and cost implication of GPS applications with traditional surveying methods with another five-level Likert items leveled as "Worst, Worse, About the Same, Better and The Best".

Part IV of the questionnaire was carrying four questions looking for respondents' recommendations on GPS techniques, comparison of accuracy of those techniques and the challenges related with GPS survey applications for controlling verticality in high-rise buildings. At first the respondents were expected to recommend on different GPS techniques whether they are applicable for vertical alignments in High-Rise building based on their effectiveness or efficiency by choosing an item from typical five-level Likert items given as "Strongly Not Recommended, Not Recommended, Questionable, Recommended and Strongly Recommended". Then it was comparing the accuracy of those techniques by asking the respondents to assess them by indicating their view in given Likert items ranged as "Poor, Average, Good, Very Good and Excellent".

Third question of this part was a simple question with 'YES' or 'NO' answering options. It was to check the general overview of the respondents on the problems in GPS applications for vertical alignment in high-rise buildings. The final section of this part was exposing some problems or challenges related with such GPS applications in high-rise buildings during construction. According to the nature of the challenges, they were divided into three subsections as Practical Challenges, Operational Challenges and Space Related Challenges. The problems directly related with GPS applications in high-rise buildings were categorized as Practical Challenges whereas the Operational Challenges and Space Related Challenges convey the problems, issues or constraints related with the operation of GPS and other necessary equipment and the disturbances to GPS signals in the space respectively. Here also the respondents were expected to cast their level of acceptance by choosing a level from the typical five-level Likert items as above for traditional surveying methods.

Both Part III and Part IV were having spaces for respondents to add more facts apart from the given information. Further, Part V was completely allocated for them to freely share their expertise, experience and advices. The questionnaire was prepared in two formats; one was as a word processed document and another one was as an electronic form in Google Drive. It was issued to the respondents either by hand directly and self-enumeration methods such as email, social network and other forms of internet.

3.3.6 Interviews

In order to add more value and construct the questionnaire with more details, unstructured interviews were conducted at early stage with 3 academically specialized professionals and 4 field practitioners having enough expertise experiences in GPS and high-rise building constructions. Later, semi-structured interviews with the above structured questionnaire were conducted with extended questions among the respondents who were available to reach directly. A discussion on LinkedIn social network and email discussions were also done at the early stage of the research.

3.3.7 Method of data analysis

Quantitative data analysis approach and when necessary qualitative approach was applied to conclude with results. Descriptive statistics were used with Microsoft Excel tools for the analysis. According to the questionnaire, the number of respondents and their different backgrounds has been presented in percentages with the help of Pie Chart. From first three questions in Part II of the questionnaire, the levels of experience of the respondents in constriction surveying, GPS surveying and high-rise building constructions were analyzed. The levels were categorized as shown in Table 3.1. Then it has been depicted in percentages and proportions with Pie Charts.

Table 3.1: Level of Experience

Experience	Level
Below 01 year	Interns
01 to 03 years	Novice
03 to 5 years	Intermediate
5 to 10 years	Advanced
Above 10 years	Expert

The number of stories of buildings in which the respondents were involved was categorized as shown in Table 3.2. The numbers of respondents in each category have also been presented in percentages and proportions with Pie Chart.

Table 3.2: Building Categories (Frederick & Kent, 2007)

Stories	Categories
Less than 4 Stories	Low-Rise
4 to 12 Stories	Mid-Rise
13 to 40 Stories	High-Rise
More than 40 Stories	Skyscraper

The method/methods of surveying on which the respondents are depended at present, and the GPS techniques used by them have also been demonstrated in percentages and proportions with Bar Charts by analyzing the responses for last two questions in Part II of the questionnaire. Part III and Part IV of the questionnaire demonstrated the problems or challenges of traditional surveying methods and modern GPS survey applications respectively while they are used for vertical alignments in high-rise buildings. Based on the respondent's attitudes on the problems or factors of challenges given, each and every factor were decided at first whether it was a considerable cause of problem or challenge by considering the numbers of positive and negative responses.

Table 3.3: Responses, Points and Type

Responses	**Weight**	**Type**
Strongly Disagree	1	Negative Response
Disagree	2	Negative Response
Slightly Agree	3	Positive Response
Agree	4	Positive Response
Strongly Agree	5	Positive Response

Then by assigning value to each type of response as above in Table 3.3, Relative Importance Index (RII) were calculated for each and every factor of problem or challenge as per the frequencies of responses of each item by using the formula:

$$RII = \frac{\sum W n}{A N} \times 100 \quad (3.1)$$

Where,

W - Weight assigned to each type of response

n - Frequency of responses for each type

A - Highest weight assigned

N - Total number of responses

For instance, suppose factor 'A' has responses as below in Table 3.4,

Table 3.4: Types of Responses

Responses	**Weight**	**No. of Responses**
Strongly Disagree	1	n_1
Disagree	2	n_2
Slightly Agree	3	n_3
Agree	4	n_4
Strongly Agree	5	n_5

$$RII\ of\ 'A' = \frac{1n_1+2n_2+3n_3+4n_4+5n_5}{5\,(n_1+n_2+n_3+n_4+n_5)}\ x\ 100 \qquad (3.2)$$

Then by using the calculated RII values of the factors of challenges, the significance of each factor can be compared with others and demonstrated. The results of this analysis have been illustrated in Tables and Bar Charts for easiness of understanding.

Second question in Part III of the questionnaire was to compare the GPS applications with traditional surveying methods of vertical alignments. According to the attitudes of the respondents, the level of accuracy, efficiency, quality and cost implication of GPS surveys against traditional methods were assessed by considering the percentages of positive and negative responses; and they have also been illustrated by bar charts. Since this comparison has been done in order to check the suitability of GPS survey applications in high-rise buildings, assessing the above parameters of GPS as ‘About the Same’ was also taken as a positive attitude as shown in the Table 3.5.

Table 3.5: Types of Assessments

Assessment	**Type (+) or (-)**
Worst	Negative
Worse	Negative
About the Same	Positive
Better	Positive
The Best	Positive

The first question in Part IV of the questionnaire was to check the effectiveness or applicability of different GPS techniques with the recommendations of respondents. According to the frequencies of positive and negative recommendations, it was first decided whether each and every technique is applicable or not for vertical alignments in high-rise buildings. Then by assigning weight to each type of response as given in Table 3.6, RII value of each technique was calculated as above in equation (3.2). By using the RII values, the effectiveness or applicability of the techniques can be compared.

Table 3.6: Types of Recommendations

Responses	**Weight**	**No. of Responses**
Strongly Not Recommended	1	n_1
Not Recommended	2	n_2
Questionable	3	n_3
Recommended	4	n_4
Strongly Recommended	5	n_5

Then by analyzing the responses to second question in Part IV, which compares the accuracy of the GPS techniques, the findings in the first question were supported. The method of analysis was as same as in the first question by assigning weights as in the Table 3.7 below.

Table 3.7: Level of Accuracy

Responses	Weight	No. of Responses
Poor	1	n_1
Average	2	n_2
Good	3	n_3
Very Good	4	n_4
Excellent	5	n_5

3.4 Case Studies and Experiments

In order to check and validate the findings from the preliminary data analysis of the study, case studies were carried out at some selected high-rise building construction sites of 'The Lotus Tower', 'The Elements' and 'Clearpoint' in Colombo city area. Since the Colombo Lotus Tower was the one and only high-rise building construction site where the GPS technique is used for surveying in Sri Lanka, experiments on the GPS techniques were conducted separately at other two construction sites while studying the traditional survey methods used. Detail explanations on the case studies and experiments have been given on Chapter 5.

3.4.1 2D Similarity coordinate transformation

Normally GPS estimates the coordinates based on World Geodetic System 1984 (WGS84), then they are transformed to the National Grid System SLD99 for local references. Since the entire survey activities at the selected building construction sites were based on different arbitrary coordinate systems, they were first referenced to the national grid system by 2D conformal or similarity coordinate transformations. This 4 parameter transformation is performed by translations or shifts in X and Y directions, rotation and scaling.

a. Translation

The translation parameter changes the origin from the present coordinate system to required new coordinate system. During this process the axes are not rotated and the scale is remaining not changed.

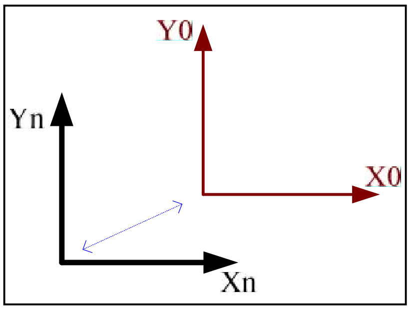


Figure 3.2: Translation

$\mathbf{X_n = X_0 \pm DX_0}$ $\mathbf{Y_n = Y_0 \pm DY_0}$ ……………………………… (3.3)

Where, $\mathbf{X_n, Y_n}$ **-** new coordinate system

$\mathbf{X_0, Y_0}$ **-** original coordinate system

$\mathbf{DX_0, DY_0}$ **-** shifts in X and Y

b. Scaling

Scaling is performed by keeping the origin and axes are fixed.

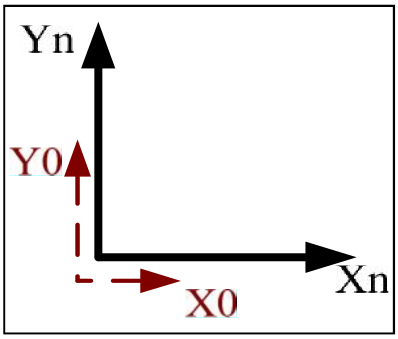


Figure 3.3: Scaling

$\mathbf{X_n = S_X \times X_0}$ $\mathbf{Y_n = S_Y \times Y_0}$ ………………………………… (3.4)

Where, **S –** scale

c. Rotation

Then the axes are rotated about the origin as in the Figure 3.4.

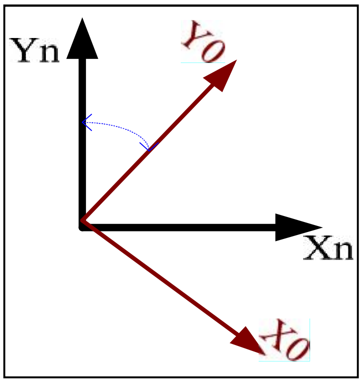


Figure 3.4: Rotation

$$\mathbf{X_n = X_0 \cdot cos(\sim) + Y_0 \cdot sin(\sim);} \qquad \mathbf{Y_n = - X_0 \cdot sin(\sim) + Y_0 \cdot cos(\sim)} \quad \ldots (3.5)$$

Where, ~ – rotation angle

By combining the above three operations, it can be written as

$$\begin{bmatrix} Xn \\ Yn \end{bmatrix} = \begin{bmatrix} a & b \\ -b & a \end{bmatrix} * \begin{bmatrix} Xo \\ Yo \end{bmatrix} + \begin{bmatrix} c \\ d \end{bmatrix} = S * \begin{bmatrix} \cos\sim & \sin\sim \\ -\sin\sim & \cos\sim \end{bmatrix} * \begin{bmatrix} Xo \\ Yo \end{bmatrix} + \begin{bmatrix} DXo \\ DYo \end{bmatrix} \quad \ldots (3.6)$$

Hence,

$$\begin{aligned} Xn &= S \cdot \cos\sim \cdot X_0 + S \cdot \sin\sim \cdot Y_0 + DX_0 \\ Yn &= -S \cdot \sin(\sim) \cdot X_0 + S \cdot \cos(\sim) \cdot Y_0 + DY_0 \end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

it can be written as

$$\begin{aligned} Xn &= a \cdot X_0 + b \cdot Y_0 + c \\ Yn &= -b \cdot X_0 + a \cdot Y_0 + d \end{aligned} \qquad \begin{bmatrix} Xn \\ Yn \end{bmatrix} = \begin{bmatrix} X_0 & Y_0 & 1 & 0 \\ Y_0 & -X_0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} \quad \ldots\ldots\ldots (3.8)$$

by applying the values for **X_n, Y_n** and **X_0, Y_0** of two known points, the values of **a,b,c**, and **d** can be calculated by using the equation (3.9).

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} X_{01} & Y_{01} & 1 & 0 \\ Y_{01} & -X_{01} & 0 & 1 \\ X_{02} & Y_{02} & 1 & 0 \\ Y_{02} & X_{02} & 0 & 1 \end{bmatrix}^{-1} * \begin{bmatrix} X_{n1} \\ Y_{n1} \\ X_{n2} \\ Y_{n2} \end{bmatrix} \quad \text{………………………..} \ (3.9)$$

Then the values of scale, rotation angle and translations can be calculated from equations shown above.

3.4.2 Least square adjustment

Since there were three known control points, number of known variables is greater than the number of unknown variables, then Least Square Adjustment theory was applied to make use of the redundancy as in the equations (3.10) and (3.11).

$$\begin{bmatrix} X_{n1} \\ Y_{n1} \\ X_{n2} \\ Y_{n2} \\ \ldots\ldots \\ \ldots\ldots \\ \\ X_{nn} \\ Y_{nn} \end{bmatrix} = \begin{pmatrix} X_{01} & Y_{01} & 1 & 0 \\ Y_{01} & -X_{01} & 0 & 1 \\ X_{02} & Y_{02} & 1 & 0 \\ Y_{02} & -X_{02} & 0 & 1 \\ \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ \\ X_n & Y_n & 1 & 0 \\ Y_n & -X_n & 0 & 1 \end{pmatrix} * \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} \quad \text{………………..…….} \ (3.10)$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$L \quad = \quad A \quad * \quad V$$

Hence, V is given by

$$V = (A^T PA)^{-1} * (A^T PL) \qquad \text{……… ....………………… (3.11)}$$

Where, P is weight matrix and it is equal to 1 (P=1) as same conditions are given for all observations (Yaron & Moshe, 2009).

3.4.3 Total RMS error

RMS error is the distance between the correct coordinates and the observed coordinates of a particular point (Jaber, 2006). In order to compare the accuracy of the GPS techniques, Total RMS Error of each GPS technique was calculated.

$$\text{RMS Error} = \sqrt{(x_r - x_i)^2 + (y_r - y_i)^2} \qquad \text{……………………… (3.11)}$$

Where, X_r, Y_r – Observed Coordinates

X_i, Y_i – Correct Coordinates

$$\text{Total RMS Error} = T = \sqrt{R_x^2 + R_y^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} XR_i^2 + YR_i^2} \qquad \text{.... (3.12)}$$

Where, Rx = x RMS Error

Ry = y RMS Error

XR_i = x Residual of Point *i*

YRi = y Residual of Point *i*

n = Number of Points

3.4.4 Paired comparison analysis and decision matrix

Finally paired comparison analysis was done among the parameters of accuracy, efficiency, time consuming and cost implications of the GPS techniques for ranking the parameters as per their significances. Then by using the weighted parameters and decision matrix, the final decision on the GPS techniques was taken.

3.5 Summary

In order to find accurate and reliable answers for the research questions towards achieving the aim and objectives of the study, the problems were approached by analyzing both primary and secondary data collected through comprehensive literature survey on the existing documents, interviews, questionnaire survey, case studies and experiments. At first, a general idea on GPS techniques and the challenges were gained through literature survey and interviews with related professionals having enough knowledge and experience in the field. Then it was presented to the selected field experts and academic professionals for validation while looking for further knowledge on the techniques and challenges through questionnaires and semi structured interviews.

Since exact population was not known, data were collected through a non-probability sample without any geographical limitations so that an expert or professional can respond from any part of the world. Then a preliminary data analysis was done with Microsoft Excel package to identify the suitable GPS techniques for vertical alignments in high-rise buildings and the challenges to be considered in such applications. According to the Relative Importance Indices (RII), the techniques and challenges were ranked as per their significances.

Then the above findings were cross-checked and validated with case studies and experiments conducted at The Lotus Tower, 'The Elements by Fairway' and 'Cleapoint' high-rise building construction sites in Colombo. The best suitable GPS survey technique was identified by comparing the techniques' accuracy, efficiency, time consuming and cost implications.

CHAPTER FOUR

4 DATA ANALYSIS

4.1 Introduction

Analysis is the main element in a research work. This chapter explains in detail how the collected data were analyzed and presented to conclude with the findings. Both quantitative and qualitative approaches have been applied to draw the conclusions and recommendations. Descriptive statistics with Microsoft Excel tools have been used for the data analysis and the results of the analysis are presented in numeric values and/or illustrated graphically for better understandings.

4.2 Background and Experience of the Respondents

The professional backgrounds of the respondents were as shown in the Table 4.1. Surveyors were the majority (72%) in the sample having altogether seventy-eight members including industrial and academically specialized professionals.

Table 4.1: Background of the Respondents

Background	No. of Respondents	%
Surveyor	56	71.79
Engineer	11	14.10
Architect	1	1.28
Academic Professional	10	12.82
Total	**78**	**100**

It can be illustrated graphically by Pie chart as in the Figure 4.1. Generally surveyors, structural engineers and also architects play important roles in the vertical alignments of high-rise buildings. As the selected sample includes those professionals who can provide reliable information on the subject, the reliability of the findings of the study is emphasized. The participation of the academically specialized professionals, who can ensure the findings of the study with their thorough background knowledge on the related fields, further emphasizes the reliability and accuracy of the findings.

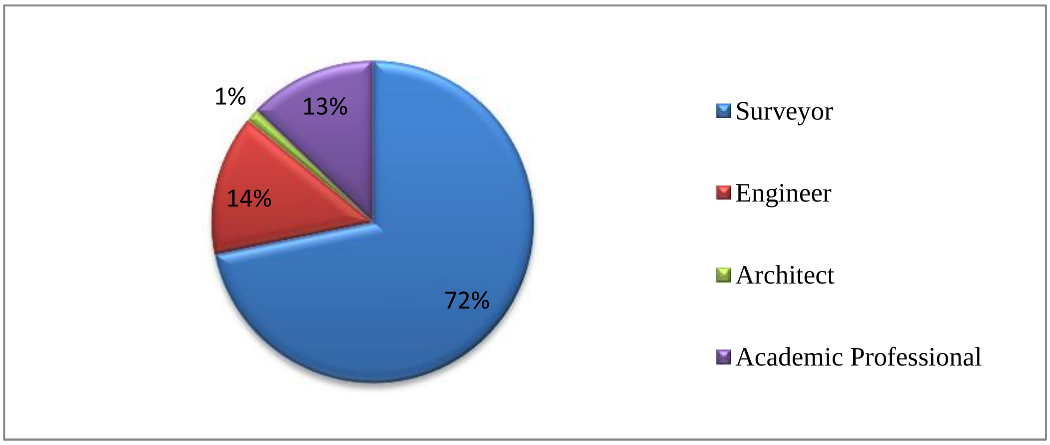


Figure 4.1: Respondents

The respondents were from seven different countries as in the Table 4.2. This expansion of the professionals' participation was actually to include the competent professionals in the sample. Sri Lankan were the majority in the sample and it includes the experts from Australia, Belgium, KSA, Qatar, UAE and USA.

Table 4.2: Workplaces of the Respondents

Country	No. of Respondents
Australia	3
Belgium	1
KSA	9
Qatar	16
Sri Lanka	30
UAE	15
USA	4
Total	**78**

As illustrated in the Table 4.3 and Figure 4.2, the experiences in construction surveying of around 74% of the members in the sample were more than 5 years so that they could be treated as matured professionals and experts.

Table 4.3: Experience in Construction Surveying

Experience	**Level**	**No. of Respondents**	**%**
Below 01 year	Interns	2	2.78
01 to 03 years	Novice	6	8.33
03 to 5 years	Intermediate	11	15.28
5 to 10 years	Advanced	28	38.89
Above 10 years	Expert	25	34.72
Total		**72**	**100**

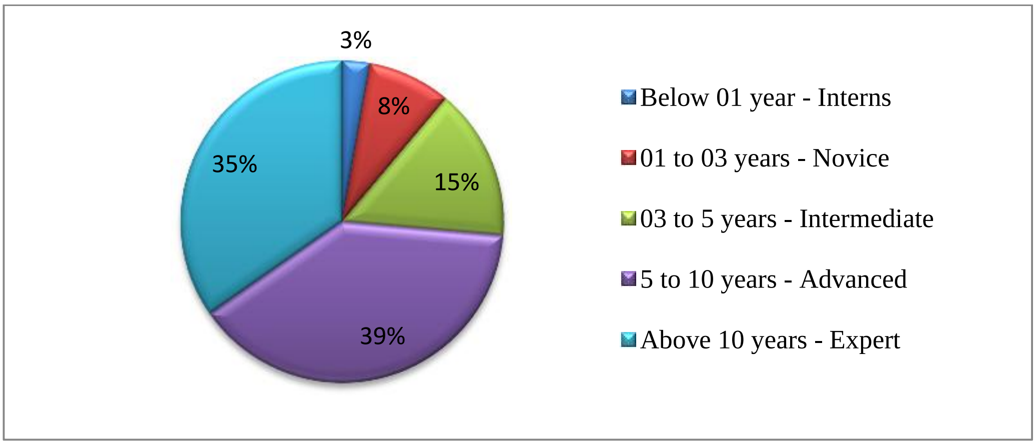


Figure 4.2: Experience in Construction Surveying

It is illustrated in the Table 4.4 and Figure 4.3 that around 77% of the members in the sample have at-least 3 years of experience in GPS surveying. It shows that the members are competent to provide reliable information towards the objectives of the study.

Table 4.4: Experience in GPS Surveying

Experience	Level	No. of Respondents	%
Below 01 year	Interns	4	5.56
01 to 03 years	Novice	12	16.67
03 to 5 years	Intermediate	14	19.44
5 to 10 years	Advanced	16	22.22
Above 10 years	Expert	26	36.11
Total		**72**	**100**

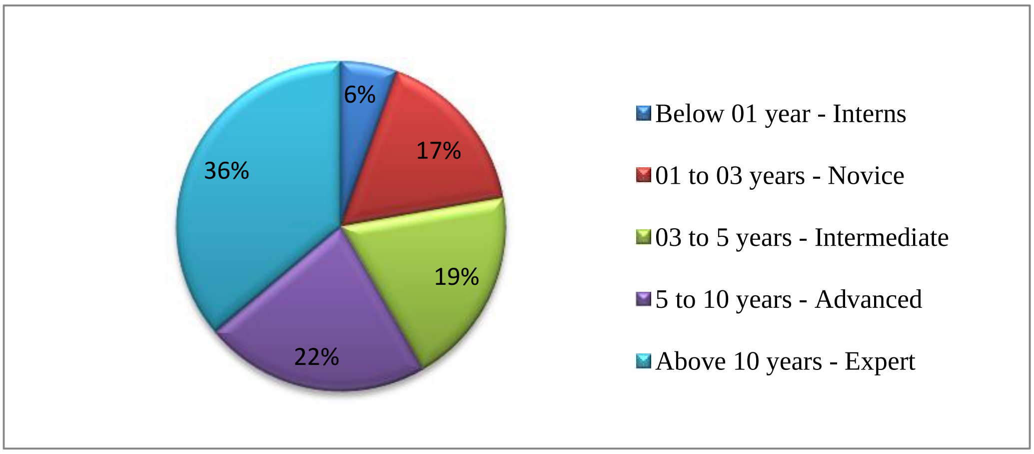


Figure 4.3: Experience in GPS Surveying

Likewise, the level of experience in construction of high-rise buildings as illustrated in the Table 4.5 and Figure 4.4 further emphasizes the validity and reliability of the information gained from the sample. Around 85% of the professionals were having at-least 3 years of experiences and 70% of them were advanced professionals and experts.

Table 4.5: Experience in High-Rise Building Construction

Experience	Level	No. of Respondents	%
Below 01 year	Interns	4	6.06
01 to 03 years	Novice	6	9.09
03 to 5 years	Intermediate	10	15.15
5 to 10 years	Advanced	23	34.85
Above 10 years	Expert	23	34.85
Total		**66**	**100**

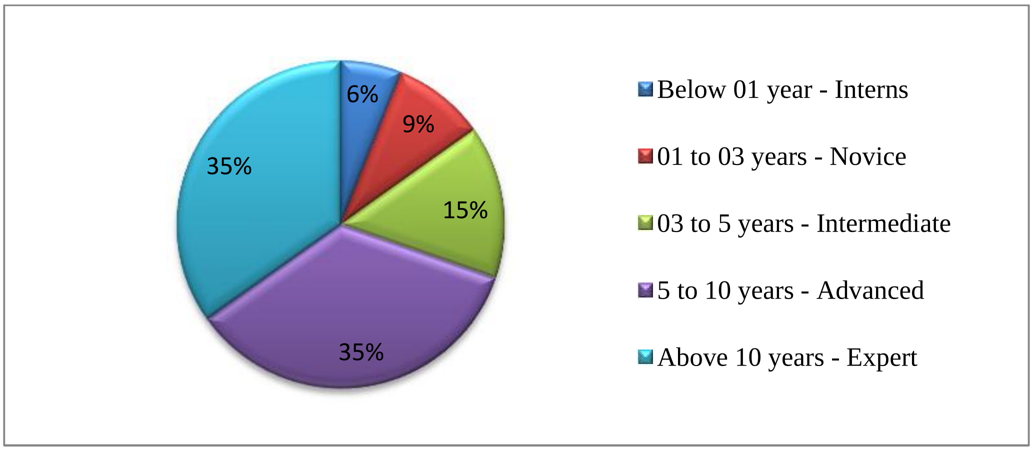


Figure 4.4: Experience in High-Rise Building Construction

Table 4.6 and Figure 4.5 express that around 75% of the members included in the sample have experience in construction of high-rise buildings of at-least 13 floors.

Table 4.6: Number of Stories of Buildings involved

Stories	Level	No. of Respondents	%
Less than 4 Stories	Low-Rise	6	8.45
4 to 12 Stories	Mid-Rise	12	16.90
13 to 40 Stories	High-Rise	22	30.99
More than 40 Stories	Skyscraper	31	43.66
Total		**71**	**100**

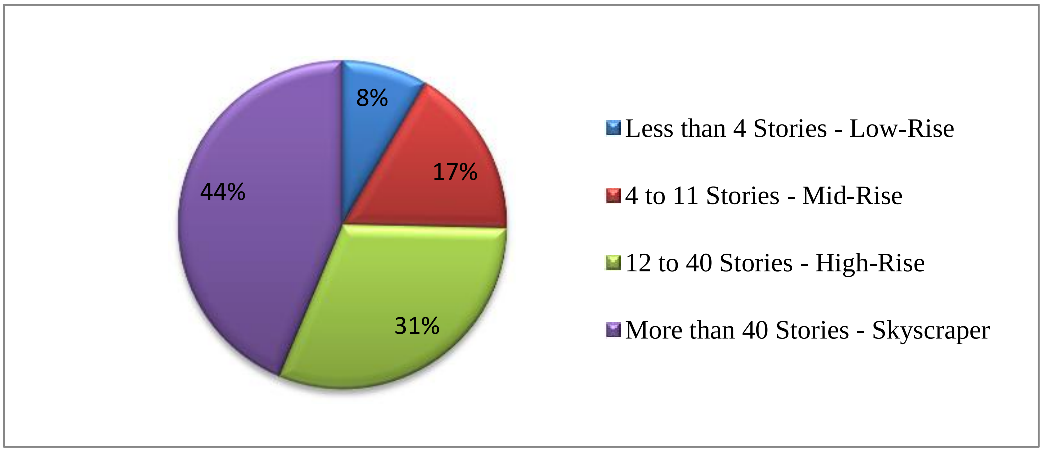


Figure 4.5: Number of Stories of Buildings involved

Methods of surveying used for horizontal and vertical alignments in the buildings where the professionals involved are shown in the Table 4.7 and Figure 4.6. It is here emphasized that the GPS techniques have not been used alone for surveying in building construction. More than 50% of the professionals in the selected sample are using both GPS and traditional survey techniques in their projects. But, in the industry, most of the projects are depended on traditional survey methods only.

Table 4.7: Methods of Surveying applied

Method	**No. of Projects**	**%**
GPS	1	1.49
Total Station/ Traditional Method	28	41.79
Combination of both	38	56.72
Total	**67**	**100**

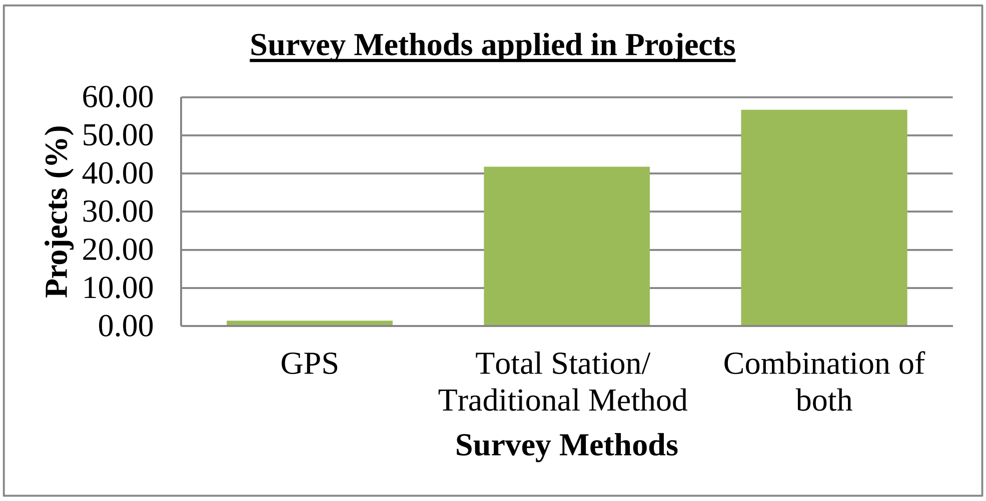


Figure 4.6: Methods of Surveying applied

Table 4.8 and Figure 4.7 illustrate the GPS techniques applied in their projects of building of constructions. It further expresses that Fast Static and Pseudo-Kinematic techniques have never been applied in their projects and even though it indicates the usage of Kinematic technique, it has been used in very less number of projects. Static and RTK techniques have been applied in several projects and the number of projects where Static GPS technique is applied is higher than that of RTK.

Table 4.8: GPS Techniques applied

Techniques	No. of Projects	%
Static	33	55.93
Rapid Static	0	0.00
Pseudo Kinematic	0	0.00
Kinematic	5	8.47
Real Time Kinematic (RTK)	21	35.59
Total	**59**	**100**

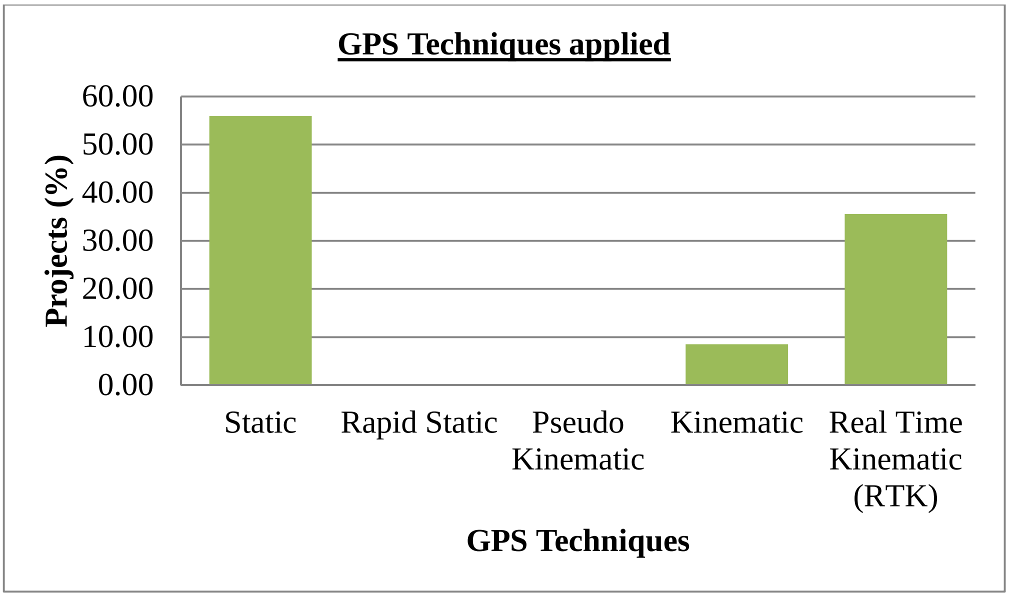


Figure 4.7: GPS Techniques applied

4.3 Problems in Traditional Surveying Methods

As per the attitudes of the respondents on problems or challenges in using traditional surveying methods for horizontal and vertical alignments in high-rise buildings, the factors listed have been indicated as cause of problems or challenges as illustrated in the Table 4.9 and Figure 4.8. The factors of challenges have been compared and ranked as per the levels of significances based on the RII values as depicted in the Figure 4.9.

Challenges in Traditional Surveying for Vertical Alignments in High-Rise Buildings		Types of Responses & Weight					No. of Negative Responses	No. of Positive Responses	Total No. of Responses	Is it a considerable problem? (Yes/No)	Relative Importance Index (RII)	Order of Significance (Rank)
		Strongly Disagree	Disagree	Slightly Agree	Agree	Strongly Agree						
		1	2	3	4	5						
S.No.	Problems/Challenges	Frequencies										
1	More time consuming	1	3	15	22	37	4	74	78	Yes	83.33	6
2	Inter-visibility between stations	0	2	4	22	50	2	76	78	Yes	90.77	1
3	Building movement	0	6	12	26	34	6	72	78	Yes	82.56	9
4	Shape of the structure	0	3	14	26	35	3	75	78	Yes	83.85	5
5	Safety	0	5	23	29	21	5	73	78	Yes	76.92	10
6	Nature of environment	0	5	11	29	33	5	73	78	Yes	83.08	8
7	Distance from reference stations	0	3	7	26	42	3	75	78	Yes	87.44	2
8	Applicability in night times	3	1	2	33	39	4	74	78	Yes	86.67	3
9	Transfering the control points to upper levels	1	1	13	17	28	2	58	60	Yes	83.33	6
10	Construction Interferences	0	0	10	13	21	0	44	44	Yes	85.00	4

Table 4.9 : RII and Ranks of Problems – Traditional Survey Methods

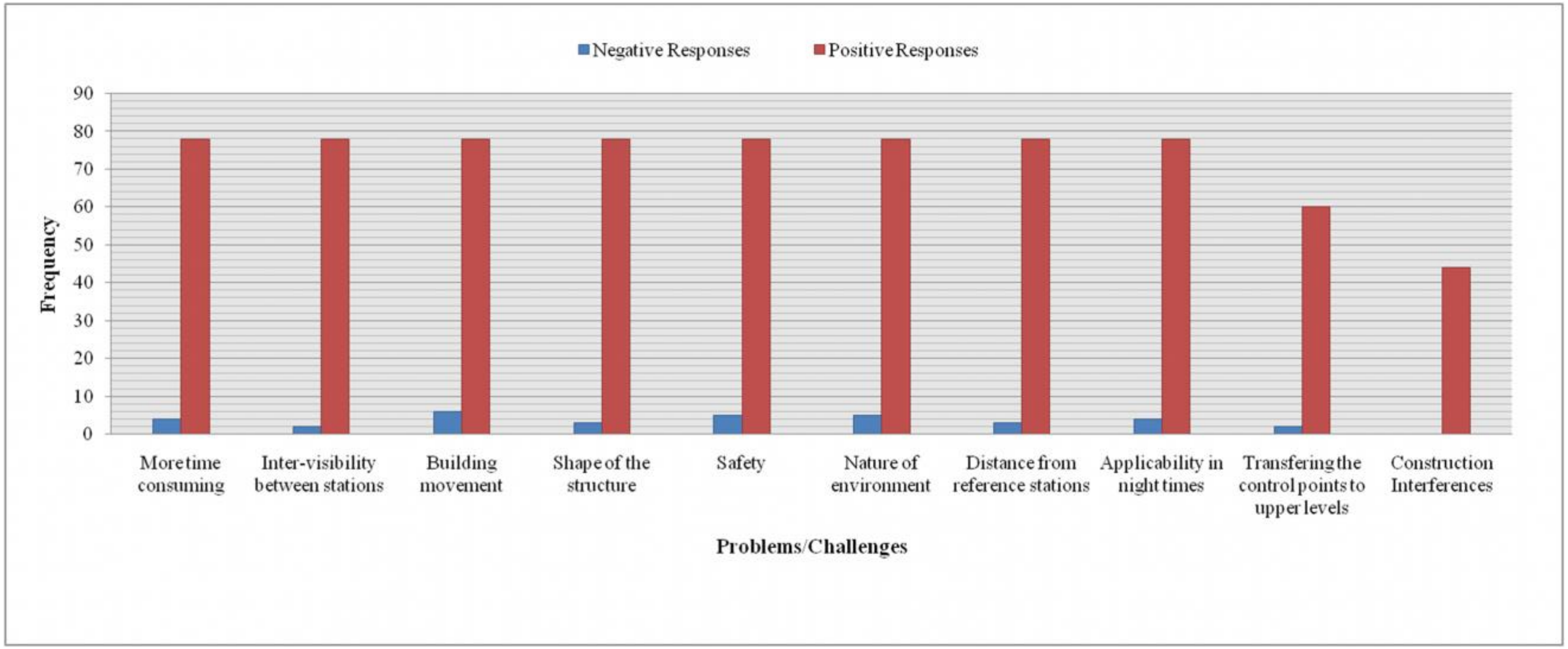


Figure 4.8 : Problems - Traditional Survey Methods

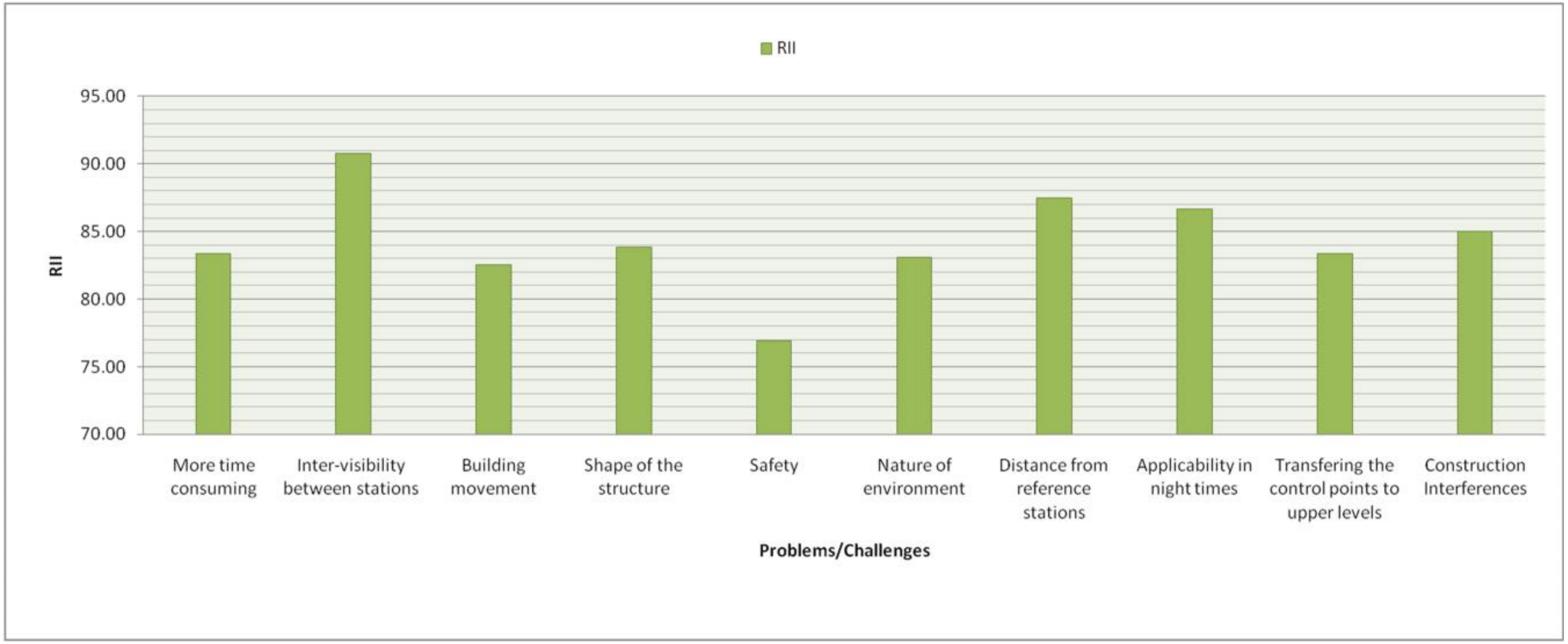


Figure 4.9 : RII of the Problems - Traditional Survey Methods

4.4 GPS against Traditional Survey Methods

As per the attitude of the respondents in the construction society, the accuracy, efficiency, quality and cost implication of GPS surveying techniques against traditional survey methods can be shown as in the Table 4.10.

Table 4.10: GPS against Traditional Survey Methods

GPS against Traditional Survey Methods	No. of Responses										
	Worst		Worse		About the Same		Better		The Best		Total
	1		2		3		4		5		
Accuracy	1	1%	10	13%	45	58%	15	19%	7	9%	78
Efficiency	0	0%	4	5%	26	33%	39	50%	9	12%	78
Quality	5	6%	20	26%	33	42%	18	23%	2	3%	78
Cost Implication	13	18%	15	21%	24	33%	18	25%	3	4%	73

As per the results, Figure 4.10 clearly illustrates that the accuracy of the GPS survey is about the same as in the traditional methods; and it further depicts that only a very less number of members in the sample view the accuracy of GPS as worse than the traditional survey methods.

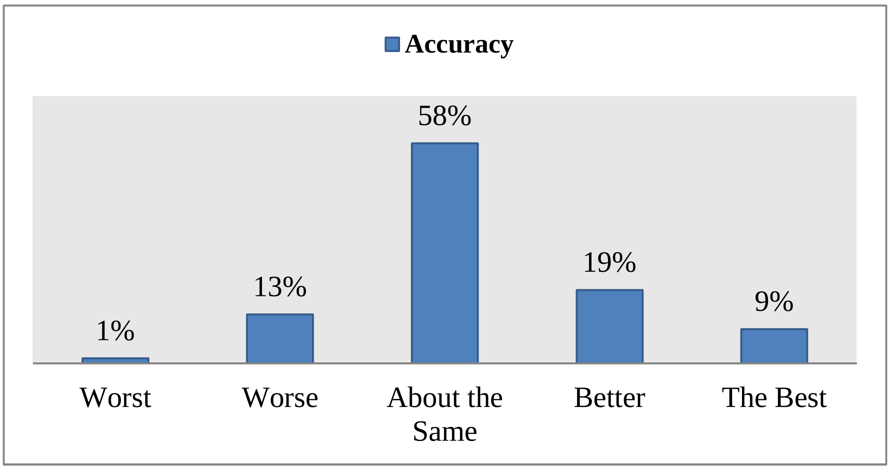


Figure 4.10 : GPS against Traditional Survey Methods

Figure 4.11 demonstrates that only 5% of the professionals in the sample have shown their negative attitudes on the efficiency of GPS. Based on the chart, it is obvious that the efficiency of GPS applications in high-rise buildings is much better than the traditional survey methods.

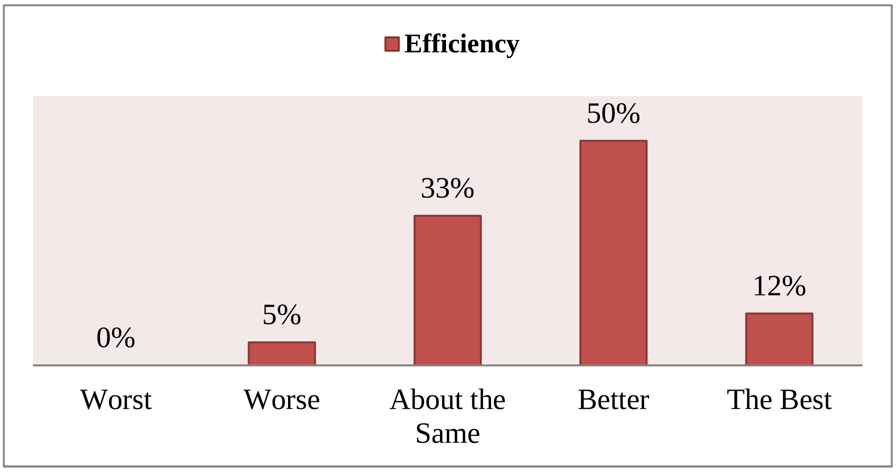


Figure 4.11 : GPS against Traditional Survey Methods

The almost symmetrical shape of the Bar Chart in Figure 4.12 clearly exposes that the quality of GPS results are about the same as the results of the traditional survey methods.

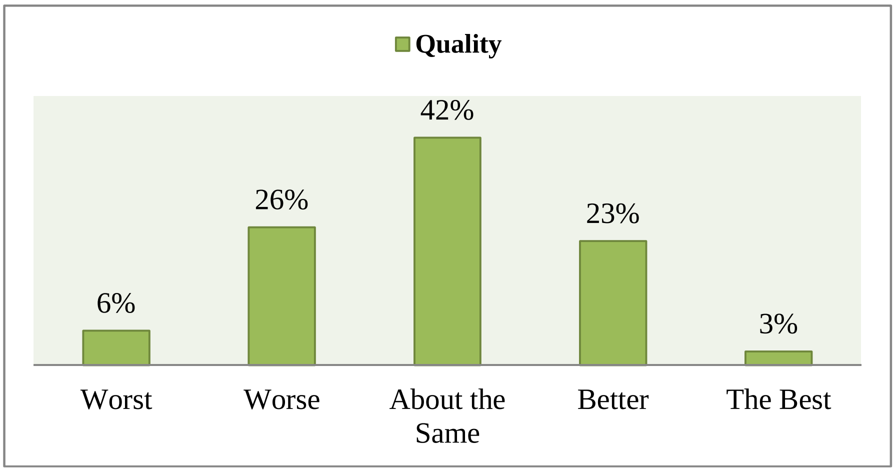


Figure 4.12 : GPS against Traditional Survey Methods

Figure 4.13 illustrates that the majority (33%) of the professionals assess the cost implications of GPS as the same as for traditional survey methods. It is notable that more than half of the balance in the sample depict the cost implication as worser than the traditional methods.

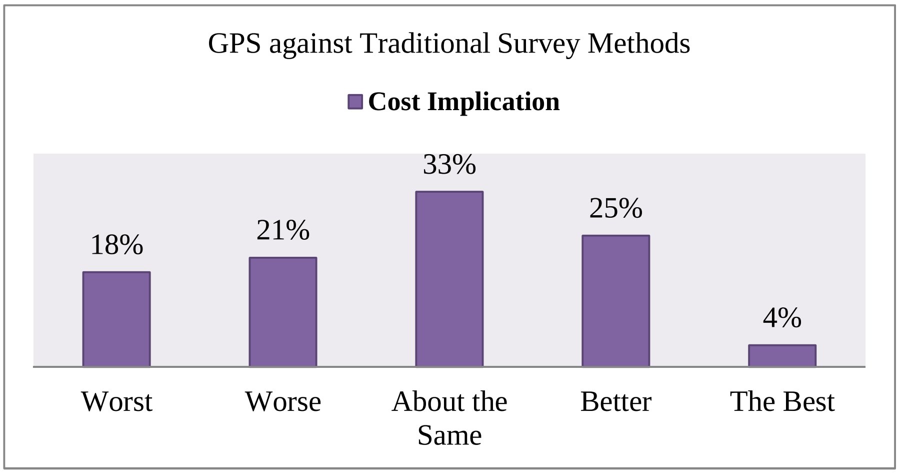


Figure 4.13 : GPS against Traditional Survey Methods

When considering the accuracy, efficiency, quality and cost implications of the GPS surveys in high-rise building, only a very less number of professionals in the sample have shown their negative attitudes on the parameters. This general attitude highly emphasizes the applicability of GPS techniques in high-rise building constructions.

4.5 GPS Survey Techniques in High-Rise Buildings

According to the recommendations of the experts in construction industry on different GPS survey techniques for vertical alignments in high-rise buildings, only the Static and RTK GPS techniques can be applied for the particular survey tasks. Though the Kinematic technique has gained a higher RII score, since its number of positive recommendations is less than that of negative recommendations, it has been not shown as a recommended technique in the list. The results are presented in Table 4.11 and Figure 4.14.

Table 4.11 : GPS Techniques Recommended for Vertical Alignment

Recommendation on GPS Survey Techniques for Vertical Alignments in High-Rise Buildings		Recommendations & Weight					No. of Negative Responses	No. of Positive Responses	Total No. of Responses	Is it recommended for Vertical Alignment? (Yes/No)	Relative Importance Index (RII)	Order of Significance (Rank)
		Strongly Not Recommended	Not Recommended	Questionable	Recommended	Strongly Recommended						
		1	2	3	4	5						
No.	**GPS Techniques**	**Frequencies**										
1	Static	2	5	3	37	17	7	54	64	Yes	79.38	1
2	Rapid Static/Fast Static	15	33	9	2	0	48	2	59	No	39.32	4
3	Pseudo Kinematic	20	25	10	1	0	45	1	56	No	37.14	5
4	Kinematic	10	12	19	16	4	22	20	61	No	57.38	3
5	Real Time Kinematic (RTK)	2	3	15	29	15	5	44	64	Yes	76.25	2

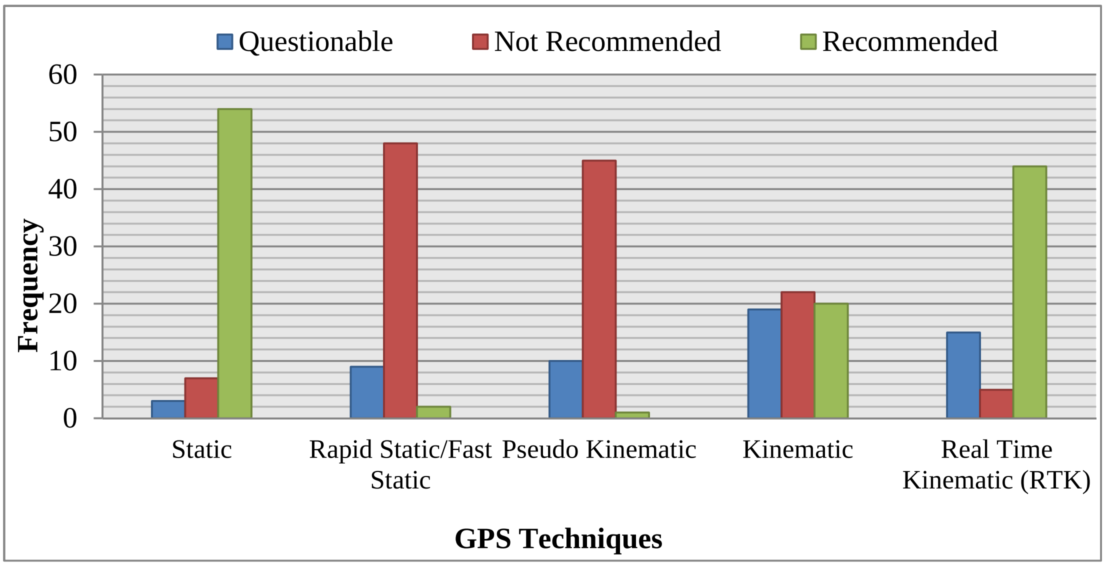


Figure 4.14 : GPS Techniques recommended for Vertical Alignment

Based on the RII values computed from these different types of recommendations, the overall effectiveness or efficiency of the techniques for vertical alignments in high-rise buildings can be compared as depicted in the Figure 4.15.

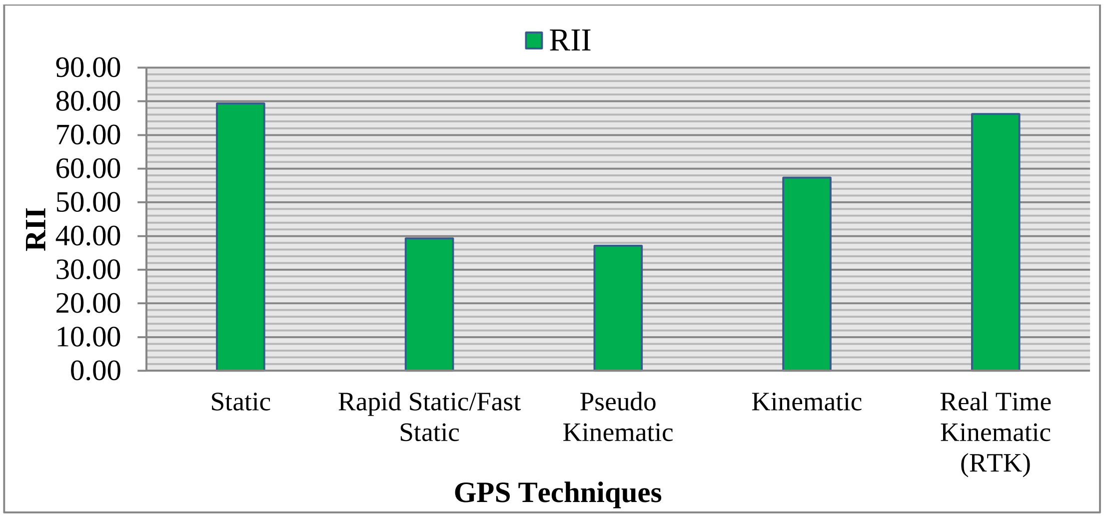


Figure 4.15 : GPS Techniques recommended for Vertical Alignment

4.5.1 Comparison of accuracy of GPS survey techniques

The accuracy of different GPS survey techniques can be compared as presented in the Table 4.12 and Figure 4.15 based on the attitudes of the respondents. According to the Relative Importance Index of the techniques, the Static GPS technique has been ranked first in the order of best accuracy.

Table 4.12: Assessment of Accuracy of GPS Techniques

Accuracy of Different GPS Techniques		Level of Accuracy & Weight					Total No. of Responses	Relative Importance Index (RII)	Order of Significance (Rank)
		Poor	Average	Good	Very Good	Excellent			
		1	2	3	4	5			
No.	GPS Techniques	Frequencies							
1	Static	1	3	5	21	35	65	86.46	1
2	Rapid Static/Fast Static	21	20	13	5	0	59	40.68	4
3	Pseudo Kinematic	25	19	13	2	0	59	37.29	5
4	Kinematic	5	20	18	15	6	64	59.06	3
5	Real Time Kinematic (RTK)	3	9	23	20	10	65	67.69	2

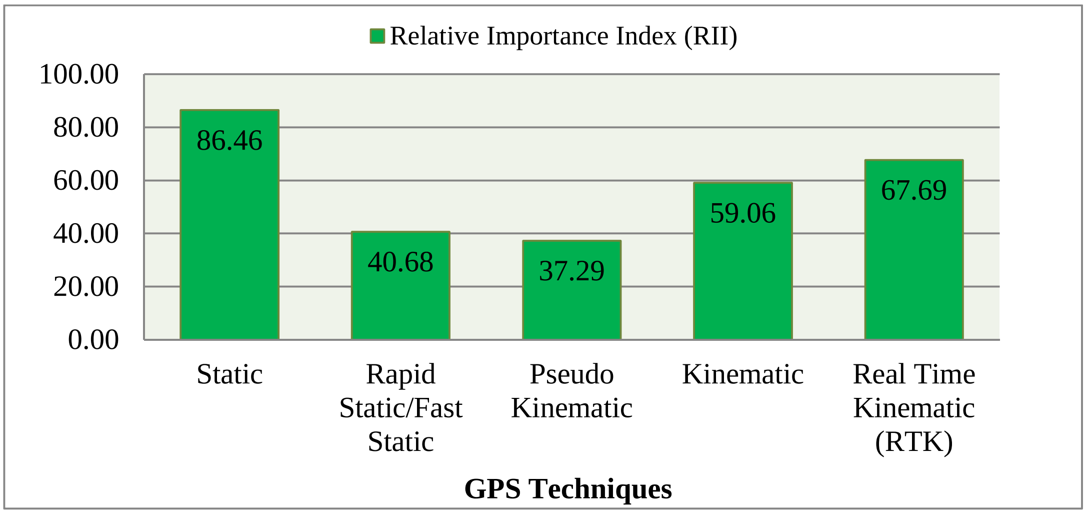


Figure 4.16 : Assessment of Accuracy of GPS Techniques

4.5.2 Challenges in GPS surveying

In order check the general idea of the construction society on the applications of GPS surveying in high-rise buildings, it was questioned whether such applications are problematic or not. As illustrated in Table 4.13 and Figure 4.16, the majority (80%) of the respondents have indicated the applications as problematic. The majority of the construction society is still depended on the traditional survey methods. The above general attitude on GPS surveys may be the reason for this situation in the industry.

Table 4.13: GPS Surveys in High-Rise Buildings

	Are GPS applications in high-rise buildings problematic?		**Total**
	YES	**NO**	
No. of Responses	56	14	70
Percentage (%)	80	20	100

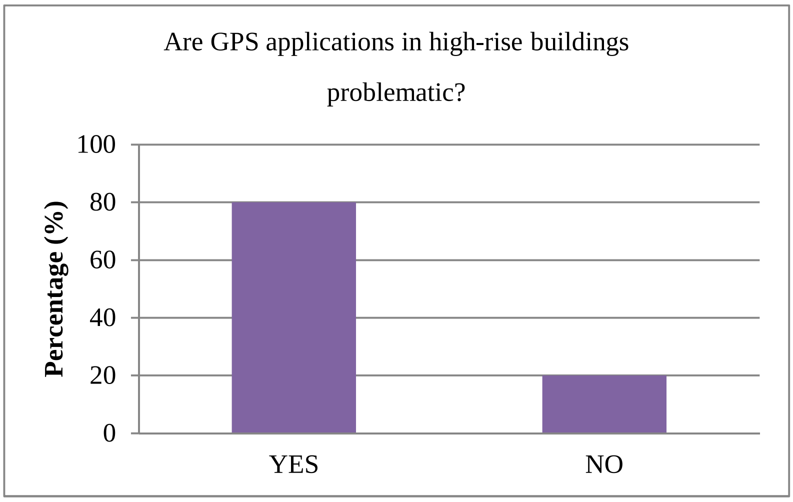


Figure 4.17: GPS Surveys in High-Rise Buildings

As per the attitudes of the experts on given problems or challenges in using GPS surveying techniques for vertical alignments in high-rise buildings, they can be ranked as illustrated in the Table 4.14, Figure 4.18 and Figure 4.19 based on the their Relative Importance Index (RII). The results express that the factors of challenges which were identified in the literature and preliminary interviews have been verified by the experts as the real causes of problems or challenges.

Table 4.14 : Challenges in GPS Surveying

Problems in GPS Surveying for Vertical Alignments in High-Rise Buildings		Types of Responses & Weight					Total No. of Responses	Negative Responses (%)	Positive Responses (%)	Is it a considerable problem? (Yes/No)	Relative Importance Index (RII)	Order of Significance (Rank)
		Strongly Disagree	Disagree	Slightly Agree	Agree	Strongly Agree						
		1	2	3	4	5						
S.No.	**Problems/Challenges**	**Frequencies**										
	Practical Challenges											
1	Building Movement	4	11	13	19	25	72	21%	79%	Yes	73.89	7
2	Shape of the Structure	0	8	12	14	43	77	10%	90%	Yes	83.90	2
3	Safety	4	5	21	27	19	76	12%	88%	Yes	73.68	8
4	Nature of Environment	0	3	4	25	45	77	4%	96%	Yes	89.09	1
5	Quality Control	3	9	18	25	21	76	16%	84%	Yes	73.68	8
6	Electromagnetic Signal Interferences	4	10	19	26	16	75	19%	81%	Yes	70.67	11
7	Construction Interferences	2	2	5	11	23	43	9%	91%	Yes	83.72	3
	Operational Challenges											
8	Operation of Reference Receivers/CORS	5	6	17	20	28	76	14%	86%	Yes	75.79	6
9	Distance from Reference Receivers	2	3	12	21	38	76	7%	93%	Yes	83.68	4
10	Data Latency	5	7	17	12	5	46	26%	74%	Yes	62.17	15
11	Ambiguity Resolution (AR)	2	7	15	19	5	48	19%	81%	Yes	67.50	14
12	Difficult to Determine the Observation Span for AR	7	14	15	8	1	45	47%	53%	Yes	52.00	18
13	Need of Powerful Communication Link	4	6	4	32	30	76	13%	87%	Yes	80.53	5
14	Expensiveness	6	10	23	23	14	76	21%	79%	Yes	67.63	13
15	Cycle Slip	5	10	18	12	2	47	32%	68%	Yes	58.30	16
16	Number of Visible Satellites and Selective Availability	7	9	14	17	28	75	21%	79%	Yes	73.33	10
	Space Related Challenges											
17	Ionospheric Turbulences	4	12	17	12	1	46	35%	65%	Yes	57.39	17
18	Mesospheric, Stratospheric and Tropospheric Disturbances	2	3	20	22	2	49	10%	90%	Yes	67.76	12

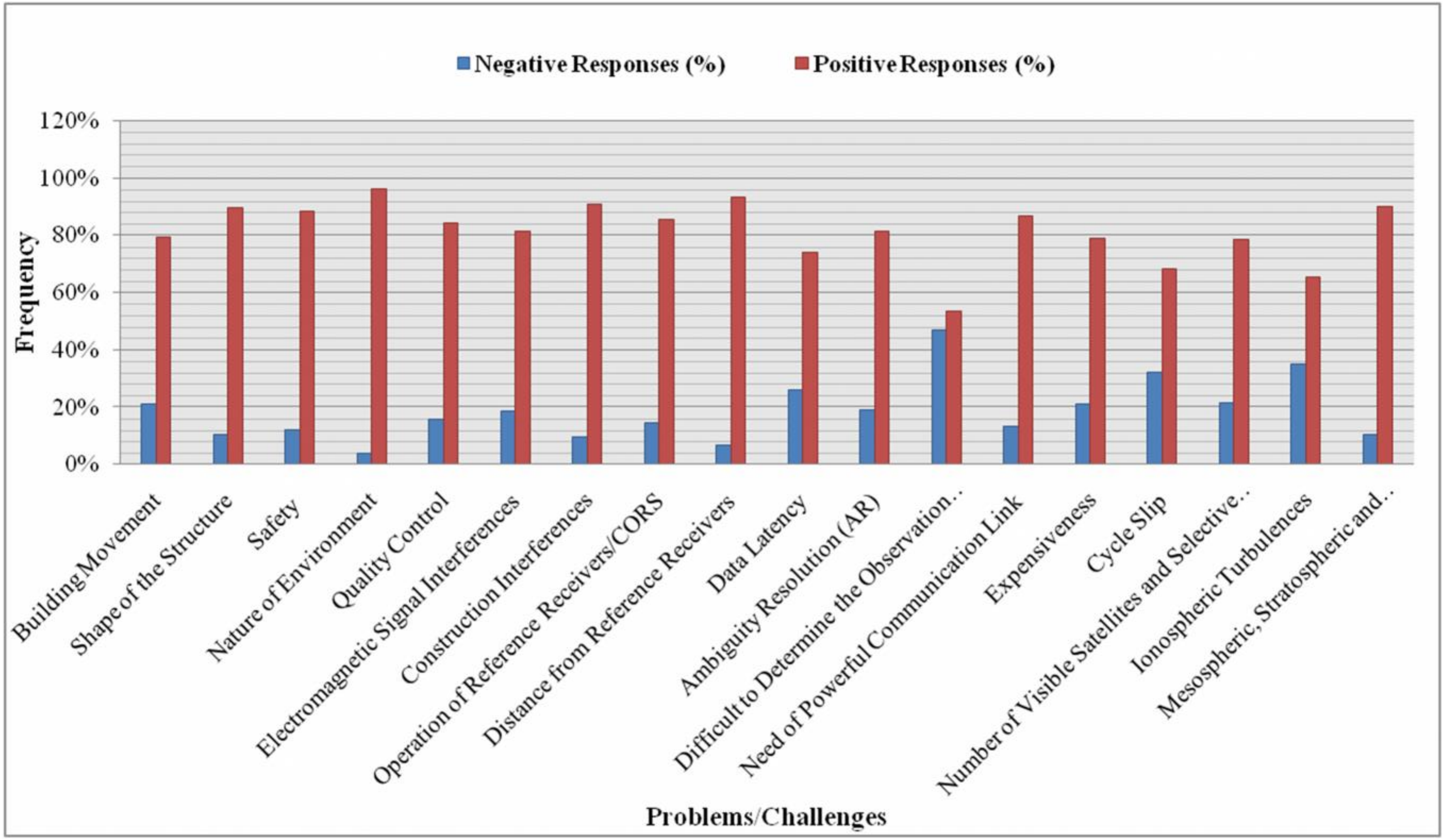


Figure 4.18 : Challenges in GPS Surveying

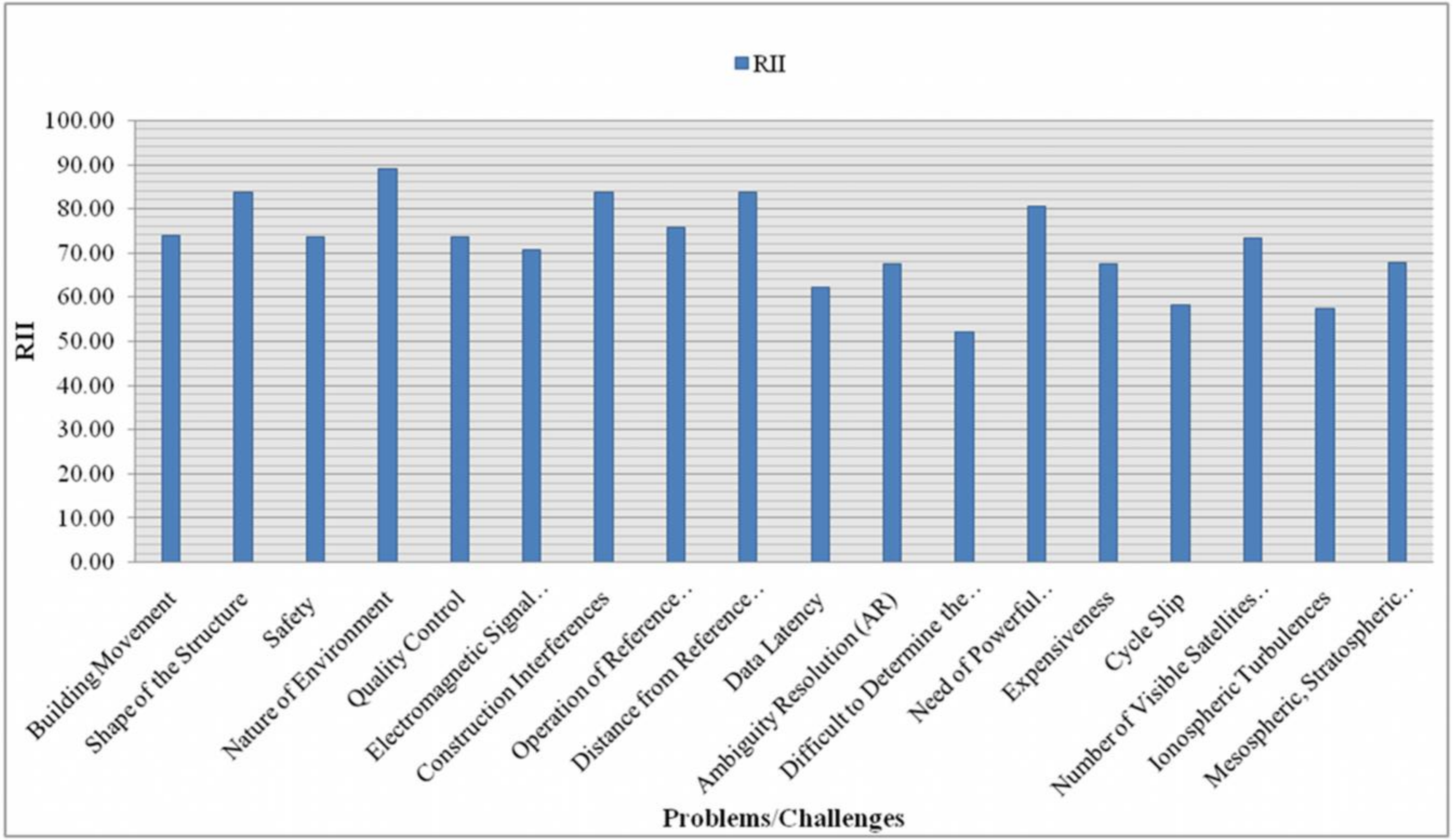


Figure 4.19 :RII of the Challenges – GPS Surveying

4.6 Summary

There were 78 different professionals in the sample having construction and academic background from different parts of the world; and the majority (72%) of them was surveyors. The professionals' level of experience in GPS surveying and high-rise building construction emphasize their competency of providing reliable information on the subject. Nearly 75% of the members in the sample have involved in construction of high-rise buildings with at-least 13 floors, and they have used GPS in around 58% of their projects. Static, Real Time Kinematic (RTK) and Kinematic are the GPS techniques applied in their projects with the combination of traditional surveying methods.

` As per the attitudes of the experts, the problems faced while applying traditional survey methods for vertical alignments in high-rise buildings have been ranked as per their relative importance indices (RII) as shown in the Table 4.9. According to the general attitudes of the professionals on GPS surveys against traditional survey methods, the efficiency of GPS applications in high-rise buildings is much better than the traditional survey methods. Further the accuracy, quality and the cost implications of the GPS techniques are about the same as in the traditional survey methods. These comparative attitudes of the professionals highly emphasize the applicability of GPS techniques in high-rise building construction.

Based on the recommendations of the experts on the suitability of GPS techniques for vertical alignments in high-rise buildings, the Static GPS was ranked as the best; thereafter the RTK, Kinematic, Fast Static and Pseudo Kinematic GPS techniques were placed next in the order given. Further the results of the expert's comparison on the accuracy of the techniques were also in the same significance order as supporting the recommendations.

When considering the GPS applications in high-rise buildings, 80% of the experts in the sample have indicated the applications as problematic. The problems or challenges to be considered in such applications have been ranked as per their relative importance indices (RII) as given in the Table 4.14. The findings of suitable GPS techniques and the challenges have been cross-checked and validated by case studies and experiments as explained in the next chapter.

CHAPTER FIVE

5 CASE STUDIES, EXPERIMENTS AND DISCUSSIONS

5.1 Introduction

This chapter explains in detail the case studies and experiments conducted to cross-check and validate the results gained from the preliminary data analysis of the questionnaire. Further it is discussed comparatively on the results gained from the preliminary analysis, and the case studies with experiments to conclude with reliable findings.

5.2 Case Studies

The research study was actually focusing on identifying the best suitable GPS surveying techniques for vertical alignments in high-rise buildings and the challenges faced while their applications. As per the attitudes of the respondents having enough background knowledge and the experience in the industry, Static and Real Time Kinematic techniques among five basic GPS techniques have been identified as applicable. In order to check, validate and confirm the reliability of these findings from the experts' comments and questionnaire, case studies have been carried out at some selected high-rise building construction sites for final conclusion by comparing their accuracy, efficiency, time consuming, cost implication and other advantages and disadvantages.

Since the study had been designed to check the suitability of different GPS survey techniques for the particular task, preciseness of the GPS observations had to be ensured. Unobstructed view of the sky in all directions, and free from multipath error sources and electromagnetic signal interferences are the basic environmental requirements to be met for precise GPS observations. The literature and the findings of the preliminary analysis of the survey data further emphasized that the nature of environment is the foremost challenge in GPS survey applications for vertical alignments in high-rise buildings. Thus the environmental requirements had to be seriously considered in the selection of suitable building construction sites for the study. Further, since the entire GPS surveys in the study were based on the CORS and VRS network of a service provider, the high-rise building construction sites were also to be selected within area having good coverage of the CORS network.

When considering the above environmental conditions, the availability of reference stations and the requirement of being reached a certain height in construction progress, the construction sites of “The Colombo Lotus Tower”, “The Elements by Fairway” luxury apartment and “Clearpoint Residencies” were found suitable for the study. Since the Colombo Lotus Tower was the one and only high-rise building construction site where the GPS technique was applied for surveying in Sri Lanka in that particular period of study, experiments were separately designed and conducted at other two cases.

5.2.1 Case 1: Traditional survey methods and RTK GPS in ‘The Colombo Lotus Tower’

During the period of this study, The Lotus Tower was the key national project of Sri Lanka and this multifunctional tower was under construction in Colombo. The tower will be 355.7m in height and the tallest building in South Asia in completion. It has different complicated structures which can be described as tower base, tube shaped tower body with many curves, lotus-bud shaped tower belfry, and steel longeron.

Surveying is the key point of entire project quality control. Complicated structures, limited work space due to narrow shape of the tower and multiple construction interferences has actually increased the difficulties of surveying for vertical alignments. Construction Laser, Total Station, traditional plumb bob and GPS techniques were used for ensuring the verticality. At early stage of the construction progress, Total Station and traditional plumb have been used for surveying in the base. After it has attained a certain height in the construction progress of tower body so that Total Station and the control points in the vicinity cannot be utilized, Laser Plummet was used to transfer the control points to the next level. In order to re-check and confirm the results of the laser plummet, coordinates measurements were taken with RTK GPS; and when the height of the body was increasing, Total Station was also used at every 20m to check the reliability of this method and ensure the verticality by taking outside measurements.

5.2.1.1 Laser plummet

The tower body consists of the complicated structures of Lift Shafts, Inner Tube and External Tube. Since there was no completed rigid platform to set up the instruments or targets and carry out the setting out tasks for the vertical structures, it caused major difficulties for surveyors and construction operators in setting up the correct positions of the reinforcements and formworks. According to the method statement of climbing formwork construction, two floors of inner tube and lift shaft were constructed first, and then the external tube was constructed. Based on this construction sequences, the targets were set up as follows to transfer the control points by laser plummet from the 9.95m projection platform having 66 control points at third floor of the tower base.

- Inner Tube: targets were set up on the main platform of the external climbing formwork. Altogether 16 locations at the radial direction of 22.5 degree.

- Lift Shaft: set up on the climbing formwork and wall attached supports. At least at two locations spacing 1 to 3 meters on each wall, and altogether 34 points were set up.

- External Tube: set up on the steel target supports fixed on the previously constructed inner tube external wall. Two points in radial direction on each support, and altogether 32 points in total.

5.2.1.2 RTK GPS

In this project HI-TARGET's H32 GNSS RTK receivers were used to cross check the accuracy of the results of the laser plummet and plumb bob. Once the formworks were set up by setting out the locations with laser plummet and plumb bob, coordinates of the selected points were estimated by RTK GPS observations, and then the GPS coordinates were compared with the designed coordinates of those points.

Figure 5.1: RTK GPS Observation at The Lotus Tower

In order to take external measurements and references by Total Station and GPS receivers, 4 control points on the slab of the 4th floor in the tower base and 2 points on top of the Postal Headquarters building situated closer to the tower had been established. The base station for the RTK GPS surveying had been set up on one of the two points on the postal building. The base station was being continuously operated and the corrections were transferred by GSM (Global System for Mobile Communication) transmission to the rover receiver. Before starting the survey with the rover GPS receiver at required locations, at-least one of the 4 control points on the tower base was cross-checked at first. Then the required points were occupied for at-least two minutes, and the estimated coordinates were checked with designed values.

When the difference between the coordinates exceeds the allowable deviation for the particular height of the tower, the formworks were re-checked and adjusted with the laser plummet again. Until the deviations reach its minimum within the allowable range, the procedures were repeated. After concreting the structures, post pour as-built survey was also carried out with RTK GPS observations by third party representatives for monitoring. When the progress of the tower body reaches each 20 meters in height where it has the concrete floors, Total Station was also used for as-built surveys to cross-check the verticality by taking outside measurements.

According to the quality control plan of the project, the allowable deflection in vertical alignments of the tower with height was given as in the Table 5.1.; and in completion of the tower, the maximum deflection should be not more than 80mm.

Table 5.1: Allowable Deviation in Verticality

Height (H) (m)	**Allowable Deviation (mm)**
H ≤ 30	5
30 < H ≤ 60	10
60 < H ≤ 90	15
90 < H ≤ 120	20
120 < H ≤ 150	25
150 < H	30

As of 11th April 2016, the height of the tower was 255 meter in progress; according to the as-built surveys done by both RTK GPS and Total Station up to this stage, the maximum deflection noticed in the verticality was only 20 mm whereas 30 mm was allowable for the particular height. Though the RTK GPS was here used for just cross-checking the positions, unless there were disturbances in having proper signals from the satellites and better communication with the base station, there were no considerable differences between the results gained through RTK GPS and Total Station.

5.2.2 Case 2: Traditional survey methods at 'The Elements' by Fairway

'The Elements' of Fairway Holdings Group is a forty stories luxury apartment project being constructed by MAGA Engineering in Rajagiriya. In this high-rise building construction project, Total Station and traditional plumb bob were used for horizontal and vertical alignments of the structures.

Normally the Total Station was used to transfer the control points to the next floor of the building when the control points on the ground and/or lower floors of the building were visible and being convenient for referencing. When the control points became unusable due to disturbances or the construction reached a certain height in progress, the points were transferred by using traditional plumb bob. Then the positions of the structures on the upper floors were set out by Total Station and the formworks were aligned with the help of the plumb lines.

5.2.3 Case 3: Traditional survey methods at 'CLEARPOINT' residencies

The 'Clearpoint' is the world's tallest residential vertical garden under construction in Rajagiriya, Colombo. The Clearpoint having 46 floors with meticulously designed luxury apartment was also being constructed by MAGA Engineering. When the case study was being done at the site in March 2016, the construction progress of the building was on its 40^{th} floor. As explained above in the case of 'The Elements', here also the Total Station and the traditional plumb bob were used for horizontal and vertical alignments in the building.

5.3 Experiment on GPS Techniques

Since there were no building construction projects other than the Lotus Tower, where the GPS techniques were used for vertical alignments, an experiment was conducted on different GPS techniques to cross-check their applicability and find the best suitable technique for vertical alignments in high-rise building construction. Since it was a comparison study, in order to give the same environmental condition for GPS techniques also, experiments were conducted in the same building construction projects where the case studies were carried out on the traditional surveying methods.

Entire GPS survey activities were carried out with the S82-V Integrated RTK GNSS Receivers of SOUTH. Continuously Operated Reference Stations of ‘CORSnet’ of SULECO Pvt. Ltd. were the reference and correction source for the surveys. CORSnet was the first and only virtual reference network available in Sri Lanka while conducting the experiments. The network which had its master control station at Pepiliyana had been formed with high accurate GNSS receivers coupled with Choke Ring Antenna; and it was having its coverage in the western province and adjacent cities at the outset. The real time corrections services of CORSnet were transmitted from the master station to the users through internet. Table 5.2 and Table 5.3 express the accuracy specifications of the RTK GNSS receivers used and CORS network respectively.

Table 5.2: Accuracy Specification of S82-V RTK GNSS Receivers

Static and Fast-Static GNSS Surveying	
Horizontal	2.5mm + 1ppmRMS
Vertical	5.0mm + 1ppmRMS
Real Time Kinematic (RTK) Surveying	
Horizontal	10mm + 1ppmRMS
Vertical	20mm + 1ppmRMS

Table .5.3: Accuracy Specification of CORS (CORSnet)

Static GNSS Surveying	
Base Line < 30km	
Horizontal	2.5mm + 0.5ppmRMS
Vertical	5.0mm + 0.5ppmRMS
Base Line > 30km	
Horizontal	4.0mm + 0.5ppmRMS
Vertical	9.0mm + 0.5ppmRMS
Real Time Kinematic (RTK) Surveying	
Single Base < 30km	
Horizontal	10mm + 1ppmRMS
Vertical	20mm + 1ppmRMS
Network RTK	
Horizontal	8mm + 0.5ppmRMS
Vertical	15mm + 0.5ppmRMS

5.3.1 Experiment at 'The Elements' by Fairway

According to the grid lines and alignments of the building, all the survey activities on this building were based on an arbitrary coordinates system for easy references and calculations. Since the building had not been referenced to the National Grid System SLD99 of Sri Lanka, the building was first referenced to the national grid by Static GPS surveys on known control points on the site and 2D Similarity Coordinate Transformations.

5.3.1.1 Coordinate transformation

In order to transform the arbitrary coordinate system to the national grid, 2D Similarity/ Conformal Coordinate Transformation was applied. At first Static GPS observations were done for 45 minutes over the selected well known control points where there were no disturbances environmentally for GPS observations.

Then by processing the data with the Continuously Operated Reference Stations of 'CORSnet' of SULECO Pvt Ltd, national grid coordinates of the control points were determined and the building was oriented to the national grid system.

Table 5.4: Coordinates of Control Points

Point ID	Coordinates			
	Arbitrary		National Grid System	
	Y (m)	X (m)	N (m)	E (m)
P1	139.368	84.533	490102.872	404184.950
P2	88.986	104.043	490092.693	404131.892
P3	90.767	134.322	490062.578	404128.228

The parameters of the applied 2D similarity coordinate transformations were as below.

- Translation/Shift

  Shift in *x* direction ***dx*** = 404062.9517m

  Shift in *y* direction ***dy*** = 490210.9735m

- Rotation $\boldsymbol{\alpha}$ = 79^{0} 41' 43" in anti-clockwise direction

- Scale ***S*** = 1.000004

5.3.1.2 GPS surveys and processing

With the help of the site surveyors, three control points were first established on the upper slab by traditional survey methods so that there were minimum or no disturbances for GPS observations at the points. Then S82-V GNSS receivers were setup over those points, and Static GPS observations were done for around 45 minutes. Figure 5.2 depicts GPS observation at the 'Elements' site.

Figure 5.2 : GPS Observation at ‘The Elements’ Site

Later by processing the observed data with CORS observation details for the particular time, the relative coordinates of the occupied stations on the slab were determined. By assuming the coordinates given by the traditional survey method or Total Station as the correct coordinates, the RMS Error of each control point was calculated and tabulated as in the Table 5.5.

Table 5.5: Static GPS - Coordinates and RMS Error

Point ID	**Coordinates**				**Difference (C_S - C_{TS})**		**RMS Error**
	Static GPS (C_S)		**Total Station (C_{TS})**				
	N (m)	**E (m)**	**N (m)**	**E (m)**	**dN (m)**	**dE (m)**	**(m)**
A2-2	490092.693	404131.892	490092.690	404131.891	0.003	0.001	0.003
A2-11	490062.578	404128.228	490062.581	404128.227	-0.003	0.001	0.003
J-2	490086.194	404165.627	490086.183	404165.618	0.011	0.009	0.014

The same points were observed for 10 minutes for Fast-Static processing. Table 5.6 shows the results gained in the Fast-Static surveys against traditional survey methods. It was closer to the results gained in the Static surveys.

Table 5.6: Fast-Static GPS - Coordinates and RMS Error

Point ID	**Coordinates**				**Difference (C_{FS} - C_{TS})**		**RMS Error**
	Fast Static GPS (C_{FS})		**Total Station (C_{TS})**				
	N (m)	**E (m)**	**N (m)**	**E (m)**	**dN (m)**	**dE (m)**	**(m)**
A2-2	490092.698	404131.899	490092.690	404131.891	0.008	0.008	0.011
A2-11	490062.586	404128.233	490062.581	404128.227	0.005	0.006	0.008
J-2	490086.201	404165.637	490086.183	404165.618	0.018	0.019	0.026

In order to check the results of Reoccupation or Pseudo-Kinematic GPS technique, the same control points were first observed for 5 minutes like in Fast-Static surveys. After one hour time interval, the points were observed for 5 minutes again for making use of change in the satellite geometry. Then the relative coordinates of the points were determined by processing the both epochs of data. Table 5.7 shows the coordinates and RMS errors of Pseudo Kinematic GPS.

Table 5.7: Pseudo-Kinematic GPS - Coordinates and RMS Error

Point ID	Coordinates				Difference (C_{PK} - C_{TS})		RMS Error
	Pseudo Kinematic GPS (C_{PK})		Total Station (C_{TS})				
	N (m)	**E (m)**	**N (m)**	**E (m)**	**dN (m)**	**dE (m)**	**(m)**
A2-2	490092.701	404131.900	490092.690	404131.891	0.011	0.009	0.014
A2-11	490062.593	404128.234	490062.581	404128.227	0.012	0.007	0.014
J-2	490086.214	404165.639	490086.183	404165.618	0.031	0.021	0.037

All three control points were further observed by a single receiver for 5 minutes each in Kinematic (Stop and Go) GPS survey mode to check its applicability and accuracy for vertical alignments. The relative coordinates gained through this survey were as below in Table 5.8; and it was very closer to the results of Static GPS techniques.

Table 5.8: Kinematic GPS - Coordinates and RMS Error

Point ID	Coordinates				Difference (C_K - C_{TS})		RMS Error
	Kinematic GPS (C_K)		Total Station (C_{TS})				
	N (m)	**E (m)**	**N (m)**	**E (m)**	**dN (m)**	**dE (m)**	**(m)**
A2-2	490092.697	404131.895	490092.690	404131.891	0.007	0.004	0.008
A2-11	490062.575	404128.231	490062.581	404128.227	-0.006	0.004	0.007
J-2	490086.197	404165.633	490086.183	404165.618	0.014	0.015	0.021

Finally, the coordinates of the points were instantaneously determined by RTK GPS observations with virtual reference station from the CORSnet. The coordinates and RMS errors of the technique are shown in Table 5.9. The deviations of RTK survey results from the designed positions or results gained with Total Station were higher like in the Pseudo-Kinematic.

Table 5.9: RTK GPS - Coordinates and RMS Error

Point ID	Coordinates				Difference (C_{RTK} - C_{TS})		RMS Error
	RTK GPS (C_{RTK})		Total Station (C_{TS})				
	N (m)	E (m)	N (m)	E (m)	dN (m)	dE (m)	(m)
A2-2	490092.700	404131.899	490092.690	404131.891	0.010	0.008	0.013
A2-11	490062.588	404128.233	490062.581	404128.227	0.007	0.006	0.009
J-2	490086.203	404165.641	490086.183	404165.618	0.020	0.023	0.030

Since there was a crowded surrounding with reinforcements and formworks, there was a chance for multi-path signal errors at the point J-2. Consequently, the results gained in the all five techniques show considerable deviations at the particular point.

5.3.2 Experiment at 'CLEARPOINT' residencies

The experiment on GPS techniques at the 'Clearpoint' was conducted on its 40th floor. It was carried out as same as it was done at 'The Elements' project. Since the building had not been referenced to National Grid System, it was first oriented to that system. Then the experiment was proceeded by repeating the procedure followed at 'The Elements'.

5.3.2.1 Coordinate transformation

The local coordinate system used in the project was transformed to the national grid system by transferring the control points from 'The Elements' which is closer to the site. Since an external control point of 'The Elements' project had been established on the 'Clearpoint', it was easier to transfer the control points. Arbitrary and national grid coordinates of the control points used for transformation are given in the Table 5.10.

Table 5.10: Coordinates of Control Points

Point ID	Coordinates			
	Arbitrary		National Grid System	
	N (m)	E (m)	N (m)	E (m)
P4	170.998	134.640	490194.664	403988.968
P5	118.924	128.960	490198.911	403936.757
P6	104.032	128.962	490198.500	403921.871

The parameters of the applied 2D similarity coordinate transformation were as below.

- Translation/Shift

  Shift in *x* direction ***dx*** = 403814.3341m

  Shift in *y* direction ***dy*** = 490324.5556m

- Rotation $\boldsymbol{\alpha}$ = 88^0 25’ 32” in clockwise direction
- Scale ***S*** = 1.000006

5.3.2.2 GPS surveys and processing

As explained above in ‘The Elements’ project, the same procedure was repeated with the same receivers, base stations and observation time spans. Figure 5.3 depicts the GPS observation at the ‘Clearpoint’ site.

Figure 5.3 : GPS Observation at 'Clearpoint' Site

Then the results gained in the post processing and instantaneous GPS survey techniques and the RMS Errors were tabulated. Table 5.11, Table 5.12, Table 5.13, Table 5.14 and Table 5.15 express the results of the Static, Fast-Static, Pseudo-Kinematic, Kinematic and RTK GPS techniques respectively.

Table 5.11: Static GPS - Coordinates and RMS Error

Point ID	Coordinates				Difference (C_S - C_{TS})		RMS Error
	Static GPS (C_S)		Total Station (C_{TS})				
	N (m)	E (m)	N (m)	E (m)	dN (m)	dE (m)	(m)
A	490227.112	403935.913	490227.110	403935.913	0.002	0.000	0.002
B	490198.910	403936.758	490198.913	403936.756	-0.003	0.002	0.004
C	490198.500	403921.870	490198.500	403921.871	0.000	-0.001	0.001

Table 5.12: Fast-Static GPS - Coordinates and RMS Error

Point ID	Coordinates				Difference (C_{FS} - C_{TS})		RMS Error
	Fast Static GPS (C_{FS})		Total Station (C_{TS})				
	N (m)	E (m)	N (m)	E (m)	dN (m)	dE (m)	(m)
A	490227.114	403935.923	490227.110	403935.913	0.004	0.010	0.011
B	490198.905	403936.764	490198.913	403936.756	-0.008	0.008	0.011
C	490198.508	403921.877	490198.500	403921.871	0.008	0.006	0.010

Table 5.13: Pseudo-Kinematic GPS - Coordinates and RMS Error

Point ID	Coordinates				Difference (C_{PK} - C_{TS})		RMS Error
	Pseudo Kinematic GPS (C_{PK})		Total Station (C_{TS})				
	N (m)	E (m)	N (m)	E (m)	dN (m)	dE (m)	(m)
A	490227.115	403935.923	490227.110	403935.913	0.005	0.010	0.011
B	490198.902	403936.764	490198.913	403936.756	-0.011	0.008	0.014
C	490198.513	403921.880	490198.500	403921.871	0.013	0.009	0.016

Table 5.14: Kinematic GPS - Coordinates and RMS Error

Point ID	**Coordinates**				**Difference (C_K - C_{TS})**		**RMS Error**
	Kinematic GPS (C_K)		**Total Station (C_{TS})**				
	N (m)	**E (m)**	**N (m)**	**E (m)**	**dN (m)**	**dE (m)**	**(m)**
A	490227.109	403935.918	490227.110	403935.913	-0.001	0.005	0.005
B	490198.908	403936.762	490198.913	403936.756	-0.005	0.006	0.008
C	490198.504	403921.875	490198.500	403921.871	0.004	0.004	0.006

Table 5.15: RTK GPS - Coordinates and RMS Error

Point ID	**Coordinates**				**Difference (C_{RTK} - C_{TS})**		**RMS Error**
	RTK GPS (C_{RTK})		**Total Station (C_{TS})**				
	N (m)	**E (m)**	**N (m)**	**E (m)**	**dN (m)**	**dE (m)**	**(m)**
A	490227.110	403935.923	490227.110	403935.913	0.000	0.010	0.010
B	490198.901	403936.769	490198.913	403936.756	-0.012	0.013	0.018
C	490198.491	403921.875	490198.500	403921.871	-0.009	0.004	0.010

According to the results gained in the experiment, the GPS techniques can be ranked as shown in the Table 5.16 based on the Total RMS Errors which express the positional accuracy. Since it was obvious that there was multipath path signal effects at the point J-2 at ‘The Elements’, the point was not taken into account in the calculation of Total RMS Errors.

Table 5.16: Rank of Accuracy of GPS Techniques

GPS Techniques	**RMS Error at Point**					**Total RMS Error**	**Rank of Better Accuracy**
	A2-2	**A2-11**	**A**	**B**	**C**		
Static	0.003	0.003	0.002	0.004	0.001	**0.003**	**1**
Fast Static	0.011	0.008	0.011	0.011	0.010	**0.009**	**3**
Pseudo-Kinematic	0.014	0.014	0.011	0.014	0.016	**0.013**	**5**
Kinematic	0.008	0.007	0.005	0.008	0.006	**0.006**	**2**
RTK	0.013	0.009	0.010	0.018	0.010	**0.011**	**4**

When comparing these ranks of better accuracy with the previous ranking of the techniques based on the experts' view on the accuracy, only the Static and Pseudo Kinematic GPS techniques keep their places unchanged. It should be noted that the experts placed the RTK GPS as second in the ranking; but as per the above results of experiments, Kinematic and Fast Static GPS techniques lead RTK in the order.

5.4 Comparison of GPS Techniques and Decision Making

In order to make final decision on the suitability of GPS techniques for vertical alignments in high-rise buildings, Paired Comparison analysis was conducted first by considering the accuracy, efficiency, time consuming and cost implications of the techniques. According to the scores gained, the parameters were weighted as in the Table 5.17.

Table 5.17: Paired Comparison Analysis

		A	B	C	D
		Accuracy	Efficiency	Time Consuming	Cost Implication
A	Accuracy		A,1	A,2	A,3
B	Efficiency			B,2	B,3
C	Time Consuming				C,1
D	Cost Implication				
Score		**6**	**5**	**1**	**0**
%		**50%**	**42%**	**8%**	**0%**
Rank		**1**	**2**	**3**	**4**
Weight		**0.50**	**0.42**	**0.08**	**0.00**

Then the GPS techniques were compared by assigning scores 1 to 5 against the above weighted parameters in a decision matrix. The scores on the accuracy were assigned as per the results gained in the experiments as in the Table 5.16, and the efficiency of each technique was scored according to the recommendations of the experts as shown in the Table 4.11. Similarly, the scoring on time consuming was based on the time allocated in experiments, and since the cost for the GPS surveys are almost same for all the techniques, the same scores have been assigned for all the techniques. Then by computing the total weighted score of each technique, they were ranked in the order of best suitability for vertical alignments in high-rise buildings as shown in the Table 5.18.

Table 5.18: Decision Matrix

	Weight	GPS Techniques				
		Static	Fast Static	Pseudo Kinematic	Kinematic	RTK
Accuracy	0.50	5	3	1	4	2
Efficiency	0.42	5	2	1	3	4
Time Consuming	0.08	2	3	1	4	5
Cost Implication	0.00	3	3	3	3	3
Weighted Score		**4.76**	**2.58**	**1**	**3.58**	**3.08**
Rank		**1**	**4**	**5**	**2**	**3**

As per the results of preliminary data analysis with experts' comments; only the Static and RTK GPS techniques were recommended for vertical alignments in high-rise buildings. Even though the Kinematic GPS technique has been placed third in the list with higher RII value; the positive attitudes of the experts were not adequate to recommend it as an effective survey technique for building construction. But the above final results based on the complete data analysis with preliminary data, case studies and experiments expose that the Static GPS technique keeps its first place as it was ranked in the preliminary analysis. Then the Kinematic, RTK, Fast Static and Pseudo-Kinematic techniques take their places in the order given. Unlike in the preliminary analysis, the Kinematic and RTK techniques have interchanged their places, and it should be noted that though the Fast Static technique has been placed behind the RTK, the Fast Static leads RTK GPS in its accuracy.

According to the literature, GPS techniques are not used as standalone survey techniques in high-rise buildings and they are applied with the combination of Total Station or other traditional survey methods. This situation in the industry is further supported and verified by the result gained in the preliminary data analysis as shown in the Table 4.7 which expresses the methods of surveying applied in building construction projects.

The experts' recommendations and the results of the case studies proved as shown in the Table 4.11 and Table 5.18 respectively that Static is the best suitable GPS survey technique for vertical alignment in high-rise buildings; but it should be combined with Total Station or other traditional survey methods as above.

5.5 Comparison between Traditional Survey Methods and GPS Surveys

According to the direct observations and experience gained in the case studies and experiments, and as per the view of the surveyors, structural engineers and other construction operators on the applications of different surveying techniques in the above projects, GPS and the traditional survey methods including Total Station and Laser Plummet can be compared as in the Table 5.15 below.

The comparison is based on the basic factors of performance and common problems faced while surveying for vertical alignments in high-rise buildings. The table clearly shows that the GPS application in high-rise building is better and it is manageable in most of the problematic situations than the traditional survey methods. As found in the literature, better level of accuracy, economical benefits from greater efficiency and speed of survey, reliability due to redundancy, around-the-clock operation, weather independency, no need for inter-visibility, reference can be taken from farther range etc. are the major advantages GPS over traditional survey methods. The comparison further emphasizes the suitability of GPS surveying techniques for vertical alignments in high-rise building construction.

Table 5.19: GPS vs Traditional Methods

GPS and Traditional Survey Methods in High-Rise Buildings		
Factors of Performance and Problems	**Traditional Methods**	**GPS**
Accuracy	same accuracy can be achieved in both	
Efficiency	not applicable in some places/situations	applicable in such places/situations but setting out can be done by RTK GPS only
Time consuming	may need more time	can complete in less time duration
Cost implication	overall cost is almost same	
Quality	both need cross-checking	
Reliability	reliability is high since it is conventionally used	reliable due to redundancy (but less than traditional methods due to limited usage in the industry)
Safety	safety issues are common in both	
Transferring control points to upper level	may produce much difficulties	can easily establish
Applicability at night times	difficult to work at night	around-the clock operation
Applicability in different weather conditions	weather depended	weather independency
Distance from reference stations	stations must be within the visible range	can be within 30km range
Inter-visibility between stations	inter-visibility is a must	no need for inter-visibility
Shape of the structure	may produce much difficulties	manageable with difficulties
Nature of environment	may produce much difficulties	difficulties in having proper signals
Building movement	may produce much difficulties	manageable with difficulties

5.6 Problems Faced

According to direct observations and the experience of the surveyors, structural engineers and other construction operators involved in the projects, the following problems were noticed while surveying with different survey applications.

- **Shape of the Structure:** Because of the narrow and complicated shape of the structure, limited workspaces and multiple construction interferences produced much difficulty for surveying in the Lotus Tower.
- **Nature of Environment:** There were some problems in having proper signals from the satellite due the multipath effects of the crowded surrounding with steels, tower crane, formworks etc.
- **Necessity of CORS:** Since it was necessary to make anytime availability of references from the control stations, it was necessary to continuously operate the base station at the Lotus Tower.
- **Communication Link:** GSM communication link could not maintain a proper and stronger connection between the base and rover station while there were obstacles such as reinforcement steels, formworks etc. along the virtual line between the base and rover. Consequently, RTK GPS survey could not deliver the results with required precision at such situations, and the deviations were very high.
- **Wind & Construction Interferences:** It was difficult to do survey with both GPS and traditional methods due to the disturbances caused by wind and the vibrations due to different construction proceedings.
- **Sunshine:** It was difficult to transfer the control points by laser in day time due to sunshine, and it was occurred to do the surveying and setting out at night or early morning.
- **Safety:** Safety was a serious challenge in ensuring the quality of surveying due to the congested surrounding with limited workspace, multiple construction

proceedings and the situation of not having a rigid platform to stand and set up or hold the instrument or target as required.

- **Quality:** Both the traditional and GPS survey techniques need cross-checking to confirm the quality and reliability.

According to the challenges listed in the Table 4.14 based on the experts' comments, nature of environment, shape of the structure, construction interferences, distance from the reference stations, need of powerful communication link, necessity of CORS, building movement, safety and quality control are major the surveying challenges to be considered in the GPS applications for vertical alignments in high-rise buildings. These findings are further supported and validated by the above explained problems noticed while conducting the case studies and experiments.

5.7 Summary

In order to cross-check and validate the findings of the preliminary data analysis, case studies and experiments were conducted at The Lotus Tower, 'The Elements by Fairway' and 'Clearpoint' high-rise building construction sites in Colombo. At first, the case studies on traditional survey methods and GPS surveys were done at the Lotus Tower where the RTK GPS was used for cross-checking the surveys done by traditional survey methods. Then the experiments on different GPS techniques were conducted at the other two construction sites while conducting the case studies on the traditional survey methods applied.

Since 'The Elements' and 'Clearpoint' buildings had not been referenced to the national grid system SLD99 of Sri Lanka, they were first referenced to the national grid by Static GPS observations and 2D similarity Coordinate transformations with least square adjustments. Then by establishing 3 control points each on the uppermost floors of the buildings, the points were surveyed by all five GPS survey techniques. Then by computing the Total RMS Error of the each GPS techniques, the accuracies of the techniques were compared and ranked as shown in the Table 5.16.

Then by conducting paired comparison analysis among the parameters of accuracy, efficiency, time consuming and cost implications of the techniques, the parameters were ranked and weighted. Based on the weighted parameters, the techniques were scored and ranked in the order of the best suitability for vertical alignments in high-rise buildings as expressed in the Table 5.18.

Based on the direct observations and experience gained in the study, GPS surveys were compared with the traditional survey methods for emphasizing the benefits and suitability of GPS surveys in building construction. Finally the problems or challenges faced while conducting the case studies and experiments were listed so that to support and verify the findings of the preliminary analysis.

CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter expresses the final decisions made based on the results and findings of the study. The study was oriented to find solutions for the research problems whether it is beneficial to apply GPS surveys in building construction, what GPS survey techniques are applicable for vertical alignments in high-rise buildings, which one is the best suitable technique among them, and what problems or challenges are there in such GPS applications in high-rise buildings? This chapter explains in detail how it is concluded to accomplish the problems. It further presents the recommendations and suggestions towards the improvements of GPS surveys and future researches.

6.2 Conclusions

According to the results achieved through the analysis of the data gained through experts' comments, case studies and experiments, it can be concluded as follows on the suitability of GPS survey techniques for vertical alignments in high-rise buildings and the challenges or problems to be considered in such applications.

6.2.1 GPS survey techniques in high-rise buildings

The comparison between the GPS techniques and traditional survey methods shows that though the GPS techniques except RTK cannot be used for setting out works, the difficulties of surveying in high-rise buildings are extremely simplified by their great advantages such as better accuracy, efficiency, less time consuming, no need for inter-visibility, no need for references within a shorter visible range, day-night operation, weather independency etc.

Even though the traditional methods are used for surveying in high-rise buildings, it is necessary to have a proper system for cross-checking to ensure the quality.

Thereby, the RTK GPS with a proper system of cross-checking can be used for setting out tasks in high-rise buildings. Likewise, though the other GPS techniques cannot be used for setting out tasks, the applications of those GPS survey techniques with the combination of Total Station or other traditional survey methods for vertical alignments in high-rise buildings of any forms make surveying easier and more advantageous.

When considering the suitability of different GPS techniques for surveys in high-rise buildings, even though the setting out task which is the most important survey requirement in construction at the outset can be done by the RTK GPS, its questionable accuracy due to less redundancy drags it back in the order of the best suitability. Thus, the effectiveness and efficiency of GPS survey techniques on their standalone applications for vertical alignments in high-rise buildings are still lacking. Hence, it can be concluded that the GPS techniques can be applied for vertical alignments in high-rise buildings, but it should be combined with a proper system of cross-checks with traditional survey methods.

According to the literature, GPS techniques are not used as standalone survey techniques in high-rise buildings and they are applied with the combination of Total Station or other traditional survey methods. This situation is further supported and verified by the result gained in the preliminary data analysis on the methods of surveying applied in building construction projects in the industry. Thus suitability of GPS techniques for vertical alignments in high-rise buildings has to be considered with the combination of traditional survey methods.

According to the accuracy, efficiency, reliability and time consuming, both the experts' recommendations and the results of the case studies prove that Static GPS with the combination of Total Station or other traditional survey methods is the best suitable GPS survey technique for vertical alignments in high-rise buildings. Thereafter, Kinematic, RTK, Fast Static and Pseudo-Kinematic techniques take their places in the order given with the combination of traditional methods as above. It should be emphasized that the Kinematic technique was not recommended by the construction experts as an effective GPS technique for vertical alignments in building construction, but the final results express that Kinematic is the second best suitable GPS technique for the particular task. Core Wall Control Survey System is the best example for ensuring the suitability of GPS techniques in high-rise buildings. The combination of GPS techniques and Total Station simplifies the tasks of surveying for vertical alignments in buildings with different morphology and heights.

6.2.2 Challenges

Even though the GPS surveys eliminate some problems faced while applying the traditional surveys methods, such as greater efficiency, less time consuming, no need for inter-visibility, no need for references within a shorter visible range, around-the-clock operation, weather independency etc., still there are many challenges to be vigilant while applying the GPS surveys in building constructions.

Generally the operational and space related challenges are common for any kinds of GPS surveys. As per the comments of the related professionals and field experts, the relative importance indices express that the nature of environment, shape of the structure, construction interferences, distance from the reference stations, need of powerful communication link, necessity of CORS, building movement, safety, quality control and electro-magnetic signal interferences are the major challenges to be considered while applying the GPS techniques for vertical alignments in high-rise buildings. As explained in the previous Chapter, these findings are further supported and verified by cross-checking done in the case studies and experiments.

Although the other space related and operational challenges such as visibility to sufficient number of satellites, atmospheric disturbances, expensiveness, ambiguity resolution, data latency, cycle slip, ionospheric turbulences etc., are covered in the list of challenges, they are very common for all kinds GPS survey applications and do not particularly influence the task of vertical alignments in high-rise buildings only.

6.3 Recommendations

As per the direct observations, experience and results gained in the study, the followings can be suggested on the GPS survey applications for vertical alignments in high-rise buildings towards further improvements of the techniques and future researches on the subject.

- With a proper system of quality control or cross checks, GPS survey techniques can be applied without any hesitation for horizontal and vertical alignments in construction of buildings with different morphology and heights.

- As explained in the Core Wall Control Survey System, the combination of GPS techniques, Total Station and other necessary items such as clinometers can provide precise and reliable solutions for the challenging vertical alignment tasks in super high-rise buildings.

- Vertical alignment in high-rise buildings is a very important aspect and it should be performed very accurately. As per the results of the study, GPS survey techniques can be applied for this purpose as above. Thus it can be strongly recommended that there is no hesitation in using GPS surveys for other construction tasks also.

- Generally local Continuously Operated Reference Stations (CORS) are established for projects by spending large amount of money; this study emphasizes that the data and correction services of CORS network service providers can be utilized for precise survey tasks economically. But the reliability of the service should be ensured.

- Precise setting out with GPS is still a big challenge. Hence the future researches or inventors should focus on the improvement of GPS techniques to make possible the precise and reliable setting outs with GPS.

- Fast Static and Pseudo Kinematics GPS techniques are not widely used for surveys; but the accuracy of Fast Static technique is better than RTK GPS, and the Pseudo Kinematic GPS also provides the results very closer to RTK. This level of accuracy of the techniques emphasizes their applicability for precise surveys.

- It is necessary to take necessary precautions or be prepared to face the above challenges may arise when applying the GPS techniques for surveys in building constructions.

- Communication link is a serious problem in GPS surveying. Even though the master and user receivers function perfectly, there will be no use if there is no proper communication link between them. Thus it is a must to have a powerful communication link between the master and user receivers for better transmission of correction data. External radio and satellite data modem are recommended.

- In order to develop or further improve the GPS survey techniques, the future researchers and inventors can concentrate on finding solutions for the above problems or challenges.

- Providing solution for the above problems in GPS surveys will result a greater revolution in construction surveying.

- The control points established for the experiments in the buildings can be utilized for other purposes which deal with national grid system of Sri Lanka, SLD99.

- Since this report explains in detail the application of GPS surveys in building construction and related challenges, it will be a very good reference as a handbook for construction professionals who are looking to use GPS in their projects or find alternative solutions for traditional survey methods.

6.4 Future Researches

Based on this research approach and findings, future researchers can focus on the following facts or problems for further analysis towards the further developments of the GPS survey techniques and construction surveying.

- Effectiveness and efficiency of GPS survey techniques for vertical or elevation controls in high-rise buildings.

- A comparison study between the VRS network RTK and single base RTK GPS performances.

- Performances of different RTK communication links in construction environment.

- The economical impact of CORS network services on the construction industry of Sri Lanka.

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Appendix - A: Questionnaire

QUESTIONNAIRE

This questionnaire is issued to collect data for an academic research on the topic of IDENTIFYING THE TECHNIQUES AND CHALLENGES OF GPS SURVEYING FOR VERTICAL ALIGNMENT IN HIGH-RISE BUILDINGS.

It is brought to you to involve your honor to add more value to the research by sharing your expertise and experience to identify the techniques and challenges. The information given by your voluntary responses will be used only for the analysis of this academic research and it will be ever confidential.

Part I

Please tick **(✓)** and write in the spaces given as appropriate.

1. Designation/Status

Surveyor	
Engineer	
Architect	
Academic Professional	
Other ………………	

2. Workplace/ Country: …………………………………………………...........
3. Name (Optional): ………………………………………….…………………
4. Company/ Organization (Optional): …………………………………………

Part II

Please tick **(✓)** and write the most appropriate one and skip if not applicable.

1) Experience in Construction Surveying

Below 1 year	
1 to 3 years	
3 to 5 years	
5 to 10 years	
Above 10 years	

2) Experience in GPS Surveying

Below 01 year	
01 to 03 years	
03 to 5 years	
5 to 10 years	
Above 10 years	

3) Experience in Construction of High-Rise Buildings

Below 01 year	
01 to 03 years	
03 to 5 years	
5 to 10 years	
Above 10 years	

4) Maximum number of stories involved

Less than 4 Stories	
4 to 12 Stories	
13 to 40 Stories	
More than 40 Stories	

Name of the Project: - ……………………………………………………….

5) Which method do you use for Horizontal and Vertical alignments in High-Rise Building?

GPS	
Total Station/ Traditional Method	
Combination of both	

6) If GPS, which technique do you use?

Static	
Rapid Static	
Pseudo Kinematic	
Kinematic	
Real Time Kinematic (RTK)	

Part III

Please indicate (✓) your level of acceptance, and write in the spaces given if there is anything to add.

1. Problems in using traditional surveying methods for Horizontal and Vertical alignments in High-Rise Building

	Strongly Disagree	**Disagree**	**Slightly Agree**	**Agree**	**Strongly Agree**
	1	**2**	**3**	**4**	**5**
1. More time consuming					
2. Inter-visibility between stations					
3. Building movement					
4. Shape of the structure					
5. Safety					
6. Nature of environment					
7. Distance from reference stations					
8. Applicability in night times					
9. Transferring the control points to upper level					
10. Construction Interferences					
……………………….					

2. How do you assess the level of accuracy, efficiency, quality and cost implication of GPS application for vertical alignments in High-Rise building against traditional survey methods?

	Worst	**Worse**	**About the Same**	**Better**	**The Best**
	1	**2**	**3**	**4**	**5**
1. Accuracy					
2. Efficiency					
3. Quality					
4. Cost implication					
…………………					

Part IV

1. Please indicate **(✓)** your level of recommendation on GPS techniques applicable for controlling verticality in High-Rise building during construction.

	Strongly Not Recommended	**Not Recommended**	**Questionable**	**Recommended**	**Strongly Recommended**
	1	**2**	**3**	**4**	**5**
1. Static					
2. Rapid Static/Fast Static					
3. Pseudo Kinematic					
4. Kinematic					
5. Real Time Kinematic (RTK)					

2. How do you assess the level of accuracy of those GPS techniques?

	Poor	**Average**	**Good**	**Very Good**	**Excellent**
	1	**2**	**3**	**4**	**5**
1. Static					
2. Rapid Static/Fast Static					
3. Pseudo Kinematic					
4. Kinematic					
5. Real Time Kinematic (RTK)					

3. Are there any Challenges in using GPS for controlling Verticality in High-Rise Buildings?

YES		NO	

4. Some of the possible Challenges are given below. Please indicate **(✓)** your level of acceptance appropriately; and write in the spaces given if there are more apart from these.

	Strongly Disagree	**Disagree**	**Slightly Agree**	**Agree**	**Strongly Agree**
	1	**2**	**3**	**4**	**5**
I. Practical Challenges					
1. Building Movement					
2. Shape of the Structure					
3. Safety					
4. Nature of Environment					
5. Quality Control					
6. Electromagnetic Signal Interferences					
7. Construction Interferences					
………………………..					
………………………..					

	Strongly Disagree	**Disagree**	**Slightly Agree**	**Agree**	**Strongly Agree**
	1	**2**	**3**	**4**	**5**
II. Operational Challenges					
8. Operation of Reference Receivers/CORS					
9. Distance from Reference Receivers					
10. Data Latency					
11. Ambiguity Resolution (AR)					
12. Difficult to Determine the Observation Span for AR					
13. Need of Powerful Communication Link					
14. Expensiveness					
15. Cycle Slip					
16. Number of Visible Satellites and Selective Availability					
………………………..					
………………………..					
………………………..					
………………………..					

	Strongly Disagree	**Disagree**	**Slighty Agree**	**Agree**	**Strongy Agree**
	1	**2**	**3**	**4**	**5**
III. Space Related Challenges					
17. Ionospheric Turbulences					
18. Mesospheric, Stratospheric and Tropospheric Disturbances					
…………………					
…………………					

Part V

If you wish to give any important comments or advices, please write here.

………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………
……………………………………………………....

Appendix - B : Transformation Parameters (WGS84 to SLD99)

7 parameters to transform coordinates from WGS84 to SLD99,

- Translation ΔX = 0.2933 m
- Translation ΔY = -766.9499 m
- Translation ΔZ = -87.7131 m
- Rotation about X axis = 0.1957040”
- Rotation about Y axis = 1.6950677”
- Rotation about Z axis = 3.4730161”
- Scale factor = 1.0000000393

Appendix - C : Coordinate Transformation Matrices – 'The Element'

- **Matrix A**

84.533	139.37	1	0	
139.37	-84.533	0	1	
104.043	88.986	1	0	
88.986	-104.043	0	1	
134.322	90.767	1	0	
90.767	-134.322	0	1	6 X 4

- **Matrix P**

1	0	0	0	0	0	
0	1	0	0	0	0	
0	0	1	0	0	0	
0	0	0	1	0	0	
0	0	0	0	1	0	
0	0	0	0	0	1	6 x 6

- **Matrix L**

404184.950	
490102.872	
404131.892	
490092.693	
404128.228	
490062.578	6 x 1

- **$(A^TPA)^{-1} * A^TPL$**

-0.178883324	
0.983877065	
404062.9517	
490210.9735	4 x 1

Appendix - D : Coordinate Transformation Matrices – ‘Clearpoint’

- **Matrix A**

134.640	170.998	1	0
170.998	-134.640	0	1
128.960	118.924	1	0
118.924	-128.960	0	1
128.962	104.032	1	0
104.032	-128.962	0	1

6 x 4

- **Matrix P**

1	0	0	0	0	0
0	1	0	0	0	0
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0	1	0
0	0	0	0	0	1

6 x 6

- **Matrix L**

403988.968
490194.664
403936.757
490198.911
403921.871
490198.500

6 x 1

- **$(A^TPA)^{-1} * A^TPL$**

0.0274759
0.99962844
403814.3341
490324.5556

4 x 1