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Construction of An Earth Retaining System in the Heart of CBD- A Case Study

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Abstract: The current trend of building skyscrapers in busy urban areas has led to the unique problem of facilitating deep excavation without disturbing the adjacent structures or roads. This excavation support should be both Earth retaining as well as Water Excluding. This paper details the construction of the earth retaining system for the 'The ONE' project, located in the heart of CBD (Colombo Business District), and the challenges encountered. Design of the system is also briefly discussed. A secant pile wall consisting of 871 piles was constructed to ensure the water tightness. Inclinometer pipes were installed in the secant pile wall at selected locations to monitor the deflection of the wall during excavation. Additional pressure grouting was carried to ensure stability of the adjacent structures. Boundary scanning was carried out to locate the underground utilities to carry out the temporary ground anchors. In addition to these activities, the paper also briefly discusses the building health monitoring activities carried out during the project.

Keywords: Earth retaining system, Secant pile, Pressure grouting, Vibration monitoring, Ground Anchoring, Ground settlement monitoring.

1. Introduction

1.1 The Project

The ONE construction project (previously known as the "KRRISH Square") is being undertaken by the ONE Transworks Colombo (Pvt) Ltd. The location of the project is given in Figure 01.

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As it can be observed, the project is located in one of the busiest and highly trafficked areas. The project consists of three super high rise buildings rising out of a common podium. The podium consists of nine floors for parking including three basements.

The foundation for the towers mainly consists of raft and isolated pad footings, which were directly placed on the rock strata. In order to achieve this, deep excavation exceeding 15 m was carried out. It was required to construct an earth retaining system that will also act as a water excluding system. The secant piling wall was selected as the earth retaining system.

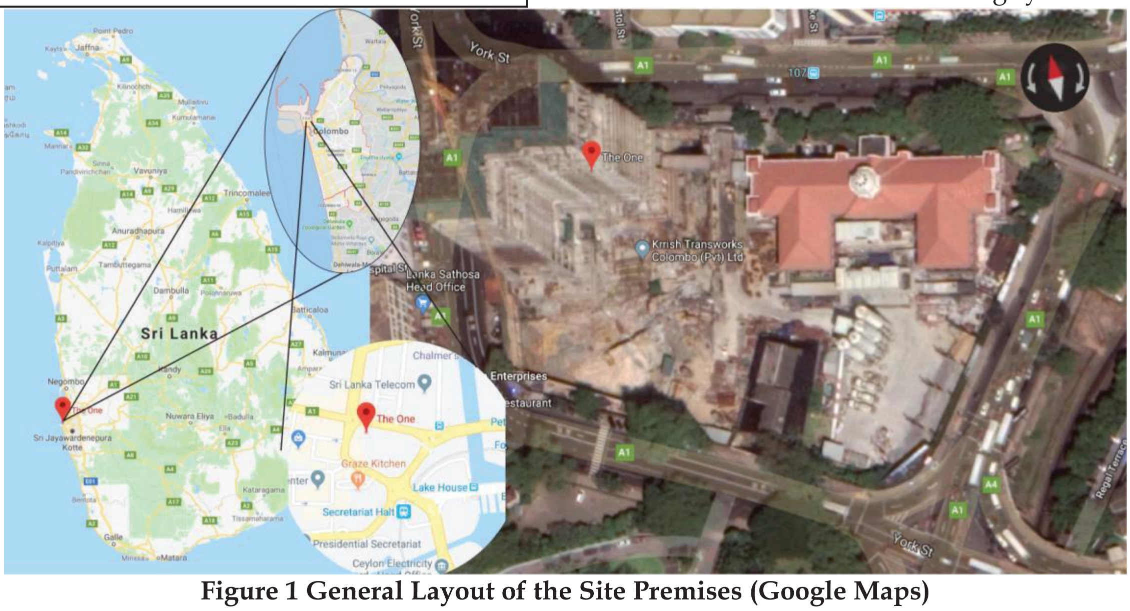

Figure 1 General Layout of the Site Premises (Google Maps)

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1.2 Embedded Retaining Wall

Secant pile is an embedded retaining wall, which is a type of externally stabilised earth retaining system which derives the stability from flexure and depth of embedment and lateral supports [4], [5]. Figure 02 shows a schematic of the free- standing embedded wall type. The depth of the embedment can be reduced by providing braces/ props to the wall or by tying it back (Figure 03) [3].

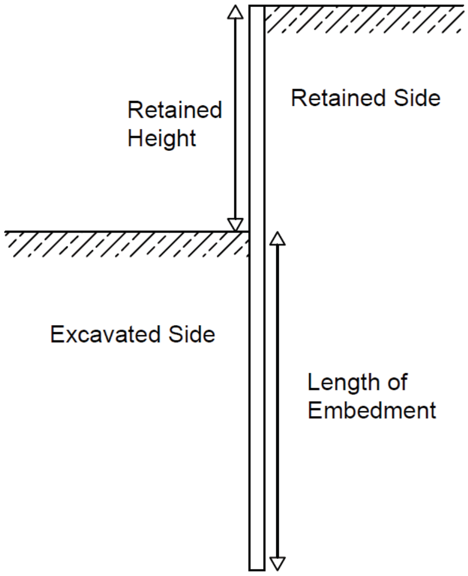

Figure 2 Embedded Retaining Wall

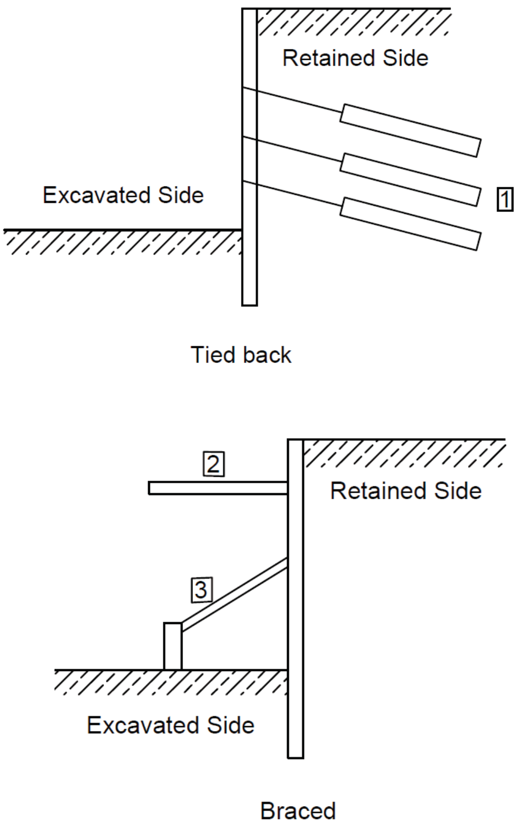

Figure 3 Reduced embedment depth using 1. Anchors 2. Struts 3. Rackers

The braces/props can be classified as either struts or rackers. In addition to the failure modes of the gravity retaining wall (sliding, overturning & bearing failure), the bending of the wall as well as the top deflection needs to be considered in the design of the embedded retaining wall. In this project, it was decided to have a minimum 1 m of rock socketing. This eliminated the possibility of failures relating to the pile toe, such as sliding, bearing etc. The top of the wall is connected by a capping beam, which distributes and controls the deflection on the top. The main failure criteria considered was 'the bending of the wall'.

1.3 Secant Piling

The secant pile wall is made by overlapping bored piles. The water exclusion is provided by this overlapping [6]. The secant pile system consists of two pile types, Primary/Female piles and Secondary/Male piles. Depending on the reinforcement provision the piles are classified as either hard (with reinforcement) or soft. The sequence of construction is detailed on the Figure 04.

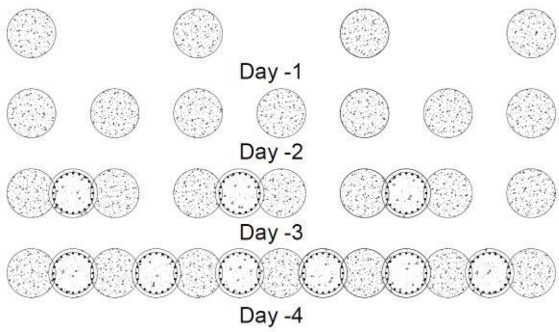

Figure 4 Secant Piling Sequence

1.4 The Back Anchoring

As shown in the Figure 05, the retaining system employs both back anchoring and props. This paper covers the secant piling and back anchoring. Future publications will expand on the construction of rackers and struts. The back anchoring mainly involves three processes. Those are;

- Ground anchoring and grouting
- Wailer beam construction
- Anchor stressing

The main components of a back anchor are;

- Anchor head: Transmits the anchor force to the structure via the combination of bearing plate and wailer beam.
- Free length of the tendon
- Grouted length: Contains the surface area where the tensile force is transmitted to the surrounding ground

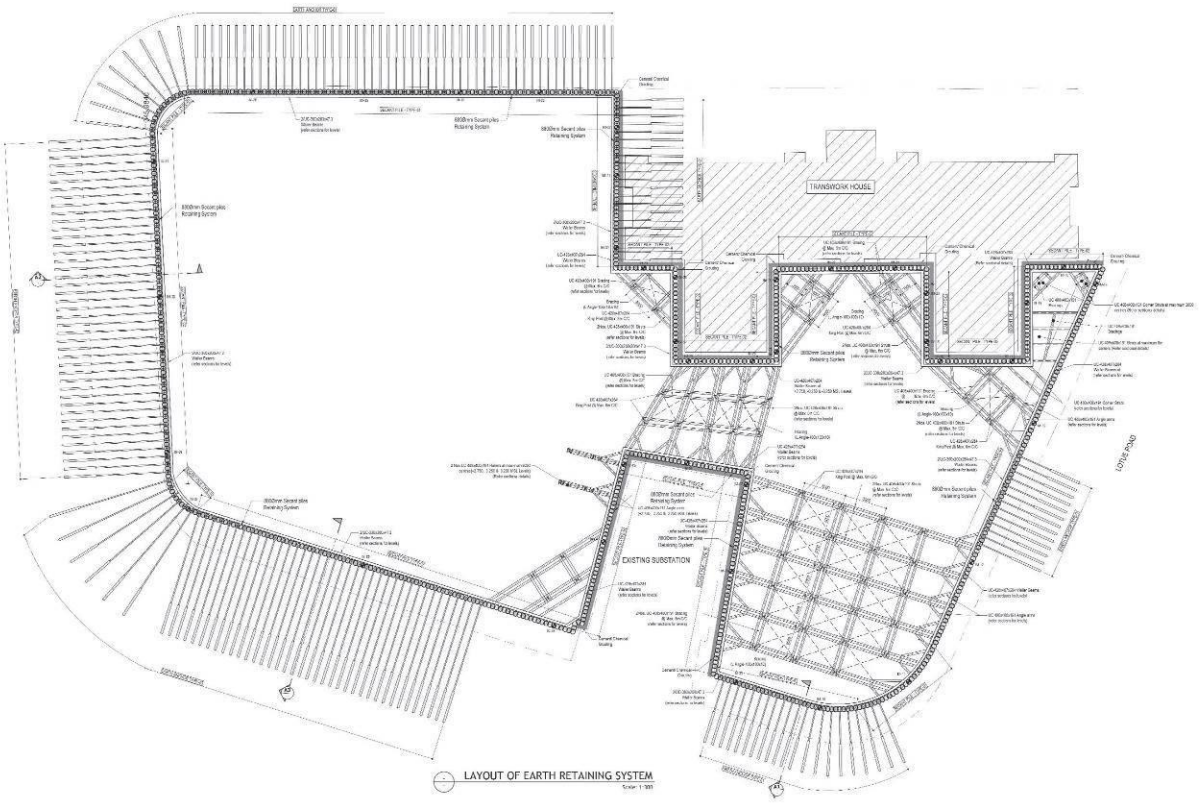

Figure 5 Earth retaining system of The ONE project

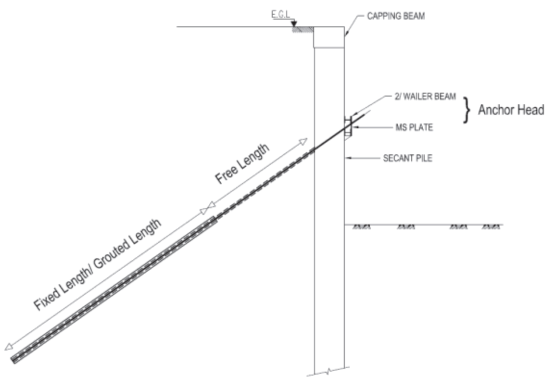

Figure 6 Components of a Back anchor

The back anchoring works on the following concept,

"If the retaining wall bends, it will try to move the ground anchors towards the excavated side. This will mobilise the shear resistance of the retained soil, thus stopping the movement. The force developing on the ground anchor tendon can be calculated using finite element software. By prestressing the tendon to that force, we can mobilise the shear resistance of the soil and stop the movement from ever initiating"

1.5 The Challenges Encountered

The main challenge during the construction of the secant pile was the vibration from the rock drilling. As shown in the Figure 06, the piling line is very close to the Transworks House building as well as the CEB sub-station. Because of their importance, both were to be guarded against any damage from the vibration.

These two buildings also needed to be protected from any settlements. Since the piling was done to a depth far deeper than either buildings' foundation levels, certain measures had to be taken against any leaks or reduced section in the secant pile wall.

From Figures 01 & 05, it can be observed that the ground anchors extend in to the public roads. It had to be confirmed that none of the public utilities would be damaged or disturbed during the back anchoring process.

Furthermore, during the excavation and construction stages, constant and vigilant monitoring have to be carried out to make sure of the stability of the retaining system as well as the continued function of the project. Contingency plans have to be established against any failures observed during the monitoring.

2. Design Phase

2.1 Site Investigation

Originally 13 boreholes were done by Geotech (Pvt) Ltd in 2103 and later in 2017, 9 additional bore holes were done by GeoLab (Pvt) Ltd. In addition, 32 observation boreholes (only extending 0.5 m in to the rock) were also done by the GeoLab (Pvt) Ltd to determine the rock profile.

From the information collected from these boreholes, three types of soil profiles were established for design (Figure 07) [1].

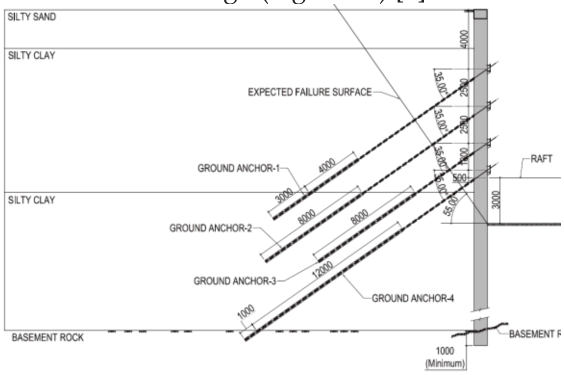

Figure 7 Idealised Soil Profile for Type 1

2.2 Design of the Secant Piles

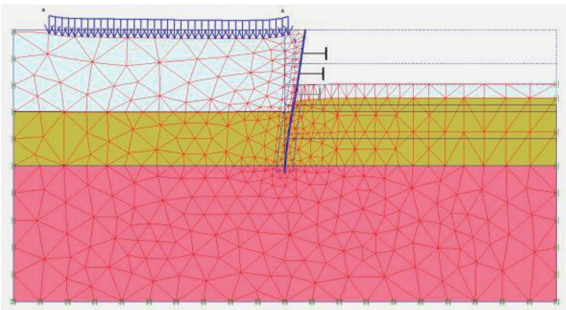

Figure 7 Finite element model

The excavation was modelled in the finite element software (Plaxis 8.2 & Geo5) and analysed in the following construction stages (Figure 8) [2];

- Excavation up to 5 m
- Excavation up to 7.5 m after the installation of first ground anchor at 4 m level
- Excavation up to 10 m after the installation of second ground anchor at 6.5 m level
- Excavation up to 12.5 m after the installation of third ground anchor at 9 m level
- Excavation up to 15 m after the installation of fourth ground anchor at 11.5 m level

Three types of retaining systems were analysed based on the three soil profiles identified. Same analysis was carried out for the condition of propping as well. Table 1 shows the values derived from the analysis for a type of retaining system.

Table 1 Summary of Analysis for Type 1

Design Parameter	Attained Value
Max Horizontal Deflection	54 mm
Max Pile Bending Moment	785 kNm/m
Max Shear Force above rock	345 kN/m
Max horizontal reaction at 4 m	150 kN/m
Max horizontal reaction at 6.5 m	255 kN/m
Max horizontal reaction at 10 m	196 kN/m
Max horizontal reaction at 11.5 m	150 kN/m

During the design a safety factor 1.2 was considered for all the internal forces. The secant piles were analysed using a finite element package (PROKON V3) and also by means of manual calculation. Based on this analysis, reinforcement provision was given as shown in Figure 9.

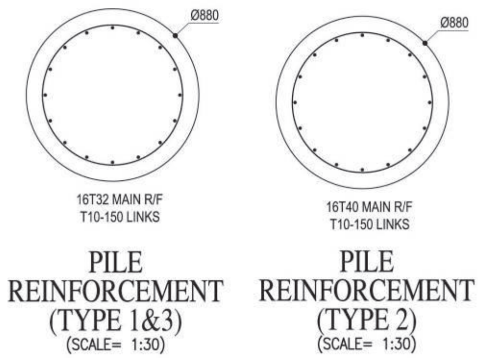

Figure 9 Secant Pile reinforcement

2.3 Design of Ground Anchors

The design force was calculated modifying the values derived from the analysis considering the following;

- Spacing between the ground anchors
- The inclination during installation
- The safety factor

Ground anchors having 4-5 active strands were used in the project. A strand consists of seven individual wires braided to achieve a single strand of diameter 15.2 mm. These strands have yield stress of 1590 MPa and Ultimate tensile stress of 1870 MPa. In the design, two failure mods are considered when calculating the bonded length;

- Failure between the grout and soil mass
- Failure between the tendon and the grout

Minimum of these two values will be considered as the strength of the bond. In the calculation of the Jacking force, allowance should be made for the losses. Based on the jacking force and the number of strands, the allowable elongation shall be determined.

3. Construction Phase

3.1 Secant Piling

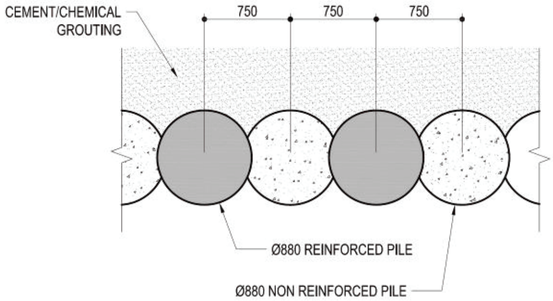

Figure 10 Secant Pile- Typical Detail

Figure 11 Concreted Guide wall

Alignment, location and the verticality are the main criteria for the secant pile construction. In order to ensure that the piles are bored in the correct position, a guide wall (Figure 11) is placed initially. The secant piling was carried out using the casings. After inserting the first and second casing, coordinate of the casing is checked to determine the position the pile. While installing each casing, the verticality is checked using a spirit level.

Figure 12 Concreting the Secant pile

After the installation of the reinforcement cage, the concrete is placed using tremie method (Figure 12). The secant piles were hacked 1 m to the sound concrete and a capping beam was made connecting the entire secant pile wall.

3.2 Pressure Grouting

Figure 13 Pressure Grouting

Pressure grouting was carried out along the building lines to ensure against any foundation settlements. After drilling the holes at 750 mm intervals (coinciding with the location of the reduced section of the wall) 400 mm distance from the boundary wall, perforated PVC pipes were installed in them. A grout mixture made of cement, water and an additive (Flowcable 50), was pumped at pressure of 3-5 bar.

3.3 Ground Anchoring

As mentioned earlier, the ground anchors have to be drilled below the roads. Retrievable temporary anchors were used as the ground anchors. The main concern during the drilling was not to disturb/damage any service lines. Specialist sub-contractor was brought to scan the service lines around the site (Figure 14).

Figure 14 Equipment used for scanning

Using the scan results and the available maps, section profiles were made to ensure that the ground anchors won't damage the service lines (Figure 15).

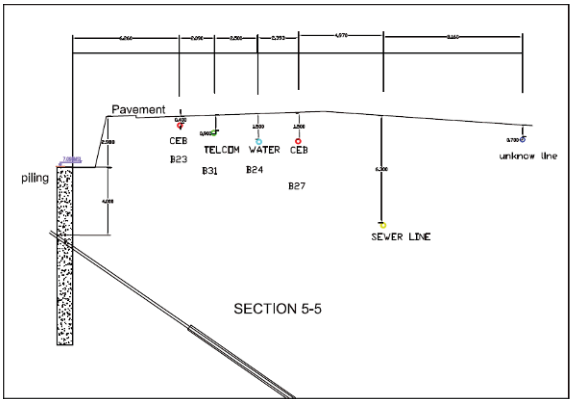

Figure 15 Developed cross-section

The holes for the anchors were drilled using the casings, up to the soil length and pneumatic rock drilling was used to core the rock (Figure 16). High pressure water was used for flushing the holes. After installing the tendons, the casings were retrieved and grouting was carried out using a cement-water mix (W/C ratio of 0.45) under pressure of 0.8-1.0 MPa.

Figure 16 Drilling the Anchor hole

Figure 17 During GA stressing

It should be noted that in order to avoid any water leakage through the ground anchors, it was completely grouted up to secant pile wall. After grouting, a wailer beam was fixed to the secant pile and anchor block was fixed to it connecting the wailer beam and anchor. The grout cubes were crushed to confirm that the anchors have achieved the required strength (7 days- 27 MPa). Following that, the anchors were stressed to the force specified in the drawings (Figure 17).

4. Monitoring & Mitigation

4.1 Vibration Monitoring

The problems encountered during the piling with regard to vibration and the measures taken to mitigate them are discussed in detail in the paper "Monitoring Construction Vibrations- A Case Study" [7]. Limits for the vibrations were established and measures were taken to control the vibration within the established limits.

Figure 18 Instrument used for Data collection

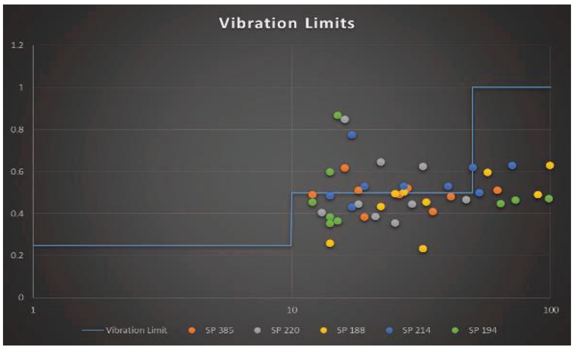

Figure 19 Collected Data

4.2 Deflection Monitoring

Deflection of the secant pile wall during the excavation was monitored using the inclinometer pipes. 4' GI pipes were installed in the selected secondary piles along with the reinforcement cage (Figure 21). Prior to start of the excavation, inclinometer casing tubes were installed in these pipes and grouted with cement grout.

Based on the amount of disturbance from the initial reading, three limits were established (Table 2);

- Alert limit.
- Alarm limit
- Action limit

Figure 20 Inclinometer Instrumentation

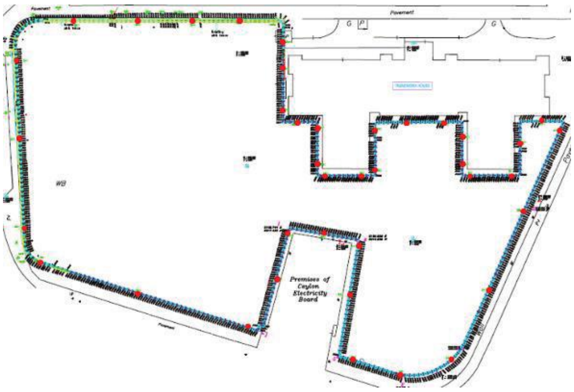

Figure 21 Inclinometer Location

The inclinometer probe was inserted in to the casing and the measurements were taken at 0.5 m intervals, from the bottom to the top. The deviation from the initial reading was plotted and the deflection was measured.

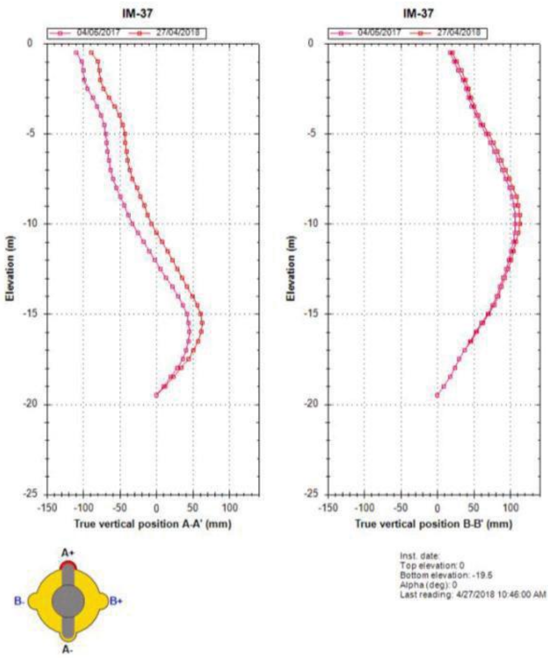

Figure 22 Inclinometer Reading

The inclinometer readings obtained throughout the first phase of the excavation are given in the Figure 23. As it can be observed from the figure, the inclination of the wall is increasing with the increased depth of excavation. The maximum recorded inclination was around 30 mm at IM-37. In this instance, the excavation was deeper than expected and external supports were provided to stabilise the structure. The total inclination was accommodated in the basement wall construction. In the event of deeper excavation, it was proposed to add additional layers of ground anchors to control any excessive deflection.

Table 2 Established Limits (Extract)

Monitoring System	Alert Limit	Alarm Limit	Action Limit
Inclinometer	5 mm	16 mm	20 mm
Ground Settlement	-10 mm	-25 mm	-50 mm

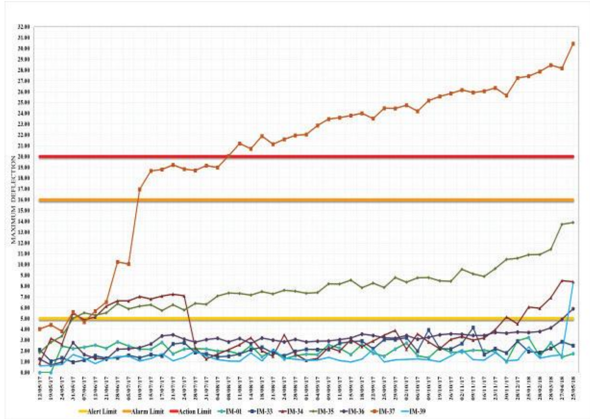

Figure 23 Inclinometer Reading Variation

4.3 Water Level Monitoring

It is crucial that no settlement occur in the retained side of the project as this housed important public roads. To ensure this, ground settlement monitoring as well as the water level monitoring was carried out at regular intervals. Figure 24 shows recent readings from one of the two established water level monitoring wells.

Some water leakage was observed through the ground anchors. This could have occurred due to the settlement of the grout inside the ground anchor. A specialist sub-contractor was employed to seal these water leaks. Water leaks in the secant pile wall due to misalignment of piles was a rare occurrence in this project. These leaks are to be closed using quick hardening cement grout (with the use of additive) pumped at high pressure.

In the event of high drawdown, it was proposed to recharge the retained side using some boreholes.

Figure 25 Secant Pile wall during excavation

4.4 Ground Settlement Monitoring

The ground settlement markers (Figure 26) were established around the site and regular readings were taken. The maximum observed settlement was 10 mm from the initial position.

Figure 26 Ground Settlement Marker

4.5 Other Monitoring Activities

A pre-condition survey was carried out documenting the existing condition (cracks or forms of any distress) of all the surrounding buildings in 100 m radius of the project, prior to project commencement.

Noise monitoring was carried out during the drilling of secant piles. The pile boring was limited to 10 p.m. to control the noise.

5. Conclusions

The main challenge of building a retaining system in an urban area is that the whole operation has to planned, designed and executed in a manner that will not cause any disturbance to the neighbouring community.

The monitoring against the possible failures have to be carried out constantly and vigilantly. Contingency plans have to be prepared to deal with such failures.

The findings and observations made during this process will be valuable for future projects of similar nature.

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PREDICTION OF THE BEHAVIOUR OF LATERALLY LOADED PILES INSTALLED IN GEOLOGICAL FORMATIONS IN SRI LANKA

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Abstract: The lateral loads are more significant in piles especially supporting structures such as high-rise buildings, tall towers, offshore and onshore harbor structures, bridge abutments, viaducts and bridge piers etc. due to high lateral loads on such structures as a result of the actions of seismic, wind, sea waves, lateral earth pressure, vehicular movements etc. For designing and analyzing the piles under lateral loads, the P-Y method and elastic subgrade reaction method are widely used in the industry for few decades. These two methods are more popular due to their simplicity and easiness of use in the manual calculations and implementing in analysis using software. However, the accuracy of the response of the piles in the soil and/or rock mediums estimated from the analysis depends heavily on the material parameters used for the analysis and so far no research is done in that respect to check the predictions against the actual behavior in geological formations in Sri Lanka. At present, the designers use the material parameters available in the literature for other geological formations without any verifications.

In this research, the actual behavior of piles against the lateral loads obtained from the results of the lateral load tests are compared with the predictions using different analytical approaches. By doing so, it is intended to find the best method of analysis out of the two approaches: P-Y curve method and/or elastic subgrade modulus method, and the material parameters for soil/rock layers found in Sri Lanka. Recommendations are also given how to use these methods in pile designing under lateral load in layered soil mediums by 3D simulation of the soil layers obtained from the ground investigation methods. The comparison studies are done using the limited analysis involving the simple manual calculation procedures and use of the software such as LPILE, which can model the piles in multi-layered systems using P-Y method.

Keywords: Modulus of Subgrade reaction, bored pile, driven pile, lateral load, P-Y method, Elastic subgrade method

1. Introduction

The pile foundations are widely used in modern construction industry for substructures. The main reason is the bearing capacity of the pile foundation being much higher than the shallow foundation. Hence, pile foundations are used to transfer higher structural loads into the ground even in the weak ground conditions. The pile foundations are subjected to both vertical and lateral loads. Thus, the design engineer has to consider both loads when designing the pile, to avoid the failure and to secure the serviceability of the structure. When designing some of the structures, more attention should be given to lateral loads as lateral loads are more significant in some of the structures. For example, tall buildings and towers are subjected to lateral loads due to the action of the wind and seismic loads, and harbor structures are subjected to lateral loads due to sea waves and the collision force during the ship berthing. Further, earth retaining structures are subjected to lateral loads due to lateral earth pressure. Hence, lateral loads are very important for designing of piles for similar structures.

There are two main approaches available for analyzing and designing of the piles under lateral loads. Those methods are continuum approach and subgrade reaction approach. Due to the simplicity and easiness, the subgrade reaction approach is widely used in the industry for pile analyzing and designing. In this methods, soil and pile interaction are considered as the discrete set of springs. There are two major methods which come under this subgrade reaction approach. One method is P-Y criteria and the other is elastic subgrade reaction approach. The comparison of these two methods with lateral load test data was conducted throughout the research to select the better method between them, for designing of

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pile in Sri Lankan soil for both driven and bored piles.
The P-Y method shows the relationship between the lateral deflection and soil reaction per unit length along the pile shaft for soil or rock medium surrounding the pile. This relationship has been represented by an equation or graphically for different types of soil and rock. The different researchers proposed methods for soil and rock mediums such as Reese (1974) for sandy soil, Matlock (1970) for soft clay etc.
The elastic subgrade reaction method is another popular method for analyzing and designing piles subjected to lateral loads in different mediums. The modulus of horizontal subgrade reaction (k_h) is directly used as a parameter for analyzing the laterally loaded piles. Different methods are available to obtain the modulus of subgrade reaction for different soil and rock types. Most of the methods used to find the modulus of subgrade reaction, are empirical correlations which depend on the soil parameters such as Poisson ration, Elastic modulus and relative density etc.

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2. Literature Review

2.1 Parametric studies and parameter values

The soil, rock and pile parameters are very important to predict the behaviour of laterally loaded piles. Parameters evaluated by different researchers and some of the literature reviews used in this research give a better understanding about the significant parameters and their typical value range.
Some of the important parameters are cohesion(c), friction angle(ϕ), elastic modulus (E), Poisson ratio (v), modulus of horizontal subgrade reaction (k_h), strain factor (ε_{50}) etc. The parametric studies have been carried out by researchers for piles in different mediums such as piles in cohesive soil, cohesion less soil, layered soil, weak rock, intact rock and jointed rock etc. In addition, parametric studies have been carried out for different pile types such as driven and bored pile. Furthermore, different pile combination such as single and group piles are considered in the analysis with different pile head conditions such as fixed head and free head. The following researches were selected for identifying the significant parameters.

Chong, Haque, Ranjith and Shahinuzzamman (2011) conducted a research about the behaviour of a single pile, when socketed in to jointed rock mass. The authors have used the numerical modelling technique using 3DEC software and have also used laboratory model to calibrate the software. By this research, it was found that different parameters affect the behaviour of a laterally loaded pile in different ways. Also, those researchers have identified the parameters which affect the behaviour of the pile under lateral loading. However, the authors have found that the parameters such as cohesion and friction angle were not significant.
Muthukkumaran and Prakash (2015) conducted the research with an instrumented model pile to find the behaviour of the laterally loaded pile for different parameters such as the depth of socketing and free-standing height above the ground level. The authors have checked the variation of the behaviour of the pile with the above parameters. Finally, it was found that increasing the depth of socketing would tend to increase the lateral load carrying capacity of the pile. Further, the free-standing height of pile above the ground level also affects the lateral pile deflection as well as lateral load carrying capacity of the pile.
Knowledge about some of the parameters such as soil strength parameters, compressibility parameters, modulus of subgrade reaction values are very important in designing laterally loaded piles. The soil strength parameters are cohesion(c) and friction angle (ϕ). In addition, soil compressibility parameters are elastic modulus (E) and Poisson ratio (v). Some researches use the soil compressibility in terms of the modulus of horizontal subgrade modulus (k_h). The relevant soil parameter values are obtained from the following literature reviews.
Bowles (1997) provides the method that can be used for obtaining the corrected SPT N based on the energy method. The relevant corrections for overburden (C_N), energy of the hammer (η_1), rod length (η_2), sample (η_3) and borehole diameter (η_1) are given for different conditions. Equation 1 is used for calculating the corrected SPT N.

$$N_{70}=C_N N \eta_1 \eta_2 \eta_3 \eta_4 \quad \ldots (1)$$

The estimated SPT N values can be used to estimate the soil strength parameters.
Das (2015) provides some compressibility parameters using empirical correlations based on corrected SPT N. This method is widely used in the industry to obtain the modulus of elasticity and Poisson ratio values. Poulos and Davis (1980) highlighted some methods to obtain the horizontal modulus of subgrade reaction (k_h) for different soil types proposed by different researchers. These methods can be used to obtain the modulus of subgrade reactions for both clayey and sandy soil.

2.2 Subgrade reaction method

The subgrade reaction method was developed, based on the Winkler foundation theory. In the Winkler theory, soil is considered as a set of springs and the interaction between pile and soil depend on these separate springs. Reese and Matlock (1956) proposed the subgrade reaction method, mostly used approach to study the laterally loaded pile. In this method, the soil is taken as springs and compression of these springs produce the soil reaction on the pile.

2.3 P-Y criteria

The P-Y criteria shows the relation between soil reaction per unit length along the pile shaft and relevant pile deflection. There are several P-Y criteria which have been proposed by several researchers for different soil, and rock types (described further in the methodology). Relevant curves were developed for each P-Y criteria. P-Y method is widely used for developing the software used for analysing laterally loaded pile. Reese et al (1974) have proposed a P-Y criterion for sand above and below the water table. Relevant P-Y curve can be used for analysing the laterally loaded pile in sandy soil. Results of the lateral load tests were used in developing this method and hence, this method can be adopted to sandy soil with some confidence. Matlock (1970) proposed the P-Y criteria for soft clay. This method is widely used in some of the software that are developed for analysing laterally loaded pile. The research has been conducted using instrumented steel-pipe piles of diameters 324mm and lengths of 12.8 m, in soil with the soil shear strength of 38kPa.

2.4 Use of software in the analysis of laterally loaded piles

Different software applications are used in the pile industry for analysing the laterally loaded piles. In this research, LPILE software was used for analysing the laterally loaded piles. William and Wang (2018) provided the guidance to use the LPILE software for different computational mode for different soil and rock conditions, and different pile types. Also, user manual provides the guidance for selecting required input data. William and Wang (2012) provided the guidance to select the relevant P-Y criteria for soil and rock types in LPILE technical manual. This manual includes some important parameter value range for input data. Also, several examples were provided for understanding the application of the P-Y criteria for different conditions. In the same way, this manual provided some recommendations to select the relevant P-Y criteria depending on the soil type.

Yang et al (2006) carried out a research work using LPILE software to find the behaviour of the lateral load pile. In this research, vertical test as well as a lateral load test had been carried out for rock-socketed bored pile in Pomeroy-Mason Bridge over the Ohio River. The collected data were analysed using LPILE software. They finally decided the method of p-y criteria for interim rock proposed by Reese (1997) was giving good predictions by modifying the rock properties. The authors also suggested the necessity of further lateral loaded test data related research for laterally loaded rock socketed piles, due to the lesser number of research carried out using lateral load test data.

3. Methodology

Two sites, where soil investigation results are available and lateral load tests had been carried out one on bored and cast in-situ piles and the other on driven piles, were selected for this research.

3.1 Parameter values

The site investigation reports was used to obtain the relevant soil parameters values based on corrected SPT N value using the energy methods (Bowles, 1997). Further, relevant pile parameter values were obtained from pile record.

The summary of the soil properties of each soil layer of the project site for the bored and cast in-situ pile are shown in Table 1. Subsurface of the site consists sandy, clayey and organic soil layers. The summary of the soil properties of each soil layer of the site, where the driven piles are installed, are shown in Table 2.

Table 1 Soil parameters values in the site where bored pile is tested

Depth (m)	SPT N_{70}	Layer	Soil properties					
			unit weight (kN/m³)	cohesion-c (kN/m³)	friction angle (ø)	Elastic modulus (MPa)	Poisson ratio(v)	Modulus of subgrade reaction (k_h)
0 - 0.5	-	1. Clayey Sand	12	-	29	2.0	0.2	0 833
0.5 -2.17	2	2. Sandy Clay	12	12		2.4	0.2	271.5
2.17 - 4.5	3	3. Organic Clay	15	15		3.0	0.15	162.9
4.5 - 8.17	5	4.Medium to Coarse Sand	15	-	30	5.0	0.25	15000 27200
8.17 - 13.84	15	5.Lateritic Clay	80	45		6.0	0.3	11000
13.84- 16.17	40	6.Sand Weathered Rock	20	-	40	30	0.35	34000

Table 2 Soil parameters values in the site where driven piles are tested

Depth (m)	SPT N	Layer	Soil properties					
			unit weight (kN/m³)	Cohesion c (kN/m³)	friction angle (ø)	Elastic modulus (MPa)	Poisson ratio(v)	Modulus of subgrade reaction (k_h)
0 – 3	19	1. Backfilled medium-coarse sand	16.5	-	36	17	0.2	0 40000
3 -6	10	2. Humus soil	15	50	-	4.8	0.15	108.5
6- 9.5	3	3. Fine-medium sand	18	-	28	4.5	0.2	20000 31600
9.5 – 15.9	54	4. Coarse gravel sand	20	-	48	38	0.3	35000

3.2 Lateral load test data

Only one lateral load test was carried out in the site on a bored and cast in-situ pile having a diameter of 600mm. The pile head deflection was measured using the dial gauge. The lateral load vs lateral pile head deflection of the bored pile was given in Table 3.

Table 3 - Lateral load test results on bored pile

Load Percentage	Lateral Load(kN)	Deflection (mm)
0	0	0.00
25	17	0.76
50	33	1.59
75	50	2.72
100	67	4.67
125	83	6.90
150	100	9.13

Lateral load tests have been done on 600mm diameter driven piles in the selected site and two driven test piles namely, SZ6and SZ8 were considered in this research. The tests were conducted by applying the lateral load using a hydraulic jack and a reaction frame while the lateral deflection under different loading conditions were measured using LVDT. The lateral load vs pile head deflection for the two driven piles are shown in Table 4.

Table 4 - Lateral load test results of driven pile

SZ6		SZ8	
Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
0	0.00	0	0.00
15	0.63	15	0.64
30	1.28	30	2.29
45	2.21	45	3.84
60	3.19	60	5.59
75	4.97	75	7.79
90	6.68	90	9.72
105	7.92	105	11.88
120	11.23	120	28.08
135	16.34	135	35.76
150	33.29	150	46.03

3.3 LPILE model

Tables 5 and 6 show the input parameter values used for the P-Y method in both the projects for bored pile and driven pile respectively.

Table 5 - LPILE input data for P-Y method for bored pile

Layer	P-Y criteria	$\gamma^{/}$ (kN/m^3)	ϕ	k_h (kN/m^3)	c_u (kN/m^3)	ε_{50}	Reference
Layer (1) Clayey Sand	Sand (Reese)	2.19	26	0-833	-	-	William. and Wang (2012) William and Wang (2018)
Layer (2) Sandy clay	Soft clay (Matlock)	5.19	-	-	12	0.02	
Layer (3) Organic clay	Soft clay (Matlock)	5.19	-	-	15	0.02	
Layer (4) Medium to Coarse Sand	Sand (Reese)	5.19	30	15000-27200	-	-	
Layer (5) Stiff Lateritic clay	Stiff clay with free water (Reese)	7.19	-	12000	80	0.005	
Layer (6) Completely weathered rock (sand)	Sand (Reese)	10.19	40	35000	-	-	

Table 6 - LPILE input data for P-Y method for driven pile

Layer	P-Y criteria	$\gamma^{/}$(kN/m^3)	ϕ	k_h (kN/m^3)	c_u (kN/m^3)	ε_{50}	Reference
Layer (1) Backfilled medium coarse Sand	Sand (Reese)	6.69	36	0-40000	-	-	William. and Wang (2012) William and Wang (2018)
Layer (2) Humus soil	Soft clay (Matlock)	5.59	-	50	-	0.005	
Layer (3) Fine and medium sand	Sand (Reese)	8.19	28	80000-100000	-	-	
Layer (4) Coarse gravelly sand	Sand (Reese)	10.19	48	15000-27200	-	-	

Table 7 - LPILE input data for bored piles using Elastic subgrade method

Layer	Unit weight (kN/m^3)	Elastic Subgrade Reaction(kN/m^3)	
		Top	Bottom
Layer (1) Clayey Sand	12	0	833
Layer (2) Sandy clay	15	226	980
Layer (3) Organic clay	15	590	1221
Layer (4) Clayey Sand	15	15000	27200
Layer (5) Lateritic clay	17	12000	12000
Layer (6) Completely weathered rock(sand)	20	35000	35000

Table 8 - LPILE input data for driven pile using Elastic subgrade method

Layer	Unit weight (kN/m^3)	Elastic Subgrade Reaction(kN/m^3)	
		Top	Bottom
Layer (1) Backfilled medium coarse Sand	16.5	0	40000
Layer (2) Humus soil	15	108.5	108.5
Layer (3) Fine and medium sand	18	20000	31200
Layer (4) Coarse gravelly sand	20	34000	34000

In assigning the elastic subgrade for different soil layers, it was assumed that the modulus of subgrade reaction varies linearly with the depth (n_h method). The Tables 7 and 8 show the input values for the simulation software when using the Elastic subgrade method in both the projects.

4. Discussion and Results

4.1 Bored and Cast In-Situ Pile

4.1.1 P-Y Method and Elastic subgrade method

The lateral load vs deflection graphs for both LPILE generated curve and LLT (Lateral Load Test) curve for the bored pile were shown in Figures 1 and 2 separately for P-Y and Elastic subgrade methods.

For lower lateral loads, the difference in deflection between P-Y method curve and LLT curve was comparatively less than the deflection difference for higher loads. P-Y method curve always showed less deflection than LLT curve for the bored pile for a given lateral load. However, it is noted here that the computed curve did not match well with the curve given by the LLT.

As shown in Table 6, there are six different soil layers along the shaft of the bored pile. Each layer has different horizontal modulus of subgrade reactions (k_h). The lateral load vs deflection obtained from elastic subgrade method and observed in LLT are shown in Figure 2. For both the lower lateral load and the higher lateral loads, the difference between elastic subgrade method and LLT was considerably less than middle lateral loads.

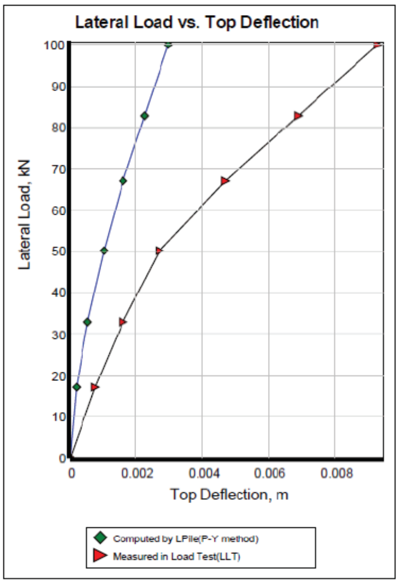


Figure 1 - P-Y method vs LLT for the bored pile

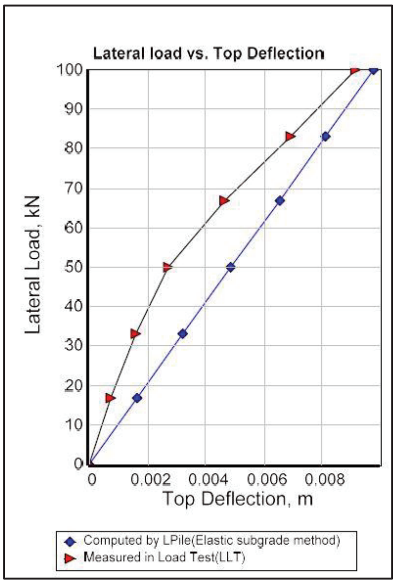


Figure 2 - Elastic subgrade method vs LLT for bored pile

4.1.2 Comparison of P-Y Method and Elastic Subgrade Method

The lateral load vs deflection of the P-Y method, subgrade method with lateral load test curve are shown in Figure 3. For the bored pile, the LPILE generated curves for both P-Y Method and Elastic Subgrade Method deviated considerably from the LLT curve. For given lateral load, P-Y method shows less lateral deflection than LLT curve and Elastic subgrade method gives higher lateral deflection than LLT curve. Thus, Elastic subgrade method gives conservative predictions. Further, Elastic subgrade method generate better results than P-

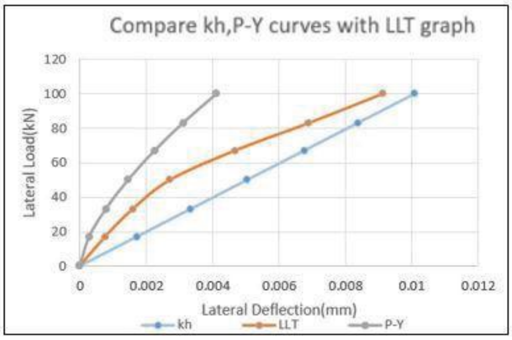


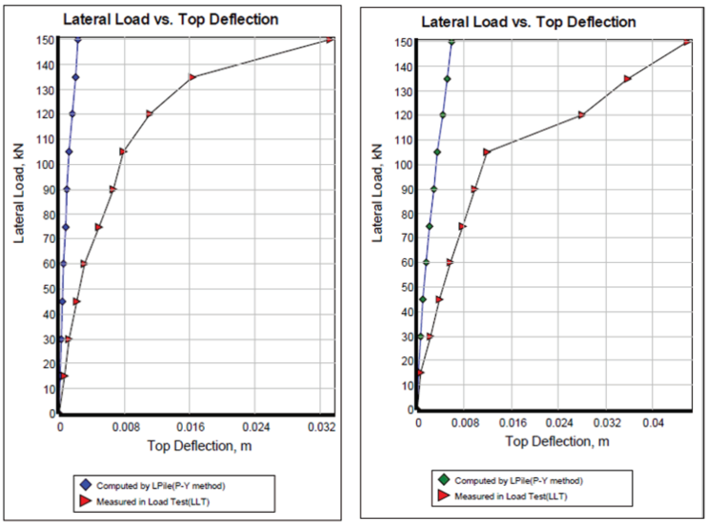
Figure 3 - Comparison (Lateral loads vs Pile head deflection) for bored pile

Y method with LLT as the lateral deflection difference between elastic subgrade method and LLT curve was less than the lateral load deflection difference between P-Y method and LLT curve. Hence, the best approach for laterally loaded bored pile designing could be selected as elastic subgrade method.

4.2 Precast Driven Pile

4.2.1 P-Y Method and Elastic Subgrade Method

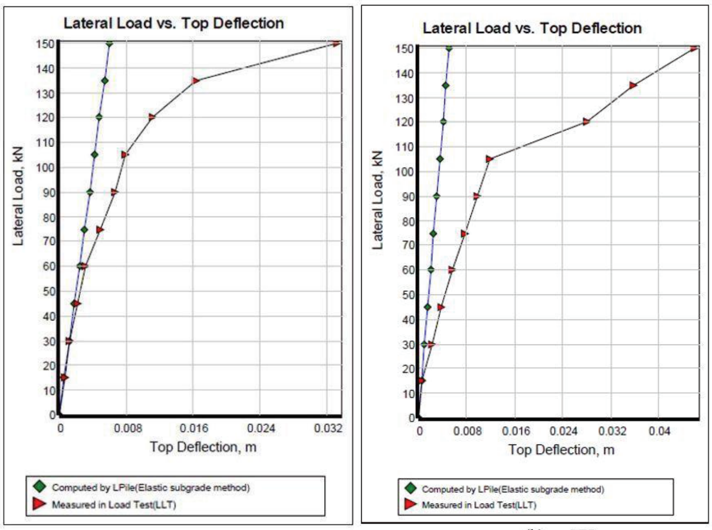
P-Y method and Elastic subgrade methods were analysed using LPILE software separately, for driven piles. The results of the two methods were compared with LLT results for the two selected test piles SZ6, and SZ8.The lateral load vs top deflection for P-Y and Elastic subgrade method with LLT were shown in Figure 4.



(a) SZ6 (b) SZ8

Figure 4 - P-Y method vs LLT for two driven piles (a) SZ6 & (b) SZ8

The results variation was different for each test pile. But P-Y method curves always show lesser lateral deflections than LLT curves for the two-test pile. For all the two sets of curves in Figure 4, similar behaviour was shown in lower lateral load. But, for loads greater than 100kN the difference in deviation of LLT curve from P-Y curve was considerably high. But P-Y method may be used for designing the driven piles using some modification factors.



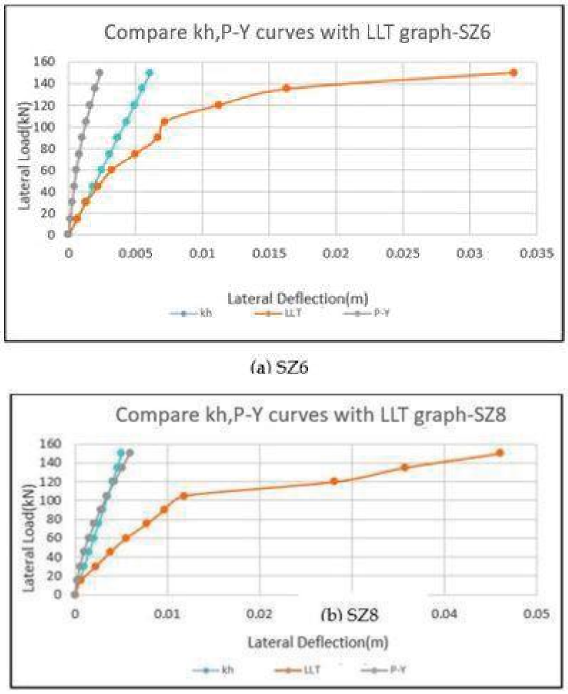
(a)SZ6 (b) SZ8

Figure 5 - Elastic subgrade method vs LLT (a) SZ6 & (b) SZ8

The lateral load vs deflection for Elastic Subgrade Method and LLT were shown in Figure 5. The lateral deflection difference between Elastic subgrade method and LLT was lesser for lower applied lateral loads. But the lateral deflection difference was significant when lateral loads were higher. Furthermore, a changing behaviour of elastic subgrade method and LLT was observed.

4.2.2 Comparison of P-Y Method and Elastic Subgrade Method

The lateral load vs lateral deflection curves for P-Y method, Elastic subgrade method and LLT are shown in Figure 6 in the same graph for different test piles. There were two lateral load tests which were conducted on test piles SZ6 and SZ8. These two graphs show the variation of P-Y Method and Elastic Subgrade method curves with LLT curve.



(a) SZ6

(b) SZ8

Figure 6 - Comparison of P-Y, k_h, LLT (a) SZ6 & (b) SZ8

P-Y method curves were always shown the lesser deflection than LLT curve and given lesser lateral deflection difference with LLT at the lower loads and higher difference at higher lateral loads. But the lateral deflection difference between the Elastic subgrade method and LLT curve were showing a lesser variation than P-Y method and the deflection predicted by the subgrade reaction method is higher than the same for P-Y method. Hence, Elastic subgrade method is more appropriate for laterally loaded pile design than P-Y method for driven piles.

4.3 Comparison of P-Y Method and Elastic Subgrade Method for both sites (Bored and cast in-situ and Precast driven)

The two sites for bored and cast in-situ pile and driven pile have different soil conditions and soil stratification. Hence, the comparison was difficult. But elastic subgrade method gave more approximate values than P-Y method with LLT for driven piles. But elastic subgrade method results deviated from LLT same as P-Y method for bored pile.

Sometimes due to the variation of soil properties within the site, it was difficult to get the accurate Modulus of subgrade reaction values for soil. Hence P-Y method gave the best results than elastic subgrade method when the modulus of subgrade reactions (k_h) of the layered soil was uncertain.

4.4 Modification Factors for P-Y curves for both sites (Bored and cast in-situ and precast driven)

The measured and predicted curves were matched with each other after applying the modification factor for deflection (y) as 20 for a given lateral load. The lateral load vs deflection of the both modified P-Y curve and LLT curve are shown in Figure 7. The relevant modification factor used for P-Y method are shown in Table 9 for the bored and cast in-situ pile.

Table 9 - Modification factors for P-Y curves for the bored pile

Modification Factors for P-Y Curve for bored pile			
Depth point	Distance from Pile Head (m)	P - Multiplier	Y - Multiplier
1	0	1	20
2	2	1	20
3	4	1	20
4	6	1	20
5	8	1	20
6	10	1	20
7	12	1	20
8	14	1	20
9	16	1	20

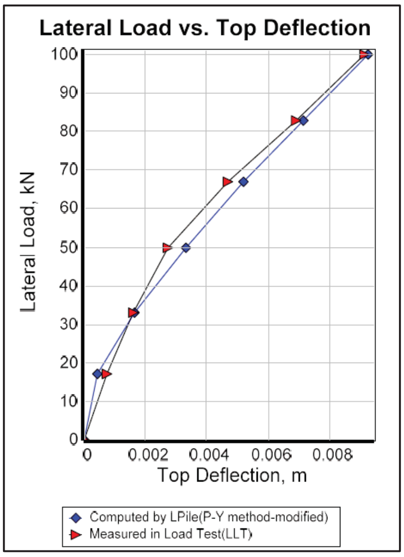
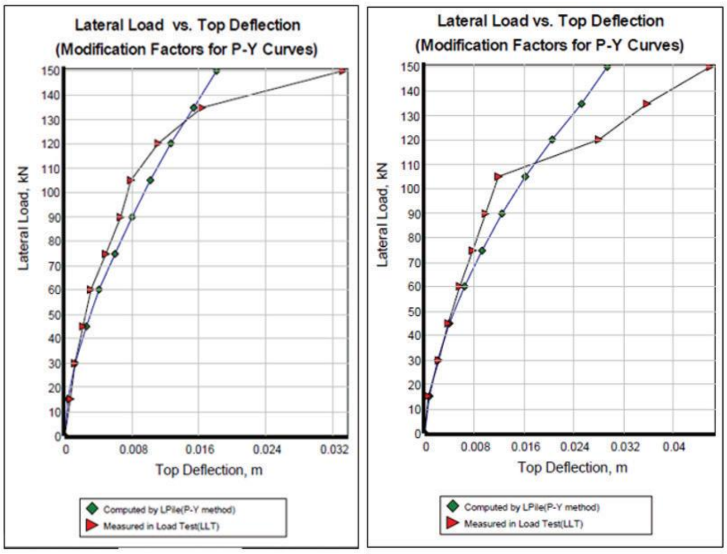


Figure 7 - After applying modification factors for P-Y curve for bored pile

The modified P-Y curves with relevant LLT curves were shown in Figure 8 for each test piles SZ6 and SZ8. The P-Y curves were matched with relevant LLT curves after applying the different modification factors for deflection(y) and lateral load (p). Different modification factors were used for test pile SZ6 and SZ8. The relevant modification factors that were used for P-Y method are shown in Table 10 for driven piles. After the modification factors were applied, both P-Y curves and LLT curves were approximately matching with each other. According to the results, modification factors for deflection can be given as 20 for driven piles. These modifications factors may be used for designing the laterally loaded precast driven piles.

Table 10 - Modification factors for P-Y curves for driven piles

Depth point	Distance from Pile Head (m)	SZ6		SZ8	
		P – Multi plier	Y – Multi plier	P – Multi plier	Y – Multi plier
1	0	1	20	1	20
2	2	1	20	1	20
3	4	1	20	1	20
4	6	1	20	1	20
5	8	1	20	1	20
6	10	1	20	1	20
7	12	1	20	1	20
8	14	1	20	1	20
9	16	1	20	1	20



(a) SZ6 (b) SZ8

Figure 8 - After applying modification factors for P-Y curves for (a) SZ6 & (b) SZ8

5. Conclusions

The P-Y method and elastic subgrade method have been used for analysing and designing of piles for several decades. Due to the simplicity and easiness, these two methods are used for different soil conditions and different pile types. Even though there are several software packages available for analysing the laterally loaded piles, a proper research has not been conducted to compare these two methods with actual lateral load tests data in Sri Lanka.

This research study reveals that the elastic subgrade reaction method shows better results than P-Y method with the lateral load for both precast driven and bored and cast in-situ piles. But due to the high variability of soil properties within the given site, especially modulus of subgrade reaction determination can be uncertain. This happens as there is no clearly defined method to obtain the modulus of subgrade, even though there are several methods available.

In that situation, laterally loaded pile analysing have to be done using the P-Y method with modification factors. Because the P-Y method always gives a lesser deflection than the lateral load test. Hence, the P-Y methods have to be used with some modified factors for a safe design when designing the pile. Because, if P-Y method was used without modifications, it will provide a lateral deflection for a given lateral load less than the actual lateral deflection, which is unsafe. But for pile designing, if the elastic subgrade method is used, it will give the safe conservative design, especially for bored piles. Because elastic subgrade method gives conservative results compared to lateral load test results even though the lateral deflections computed using the elastic subgrade reaction method varies significantly from the measured values. Also, the elastic subgrade method gives the best results with LLT for bored piles than driven piles. However, this research was conducted by using limited test data for Sri Lankan soil conditions. Hence, more lateral load tests related research should be needed to conduct in the future, for further verification of selection of the best method.

In this research P-Y curves were modified by multiplying the deflection values with some factors for a given lateral load, when the computed lateral deflections do not match with the measured. Alternatively, the values of the soil parameters can also be modified by some factors to match the measured LLT curve with the computed one. But in this research, modification of the material parameters was not adopted.

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