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SIMULATION-BASED CONTINGENCY ESTIMATING FOR HELICAL PILE INSTALLATION

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Abstract: An Excel based simulation tool was developed to guide the preparation of bid proposals on helical pile foundation projects featuring a high degree of uncertainty. This simulation tool was designed based on a systematic methodology which integrates project information generally available at the bidding stage, i.e. engineering design, subsurface conditions and site layout plans; and synchronizes takeoff, estimating, scheduling and risk analysis. The methodology behind the simulation tool is described in this paper, which effectively decomposes the whole helical pile installation project into sufficient installation work packages. The tool automatically generates cumulative distribution function (CDF) graphs indicating the estimated ranges of total project duration and total bid price. The simulation report presents the anticipated bid price and project schedule, plus the contingency estimate at a certain confidence level. The proposed methodology is effective to lend direct decision support for helical pile contractors in preparing bidding proposal and estimating contingency.

1 INTRODUCTION

A foundation transfers the load from the superstructure to the underlying soil or rock. Among numerous alternatives in deep foundation systems, pile foundations are regarded as the primary choice for situations where geological conditions are poor or upper loads are heavy and complex. Advantages in regards to helical pile construction include rapid installation, immediate loading, relatively accurate capacity verification, and all-weather installation (Perko 2009). Across North America, helical piles are increasingly selected as a cost-effective alternative to substitute for traditional deep foundation engineering systems (such as concrete cast-in-place piles and driven steel piles), particularly when hard soil layers are not existent in the field (such as rocky soil, hard sand or till).

Helical piles are screwed into the ground using a hydraulic torque motor, capable to carry heavy loads in both temporary and permanent applications. However, the installation of a helical pile can be complicated by subsoil uncertainties, onsite management constraints and various other risks, thereby presenting significant challenges for professional estimators to evaluate the contingency of construction cost in a quantitatively reliable fashion (Peck et al, 1974; Tomlinson & Woodward, 2008; Reilly 2005).

Helical pile installation operations are repetitive, where crew composition and construction technology are relatively fixed. Nevertheless, crew productivity in terms of daily production rate fluctuates broadly. So far, information specific to work items and crews for helical pile installation, including average daily production benchmarks, is not available in commercial cost data services like R. S. Means (2016). In practice, experienced field personnel apply rule of thumb to empirically estimate contingencies in connection with site specific uncertainties in the installation process.

Soil conditions differ from site to site in terms of stiffness, cohesion, natural obstacles and existing underground infrastructure (Zayed and Halpin 2001). Site constraints such as temporary road conditions, inter-pile space, special pile arrangement as per design, and the mechanical capacity and the drilling limitation of the piling equipment add more challenges to onsite management. The installation productivity is also affected by distance and time in handling piles from the lay-down area to each pile location. In addition, crew's knowhow and experience in facilitating pile installation (e.g. calibrating, aligning) is another determinant factor. At present, there is no formal methods available for defining, classifying, and decomposing the work in helical pile construction; for instance, no helical pile related work items exist in the RS Means construction cost database compiled by Construction Specifications Institute (RS Means 2016). This has hampered a data-driven, scientific approach to cost estimating of helical pile construction projects at the bidding stage.

To better predict the total installed cost of the project, the amount of money –which is added to the base estimate in order to account for unknown or uncertain factors during cost estimating and project bidding- is generally termed as *contingency* (Peurifoy and Oberlender 2004). In the remainder of the paper, contingency is specifically defined as the extra cost against the base estimate due mainly to the effect of varying ground conditions upon helical pile installation productivity. The present research attempts to formalize a framework for seamlessly integrating limited data and information obtained from a particular ground investigation program with construction cost estimating in bidding for helical pile foundation projects. Further, Monte Carlo simulation is applied on top of the cost estimating framework in order to quantitatively characterize the potential cost increase. An Excel based estimating tool featuring user-friendly input interfaces and simulation functions for helical pile project estimating is described. A real-world application case based on the bid for a power substation project in Alberta, Canada is presented.

2 PROPOSED RESEARCH METHODOLOGY

2.1 Data Collection and Information Mapping

The input data as needed for implementing the proposed methodology consist of (1) engineering design drawings; (2) geotechnical investigation report; (3) site layout information (e.g. laydown area location); and (4) historical or empirical field data encompassing installation procedures and installation time estimates. The information is generally available at project estimating and bidding stages. In this study, pile installation time data are collected by questionnaire referencing the schema given in Zayed and Halpin (2001) which decomposes the pile installation process into discrete activities. This would make it easy for field installation experts to recall data with good confidence when historical data are nonexistent or resources required to collect such data in the field are unavailable. In the present research, experienced operations personnel provided duration of activities by assessing events that would occur in the field, namely: (1) probabilities (%) for certain scenarios to occur (referring to Table 1); (2) ranges of activity duration due to numerous practical onsite factors. The activity duration was collected in three points, namely the minimum time (minutes), the most probable (minutes), and the maximum (minutes).

A construction information map indicates pile locations and types, bore hole locations and respective impact areas, material delivery zones (which are classified by the ranges of distances between the pile location and the site laydown area.), and construction phase divisions according to contractual documents. A typical construction information map is illustrated in Figure 1, which is instrumental in developing the work breakdown structure for helical pile installation. Note pile types (1 to 4) are differentiated by engineering designs which will be explained in a subsequent section.

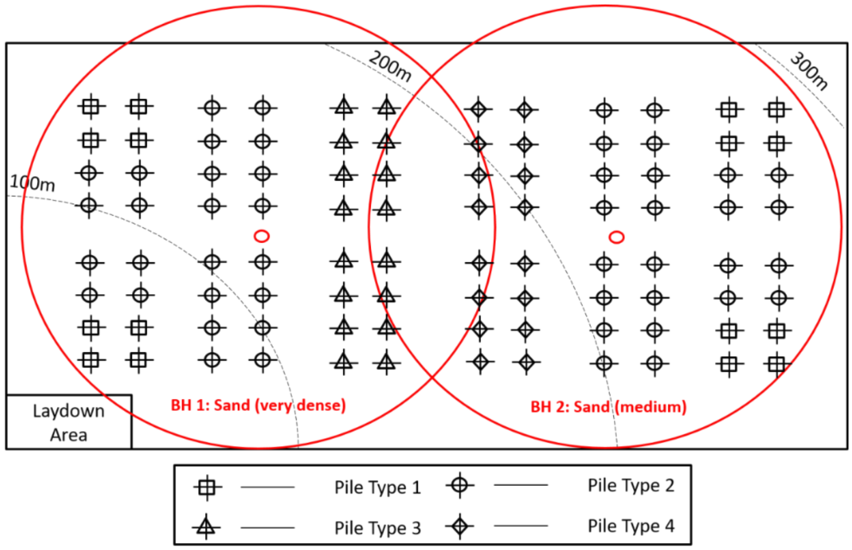


Figure 1: Construction information map. 100m,200m,300m denoted in dot arcs are ranges of distances between the pile location and the site laydown area; The borehole impact ranges are delineated by solid red circles; pile types are differentiated by notation shapes.

2.2 Work Breakdown Structure (WBS) Formalization

This research decomposes the helical pile construction into work packages by considering three factors, namely: (1) engineering design; (2) soil profile; and (3) site layout.

Engineering Design

By observing construction processes in the field, interviewing experienced industry personnel, referencing steel driven pile and concrete pile classifications in the literature (e.g. Sakr 2012), four design parameters were identified as the most influential to helical piling construction productivity, namely: (1) shaft diameter, (2) pile length, (3) helix diameter, and (4) helix quantity. Hence, these four design parameters were selected as pile type classification variables in guiding quantity takeoff and cost estimate in helical pile construction.

Soil Profile

The probabilities of encountering hard or soft soil layers that require a special method and equipment can be estimated based on borehole data and experts' experience. Given either cohesive or cohesionless soil, the degree of soil consistency is inextricably correlated with the degree of difficulty to install helical piles in the ground. Previous studies in geotechnical engineering conducted experiments in order to derive the relationships between borehole data and the helical pile installation torque in both cohesive and cohesionless soils (Sakr 2012; Sakr 2014). Significant increase in torque values was spotted in dense to very dense sand, hard till, and hard clay, where the designed pile torsional limit was easy to be reached. In this research, by referencing related literature and consulting experienced helical pile designer/field manager, we define the aforementioned three soil types plus "gravel/cobble" as relatively hard for helical pile installation. Further, we classify the soil condition as "soft", "normal" and "hard" for helical pile installation by factoring in N value of SPT (Standard Penetration Test) (Terzaghi et al. 1996), which is an field dynamic penetration test designed to indicate the geotechnical properties of soil. Note N value is a measure for the resistance of soil to a calibrated load: the larger the N value, the harder is the soil.

The present research defines two "backup method" scenarios that are likely to be employed in the field given unfavorable soil conditions, affecting construction productivity and crew use:

- Scenario “Predrill”: The torsional strength rating as per design is reached prior to achieving the minimum depth of pile penetration; under such circumstances, pre-drill could be an effective solution in the field.
- Scenario “Extension”: A pile is installed to its full depth while the as-designed torque has not been reached; under such circumstances, installing extra extension pieces to prolong the pile length is the commonly practiced solution.

Table 1 shows the classifications of soil along with corresponding possibilities in percentages (%) to encounter “backup” method scenarios, assuming the two scenarios are independent of one another and they do not occur to one same pile simultaneously.

Table 1. Soil classification for helical piles

Soil Type	Class	SPT-N value	Predrill (%)	Extension Piece (%)
Sand and silt (dense to very dense)	hard	> 30	30	2
Sand and silt (compact)	normal	10-30	21	5
Sand and silt (very loose to loose)	soft	< 10	12	17
Clay or Till (hard)	hard	> 30	36	3
Clay or Till (very stiff)	normal	15-30	25	5
Clay or Till (very soft to stiff)	soft	< 15	10	30
Cobble or course gravel	hard	> 30	40	5

Site Layout

In order to account for material handling efforts on site, the site is divided into several sections by different ranges of distance between the pile installation location and the material laydown area. Note detailed information on site layout and transit paths is generally not available in the preliminary phase of project development. To simplify the clustering of pile installation work packages, the distance interval is recommended to be set as 100 m (shown in Figure 1).

2.3 Contingency Cost Quantification

The total project duration and direct cost can be derived by simulating the complete helical pile installation process in the Excel Spreadsheet based Monte Carlo simulation tool. By adding indirect cost and profit (usually given as percentage), the total bid price can be obtained, as shown in Eqs.1-4:

[1] $$C_{total} = \left[(C_{labor} + C_{equipment} + C_{material}) \times (1 + R_{indirect})\right] \times (1+R_{profit})$$

[2] $$C_{labor} = \frac{D_{simulated}}{f} \times \sum_{i=1}^{n} \mathrm{U_i N_i}$$

[3] $$C_{equipment} = \frac{D_{simulated}}{f} \times \sum_{i=1}^{m} \mathrm{U_j N_j}$$

[4] $$C_{material} = \sum_{p=1}^{k} \mathrm{U_p N_p}$$

Where C_{labor} is total bare labor cost; $C_{equipment}$ is total bare equipment cost; $C_{material}$ is total bare material cost; $D_{simulated}$ is the simulated total project duration; f is the efficiency factor (50-min work hour); $\mathrm{U_i}$ is hourly rate for labor type i, $\mathrm{N_i}$ is the number of labor type i; i is a number series from 1 to n denoting all the labor types commonly involved in helical pile installation; $\mathrm{U_j}$ is hourly rate for equipment type j, $\mathrm{N_j}$ is the number of equipment type j; j is a number series from 1 to m denoting all the equipment types commonly involved in helical pile installation; $\mathrm{U_p}$ is unit rate for pile type p, $\mathrm{N_p}$ is the number of pile type p; p is a number series from 1 to k denoting all the pile types designed to be installed; $R_{indirect}$ denotes indirect cost (i.e. field overhead) in percentage; R_{profit} denotes the profit percentage.

Then, by rank ordering the resulting project total bid prices among all the observations from simulation, percentiles ranging from 0 to 100 with step size of 10 are estimated. In this case study, the total bid price at 80% percentile (P80) is chosen as the final bid price. Therefore, the contingency can be estimated as per Eq.5:

[5] $\text{Contingency} = [P_{80}(\$) - BaseEstimate(\$)]$

Note, *BaseEstimate* is determined by considering “most probable” values in activity durations in association with routine installation procedures under “normal” soil conditions, which are applicable to all the piles.

3 EXCEL SPREADSHEET BASED SIMULATION TOOL

3.1 Inputs

The input interface, as shown in Figure 2, consists of three major parts: (1) work package input table, (2) activity duration input table, and (3) unit rate input tables. The work package information, i.e. pile design, pile quantity, distance range, soil condition, “predrill” occurrence possibility, and “extension installation” occurrence possibility are entered into the work package information input table. Relevant activity times are extracted from “Input Reference” in the Excel program. Labor and equipment hourly rates and material (pile) unit rates are also required to be inputted to calculate project cost and contingency. Note some sensitive input data are represented with “xxx” for confidentiality issues.

RUN | Save | User Guide | Input Reference | Print Report

Work Packages

WP	Design	Quantity	Distance (m)	Soil	Predrill (%)	Extension (%)	Crew #
1	P2	20	0-100	normal-till	25.0	5.0	Standard
2	P6	2	0-100	normal-till	25.0	5.0	
3	P1	2	0-100	normal-till	25.0	5.0	
4	P1	2	100-200	normal-till	25.0	5.0	
5	P2	14	100-200	normal-till	25.0	5.0	
6	P4	8	0-100	normal-till	25.0	5.0	
7	P4	8	0-100	hard-cobble	40.0	5.0	
8	P3	8	100-200	hard-cobble	40.0	5.0	
9	P2	8	0-100	hard-cobble	40.0	5.0	
10	P5	7	0-100	hard-cobble	40.0	5.0	
11	P5	5	100-200	hard-cobble	40.0	5.0	
12	P2	20	100-200	hard-cobble	40.0	5.0	
13	P6	2	100-200	hard-cobble	40.0	5.0	
14	P1	4	100-200	hard-cobble	40.0	5.0	
15	P2	6	100-200	hard-cobble	40.0	5.0	

Activity Time

Items	L	M	U
Deliver Pile: 0-100m	xxx	xxx	xxx
Deliver Pile: 100-200m	xxx	xxx	xxx
Deliver Pile: 200-300m	xxx	xxx	xxx
Drive insertion and bolt	xxx	xxx	xxx
Level up and in position	xxx	xxx	xxx
Screw Pile # 1	xxx	xxx	xxx
Screw Pile # 2	xxx	xxx	xxx
Screw Pile # 3	xxx	xxx	xxx
Screw Pile # 4	xxx	xxx	xxx
Screw Pile # 5	xxx	xxx	xxx
Screw Pile # 6	xxx	xxx	xxx
Unbolt and Record	xxx	xxx	xxx
Pull out pile	xxx	xxx	xxx
Drill rig in position	xxx	xxx	xxx
Predrill	xxx	xxx	xxx
Pile head cut off	xxx	xxx	xxx
Tack weld	xxx	xxx	xxx
Full weld	xxx	xxx	xxx
screw extension piece (10')	xxx	xxx	xxx

Figure 2 (1): Work packages and activity time inputs

Personel

Category	Qty	Hourly Rate ($/hour)	Sum ($/hour)
Supervisor (w/ truck)	1	xxx	xxx
Install Equip. Operator	1	xxx	xxx
Loader Operator	1	xxx	xxx
Swamper	1	xxx	xxx
Welder	2	xxx	xxx
Surveyer	1	xxx	xxx
Field QA/QC	1	xxx	xxx

Equipment

Category	Qty	Hourly Rate ($/hour)	Notes	Sum ($/hour)
156K 33 Ft Reach Excavator	1	xxx	xxx	xxx
Komatsu Loader	1	xxx	xxx	xxx
Crew Truck	3	xxx	xxx	xxx
Drill Rig	1	xxx	xxx	xxx

Material

Pile Type	Unit Cost ($/ea)	Quantity	Sum ($)
P1	xxx	8	xxx
P2	xxx	78	xxx
P3	xxx	8	xxx
P4	xxx	16	xxx
P5	xxx	12	xxx
P6	xxx	4	xxx

Crew Hourly Rate ($/h)	Material Total ($)
XXX	XXX

Figure 2 (2): Unit rate inputs

Figure 2: Inputs for the tool

3.2 User Manual

"User Manual", as shown in Figure 3, guides the users on (1) how to gather the information available at bidding stage to perform estimating; (2) how to define work packages as model inputs; (3) how to prepare input data; and (4) how to interpret the outputs as decision support for users.

User Manual

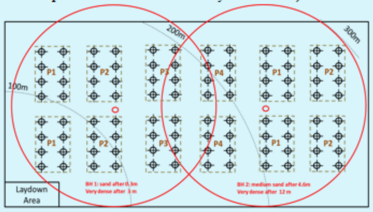
1. Raw Inputs

The input data as needed for implementing the proposed methodology include the specific information that is generally available at project estimating and bidding stages, include engineering design drawings, geotechnical investigation report, empirical parameters or historical field data, and resources information as listed below:

• Foundation detail designs drawings (e.g. pile geometry and pile cap geometry) provided by the helical pile contractor;

2. Draw Information Map

The best way of representing the collected site-specific information is to draw a construction information map. The construction information map indicates pile locations and types, bore hole locations and impact area (which accounts for underground soil information into construction planning), and material delivery zones (which are classified by the ranges of distances between the pile location and the site laydown area.). See below Figure.



3. Decompose to Installation Work Packages

A factor-based clustering method is used to decompose the helical pile construction into work packages by factoring in the specific information that is generally available at project estimating and bidding stages in regards to four factors, namely: (1) engineering design; (2)

3. Site Layout

The site is divided into several sections by different ranges of distance between the pile installation location and the material laydown area in order to account for material handling efforts on site. To simplify the clustering of pile installation work packages subject to the level of details in data available in the bidding stage, the distance interval is recommended to be set as 100 m, as shown in **Information Map.**

Sample decomposed Installation work packages for the given information map is shown in below Table.

Work Package	Soil	Material Handling Distance (m)	Design	Quantity	Predrill (%)	Extension (%)
WP. 1	Hard	0-100	P1	8	30.0	1.7
WP. 2	Hard	100-200	P1	8	30.0	1.7
WP. 3	Hard	0-100	P2	5	30.0	1.7
WP. 4	Hard	100-200	P2	11	30.0	1.7
WP. 5	Hard	100-200	P3	16	30.0	1.7
WP. 6	Hard	100-200	P4	4	30.0	1.7
WP. 7	Normal	100-200	P4	6	20.8	4.2
WP. 8	Normal	200-300	P4	6	20.8	4.2
WP. 9	Normal	200-300	P1	16	20.8	4.2
WP. 10	Normal	200-300	P2	16	20.8	4.2

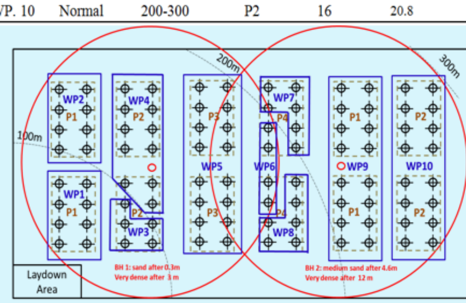


Figure 3: User Manual

3.3 Input Reference

"Input Reference", as shown in Figure 4, part contains two information tables, namely (1) activity time information table, and (2) "back up" method scenarios occurrence possibility information table. The data were collected from contractors who are specialists in construction and design of helical piles, each having over 15 years field installation experience. Users of the tool can readily add more data to expand the input database.

Input Reference

Activity	Minimum (min)	Most Probable (min)	Maximum (min)
1.Pile delivery			
Distance of 0-100m	xxx	xxx	xxx
Distance of 100-200m	xxx	xxx	xxx
Distance of 200-300m	xxx	xxx	xxx
2. Drive insertion and bolt	xxx	xxx	xxx
3. Level up and in position	xxx	xxx	xxx

Pile length	Shaft Diameter	Helix Diameter	Minimum (min)	Most Probable (min)	Maximum (min)
	≤ 5-1/2''	6 to 10''	xxx	xxx	xxx
		12 to 16''	xxx	xxx	xxx
		18 to 22''	xxx	xxx	xxx
		≥24''	xxx	xxx	xxx
	6-5/8'' to 10-3/4''	14 to 18''	xxx	xxx	xxx
		20 to 24''	xxx	xxx	xxx
		26 to 30''	xxx	xxx	xxx
		≥32''	xxx	xxx	xxx

Activity time info Table (partial)

Soil Type	Class	SPT-N	Predrill (%)	Extension Piece (%)
Sand and silt (dense to very dense)	hard	> 30	30.0	1.7
Sand and silt (medium)	normal	`10-30	20.8	4.2
Sand and silt (very loose to loose)	soft	< 10	11.7	16.7
Cobble or course gravel	hard	> 30	39.2	1.7
Clay and Till (hard)	hard	> 30	35.8	1.7
Clay and Till (very stiff)	normal	15-30	24.6	4.5
Clay and Till (very soft to stiff)	soft	0-15	9.8	30.4
…				

To infer on the probabilities of "predrill" and "extension" based on borehole data and pile's site layout, always consider the worst soil condition reported in the borehole information diagram within theminimum embedment depth.

"Backup method" scenarios occurrence possibility info table

Figure 4: Input Reference

3.4 Report

The tool will automatically generate a technical report with recommended bid price and estimated contingency, as shown in Figure 5. The possible range of total bid price is also provided in the simulation report. The company can choose any bid price within this range subject to particular bidding strategy.

Report

To whom it may concern:

The estimated total bid price is ranging from $ xxx to $ xxx, by fully considering contingencies commonly lie in helical pile installation process.

The contingency is estimated at $ xxx

The suggested bid price is $ xxx, and the project is expected to finish within xxx work days.

The suggested bid price is relatively conservative by choosing higher end of the estimated range.

However, company could offer the any price within the estimated range subjected to bidding strategy.

As for extreme scenarios such as extreme limited site access or high variability of underground condition, the company may apply an empirical factor based on top of current estimate.

Figure 5: Report

4 CASE STUDY

A local pile contractor is bidding for the construction of an Electrical Power Substation near Calgary, Alberta, Canada. The contract scope is to install pile foundations for the superstructure, electrical equipment and devices. Civil structural elements of an electrical substation consists of electrical transmission tower, electrical poll and bases for heavy transformers, maintenance room etc. The project decide to choose helical piles. There are six pile types in total. According to the borehole data provided by the geotechnical consultant, the subsoil is mainly composed of clay/till material. The red cycles are borehole impact range, with which the soil types interpreted from the geotechnical report are assumed to be the same, as shown in Figure 6. The laydown area is temporarily positioned at the left corner of the site. As contractually stipulated, the whole foundation construction is divided into two phases. The contingency estimating process of pile installation in the first installation phase (Phase I) is performed in this case study. The construction information map is shown in Figure 6.

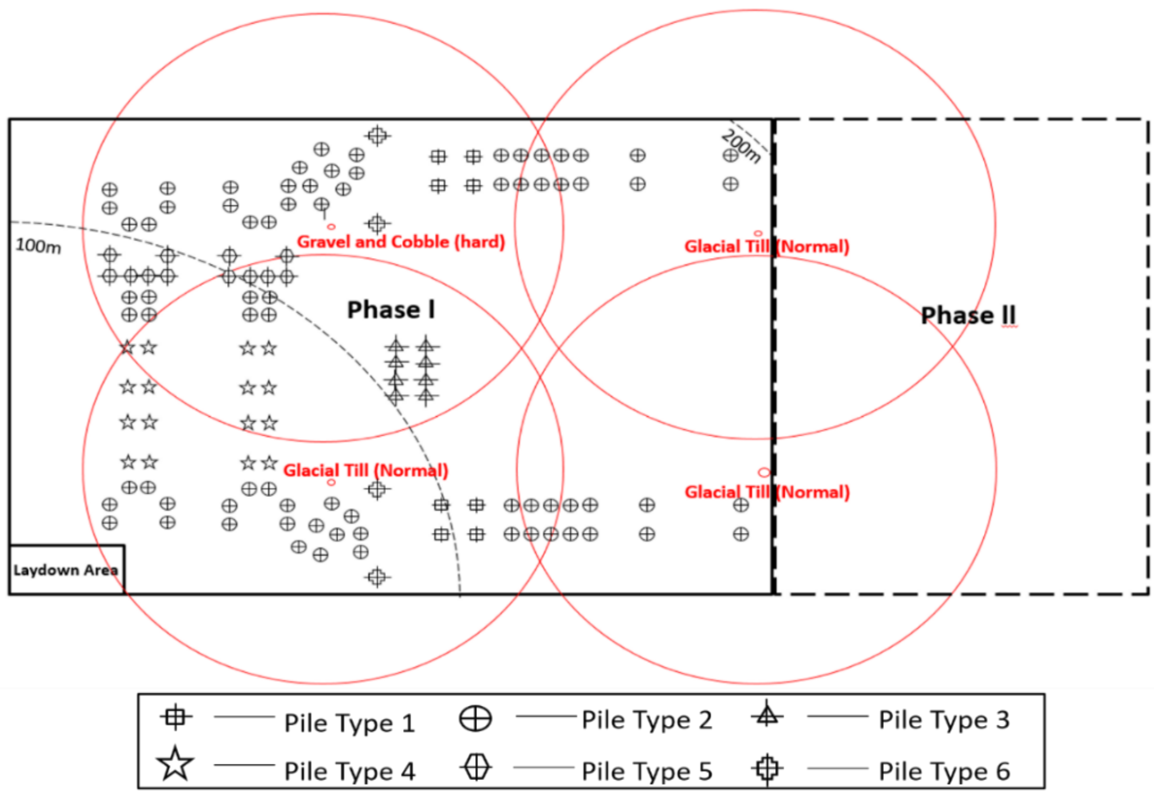


Figure 6: Power substation construction information map

With the construction information map, specific work packages for helical pile installation are identified in accordance with the proposed method, as shown in Figure 7. A total of sixteen work packages are defined to represent Phase I of the helical pile installation project.

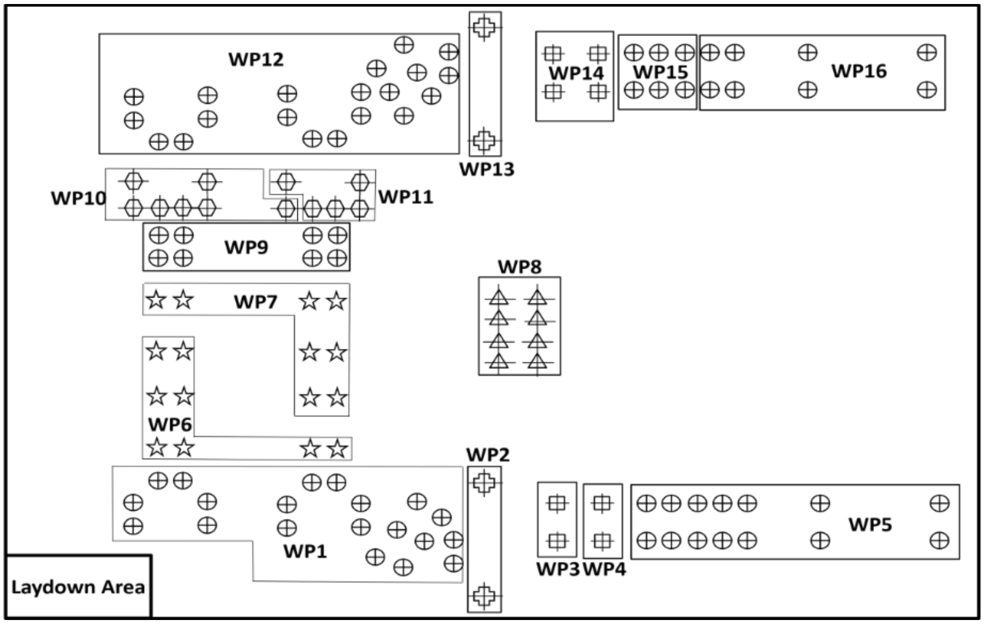
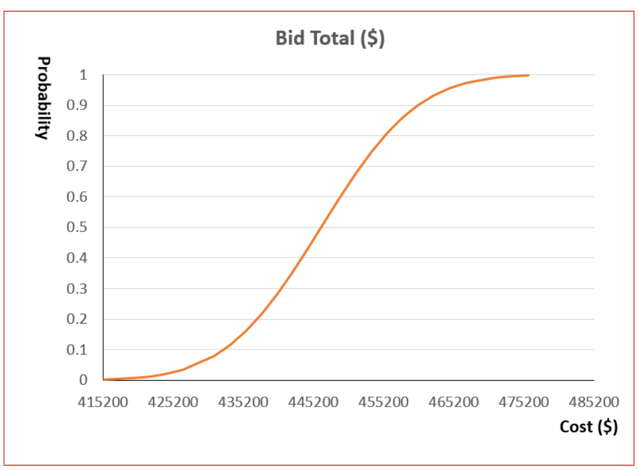
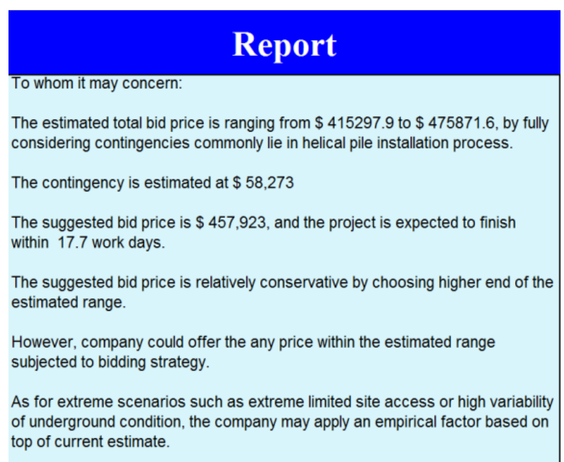


Figure 7: Work breakdown structure based on information

The defined work packages and collected input data were entered into the Excel spreadsheet based simulation tool. The simulation was performed for 100 iterations producing a range of possible outcomes on project time and cost. The simulated results are shown in Figure 8.




Report

To whom it may concern:

The estimated total bid price is ranging from $ 415297.9 to $ 475871.6, by fully considering contingencies commonly lie in helical pile installation process.

The contingency is estimated at $ 58,273

The suggested bid price is $ 457,923, and the project is expected to finish within 17.7 work days.

The suggested bid price is relatively conservative by choosing higher end of the estimated range.

However, company could offer the any price within the estimated range subjected to bidding strategy.

As for extreme scenarios such as extreme limited site access or high variability of underground condition, the company may apply an empirical factor based on top of current estimate.

Figure 8 (1): Bid total range

Figure 8 (2): Report

Figure 8: Tool Outputs

The base estimate price for Phase I pile installation was estimated to be $399,650 by considering "most probable" values in activity durations in association with routine installation procedures under "normal" soil conditions. The P_{80} bid price was determined as $457,923. By applying Eq.5, the project contingency was estimated as $457,923 - $399,650 = $58,273, which is equivalent to applying 14.58% contingency on top of the base estimate.

5 CONCLUSION

This paper presents an Excel Spreadsheet based simulation tool to facilitate bidding helical pile installation projects featuring uncertainties in design, soil, and crew productivity. The methodology behind the tool systematically integrates a formal work breakdown method and Monte Carlo simulation, encompassing (1) collecting raw inputs; (2) interpreting and processing collected data; (3) decomposing activities and defining work packages; (4) conducting Monte Carlo simulation experiments. This Excel Spreadsheet based estimating tool possesses its advantages in terms of short learning curve and flexibility in adjusting input settings, making it appealing to helical pile contractors. The presented Excel based simulation tool facilitates the collaborating piling contractor to make critical decisions in bidding and to guide cost estimators and project managers in helical pile installation project planning. Finally, the proposed methodology also provides an effective training and educational module for practitioners and engineering graduates with respect to helical pile construction planning and estimating.

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