Productivity of robotic excavators for caisson construction

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Abstract

Caisson foundation, which had been a popular foundation system in Hong Kong in 1970s and 1980s, was hand-dug by caisson workers. The advantages of using this construction method are cost-effectiveness and low mobilisation resources. However, as a result of airborne silica dust, the caisson workers working in the confined space of a hand-dug caisson may be exposed to the risk of getting pneumoconiosis. Thus, this construction method was banned by the Government in 1995. A robotic excavator was hence invented for replacing the caisson workers to deliver the excavation tasks. This new construction method can potentially improve the productivity performance of piling construction, while the workers' health can be guaranteed. Since the existing literatures focusing on benchmarking the productivity perfomance of using robotic excavators are very limited, this research study benchmarks the productivity of robotic excavator for caisson construction using site experiment data. The productivities of constructing five circular piling shafts using robotic-dug method and bored pile construction method are simulated and compared. The conclusion is drawn by discussing the cost-effectiveness using robotic-dug construction method.

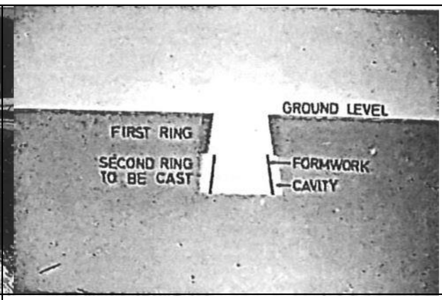
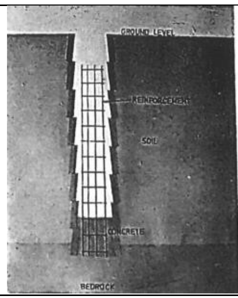
Keywords
Caisson Construction, Process Productivity, Robotic Excavator.

1 Introduction

In Hong Kong, caisson construction using hand-dug construction method was invented in 1960s. The diameter of the caissons ranges from 1m to 3m typically. Construction involves hand excavation of a circular shaft by caisson workers. The excavation activity is started by excavating a circular shaft with approximately 900mm deep from the ground level. The stability of soil in a vertical cut condition is temporarily retained by arching effect of the soil. A concrete lining would be soon cast to retain the vertical soil surface. To cast the concrete lining, a circular formwork or mould within the caisson shaft is firstly installed followed by pouring concrete into the gap between the soil surface and the formwork. The gap, which in turn the thickness of the concrete lining/ring, ranges from 100mm to 150mm. Completing the procedures of soil excavation and concrete ring casting are usually the work-done of caisson workers in a working day. The procedures would be re-performed in the next working day to cast another concrete ring below the ring cast in the previous day. The shaft construction is continued until the desired founding level is reached (Figures 1, 2 and 3).

The Hong Kong Institution of Engineers (HKIE 1981) published “guidance notes on hand-dug caissons”. This publication defines the hand-dug caisson construction, including design principles, construction methods, sequence, process, and measures. The publication mentioned that the shaft excavation (including soil excavation, placing steel mould of lining, and concreting the lining) at about or slightly less than 1000mm depth in favourable ground condition could be completed within a working shift (i.e., from 08:00 to 18:00). In other words, practically, the productivity is determined as 900 mm/day to 1000 mm/day, which is limited by daily working hours. Although the hand-dug method has the advantages of cost-effectiveness, low machinery requirement, high mobilisation and flexibility in coping with complex site conditions and limited working space (HKIE 1981), this construction method was banned by the Hong Kong Government since 1995 because of the high risk of infecting caisson workers with pneumoconiosis.

Thanks to the advancement of robotic technologies, an in-house robotic excavator for caisson excavation was prototyped by the research team (Guan *et al.* 2021). This innovation helps in replacing those caisson workers who perform the excavation tasks to potentially improve the productivity while reducing the hazards to the workers. Nonetheless, the past research works related to the caisson construction are highly limited. As such, this research study will be the first one to measure, determine, and analyse the productivity benchmarks of caisson excavation performed by a prototyped excavator. The following sections are structured as followed. The existing literatures are reviewed in context of the productivity benchmarks for hand-dug caisson excavation. The methodology is given for capturing the productivity of robotic excavator using time study technique on site, followed by simulating project process driven by the benchmarked productivity. Then, comparisons of excavating circular shafts using robotic-dug method and bored pile method are discussed. The conclusion is drawn by discussing the competitiveness of using the robotic arm for piling construction.

		
Figure 1: Starting of a caisson (Law 1981)	Figure 2: Procedure for placing concrete rings (Law 1981)	Figure 3: Diagrammatic view of a caisson (Law 1981)

2 Literature Review

There are limited research endeavours focused on deriving productivity benchmarks for planning and managing foundation construction projects. For example, Zayed and Halpin (2001, 2005a, 2005b) benchmarked the productivity of piling process using questionnaires and expert interviews. They developed simulation models to present and visualise the piling process in a construction cycle. Given the benchmarked productivity as the data inputs for simulation models, the productivity, time, and cost of piling projects were predicted. The authors developed the charts aiming to facilitate the contractors in bidding and controlling the budget of piling projects. Furthermore, the authors studied the system productivity, cycle time, and project cost of piling projects by combining the use of simulation techniques and artificial neural networks. The models were validated and proved their robustness.

Similarly, Zayed (2005) developed productivity index using simulations to quantify the impact of subjective factors on the process productivity when constructing continuous flight auger piles. Charts were developed for practitioners to quickly estimate the system productivity, cycle time, and project cost. Chong *et al.* (2006) collected the data of constructing the concrete piles from 25 highway projects. The authors developed logarithmic models to characterise the relationships between production rates and pile length. Jiradamkerng *et al.* (2011) used regressions to characterise the relationship between the productivity and critical factors, such as pile driving work and joining of two-piece pile by welding, for square precast concrete pile construction. They developed synthetic equations for determining the project time and work productivity in connection with the type and size of piles. As such, the system productivity of robotic-dug excavation using operations simulation, driven by benchmarking the time of performing excavator's motions, is yet to be explored.

3 Methodology

3.1 Prototype Robotic Excavator

A robotic excavator was prototyped with the aim of replacing the excavation tasks performed by caisson workers working in the pile shaft (Guan *et al.* 2021). Figure 4 illustrates the design of robotic excavator to perform the excavation for constructing the caisson shafts. Figure 5 shows the setup of the site trial. The data of robot performance is collected when excavating a caisson with 1.5m to 2.5m diameter and a depth not exceeding 3m. The robot replaced the manual excavation works while the caisson rings are casted by experienced concreters.

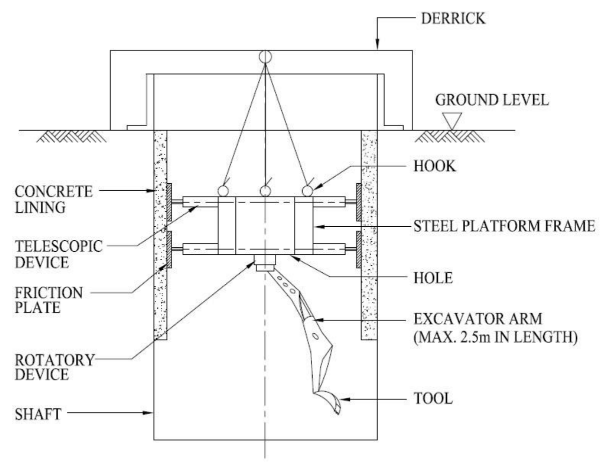


Figure 4: Design of robotic excavator

Figure 5: Setup of site trial

3.2 Methodology

Table 1 tabulates the steps for investigating the excavation productivity using the prototyped robotic excavator.

Table 1: Steps for determining the productivity of using robotic excavator

Steps	Work items	Actions	Details
1	Design and manufacture the prototyped robotic excavator.	Research and review current construction technology of available excavators which are suitable for prototyping a robotic excavator.	
2	Design and conduct site trials to test the functionality of the excavator.	Conduct full-scale experimental setup to fully test the functionality of the excavator.	
3	Determine the duration of the motion of the excavator to measure the cycle time of one excavation cycle.	Perform video recording when conducting excavation tasks. The motions of excavator are identified. The time of each motion is determined using stopwatch. The cyclic process of the excavation is identified. The cycle time which composed of the motion time are determined.	Section 3.3.
4	Develop simulation model to estimate the construction time of a caisson according to measured data.	Analyse execution sequence of the motions of a construction cycle. The measured time of excavation motion is used as the data inputs for developing simulation models.	Section 3.3.
		Use simulation software to develop a simulation model for estimating production rate and project time of caisson construction using robots.	Section 4.3. Section 4.4.
5	Conduct a case study to shed light on the competitiveness of using the prototyped robotic arm against other construction technology in piling construction.	Collect productivity data of shaft excavation using bored pile method.	Section 4.2.
		Carry out a comparison on shaft excavation performance between robotic-dug method and bored pile method with respect to resource configurations.	Section 4.5.

3.3 Time Study on Excavation Motions

Excavation was repeatedly performed by the robotic excavators in order to assemble the datasets for determining the work productivity. Table 2 shows the benchmarks of the duration of robot motions. A bucket at the end of the excavator arm is of a volume at about $0.015m^3$. A drum-skip which transports the soil spoil from caisson bottom to the ground level is $0.2m^3$ (HKIE 1981). The numbers of cycle to fill-up the drum-skip is therefore 15. The excavation cycle for transporting the soil spoil from caisson bottom level to the ground level with respect to caisson diameter is therefore formulated as Equation (1).

Table 2: Measured cycle time of excavation motions

Motions	Time (sec)	Descriptions
Rotation of robotic arm (Figure 5)	13	360° rotation
Extension and extraction of upper hydraulic jack	7	From full extraction to full extension
	7	From full extension to full extraction
Extension and extraction of middle hydraulic jack	4	From full extraction to full extension
	4	From full extension to full extraction
Extension and extraction of lower hydraulic jack	2.5	From full extraction to full extension
	2.5	From full extension to full extraction
Cycle time for one excavation motion (Figures 6a to 6f)	45	N/A

$$\text{Number of cycle} = \left(\frac{\phi^2 \times \pi}{4} \times d \right) \Big/ 0.2 \tag{1}$$

where ϕ = diameter of pile/caisson, d = depth of excavation

3.4 Simulation of Excavation Cycles

In this research study, simplified discrete-event simulation approach (SDESA) which was invented by Lu (2003) with further software redevelopment on user-interface and user-experience by Siu (2020), is used. The SDESA platform is used to simulate the construction schedules by mimicking the process workflows executed with the limited workers. What-if scenarios can be assumed to generate any better alternative solutions. In addition, the criticality of resources can be estimated for enhancing the project productivity and resource utilisations.

4 Practical Case Study

4.1 Background

To compare the time of pile shaft excavation using robotic-dug and bored pile methods, an on-going building project constructing five 1.5 diameter bored piles is used. The excavation time using the robot is estimated using traditional time study technique as shown in Figure 6(a) to Figure 6(f). The SDESA platform was used to simulate the excavation time using robots. To perform the simulation, work activities, robot motions, process and sequence, activity duration, and required resources are defined. Notably, the excavation time using bored pile method is extracted from this project.

	
(a)	(b)

(c)

(d)

(e)

(f)

Figure 6

4.2 Time and resources of shaft excavation using bored pile method

Productivity data about shaft excavation by bored pile method is summarised in Table 3. Due to the limited working space within the site, 1 set of resource (1 oscillator plus 1 crawler crane) is only allowed. The average productivity is 167.4 mins/m.

Table 3: Productivity data and resource of bored pile method

Pile number	Shaft excavation depth	Average mins / metre length	Resources
BP1	52.3m (+2.6mPD to -43.9mPD)	150.3	1 oscillator, 1 crawler crane.
BP2	To be commenced	-	1 oscillator, 1 crawler crane.
BP3	33.0m (+3.0mPD to -44.7mPD)	169.6	1 oscillator, 1 crawler crane.
BP4	52.0m (+3.0mPD to -44.5mPD)	182.4	1 oscillator, 1 crawler crane.
BP5	To be commenced	-	1 oscillator, 1 crawler crane.

4.3 Process of shaft excavation using caisson-robot

Figure 7 shows the proposed simulation model which presents construction process by sequencing work activities performed in 1 excavation cycle. Caisson shaft excavated by robots was formed on interval basis (900mm to 1000mm), followed by casting concrete lining (i.e., caisson ring). The abovementioned cycle will be repeated on interval basis from the ground level to the founding level assuming that no rock is encountered in the shaft.

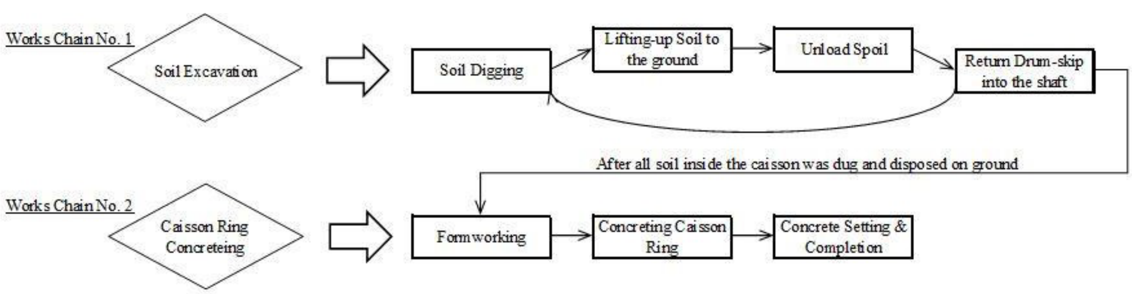


Figure 7. Activity chains for a construction of caisson shaft ring by robotic-dug method

4.4 Time and resources of shaft excavation using caisson method

The motion time of digging soil using caisson robot is given in Table 2. The time and resources of other activities to complete a shaft excavation cycle are tabulated in Table 4. The data is captured from an experienced caisson worker with more than 20 years of experience.

For a 1.5m diameter caisson, the volume of soil spoil to be excavated for a depth of 1m is calculated as $1.767m^3$. In accordance with Equation (1) in Section 4.2, the numbers of cycle for Activity 1 to 4 shall be repeated for 8.8 times before moving to Activity 5. To take practical consideration into account, 10 cycle simulation for Activity 1 to 4 is to be adopted. Finally, the mentioned data and configuration were input into SDESA to simulate the excavation time required for robotic-dug method

Table 4: Productivity data and resource of robotic-dug method

No.	Activity	Time (mins) (min. / mean / max.)	Resources
1	Soil digging to drum-skip	10 / 12 / 15 (from 0m to 15m deep)	1 robot 1 drum-skip (at $0.2m^3$)
		12 / 14 / 17 (from 15m to 30m deep)	
		15 / 18 / 24 (from 30m to 45m deep)	
2	Lifting-up soil in drum-skip to the ground	2 / 3 / 4	1 robot 1 above-ground worker 1 drum-skip (at $0.2m^3$)
3	Unload spoil	2	
4	Return drum-skip into the shaft	2 / 3 / 4	
5	Formwork	20 / 30 / 40	1 steel formwork
6	Lining concreting	40 / 50 / 60	
7	Lining concrete setting	-	-

4.5 Results and discussions

This sub-section presents the excavation time using bored pile and robotic-dug method. Excavation of a 45m deep shaft is adopted as the baseline of the pile length for comparison since the maximum caisson depth in Hong Kong was 45m deep (HKIE 1981). For the bored pile method, the excavation time (total time: 37671.9 mins) is given in Table 5. For robotic-dug method, the simulation results are summarised in Table 6 (total time: 14950.6 mins).

Table 5: Excavation time of bored pile method

Bored pile no.	Ave. mins / metre length (mins / m)	Tentative length (m)	Total excavation time (mins)
BP1	150.3	45	6763.3
BP2	167.4	45	7534.4
BP3	169.6	45	7633.5
BP4	182.4	45	8206.4
BP5	167.4	45	7534.4

Table 6: Excavation time of robotic-dug method (based on 1 set of resource)

Interval of excavation depth	Mean mins / metre length for a typical 1000mm deep excavation cycle (mins / m)	Total length of the interval (m)	Total excavation time (mins)
0m ~ 15m	303.3458	15	4550.2
15m ~ 30m	323.3458	15	4850.2
30m ~ 45m	370.0150	15	5550.2

Table 7: Comparison between bored pile method and robotic-dug method

Method	Sets of resources	Excavation time for a 45m deep shaft as per 1 set of resource (mins)	Required no. of cycle for the shaft excavation of 5 nos. of piles/caissons	Total excavation time
Bored pile method	-----	-----	-----	37671.9
Robotic-dug method	1	14950.6	5	74753.0
	2	14950.6	3	44851.8
	3	14950.6	2	29901.2

The excavation time using robotic-dug method with 1 set of resources is found not competitive to the bored pile method (Table 7). However, the productivity performance of robotic-dug method is able to catch-up or even outperform to that of bored pile method if additional sets of resources are available (Figure 8). Constrained by site area (14.7m by 7.4m), the site is fully occupied by 1 crawler crane and 1 oscillator so that the productivity performance of bored pile method is limited. However, robotic-dug method requires less working space. If more than one shaft can be excavated concurrently, the overall productivity using robotic-dug method can be improved. As such, the robotic-dug method is potentially a more competitive option for tiny and congested sites which are common seems in Hong Kong.

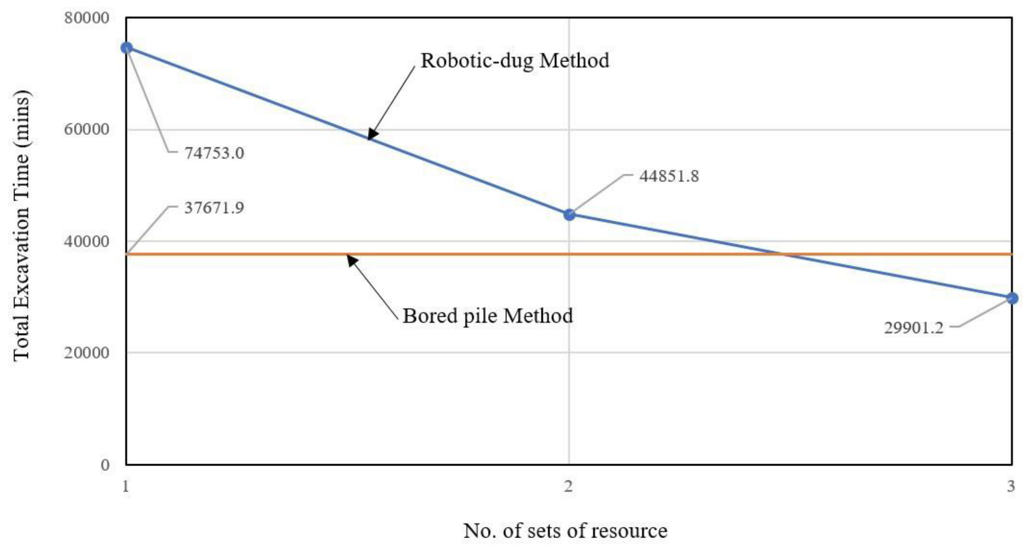


Figure 8. Time comparison between bored pile method and robotic-dug method

5 Conclusions

In this research study, the productivity of caisson shaft excavation performed by robotic excavator was successfully benchmarked based on productivity time study and operations simulation. The productivity benchmarks using bored pile method and robotic-dug method were contrasted based on 5 bored piles construction on a tiny site. The result showed that the productivity performance on shaft excavation using robotic excavator (74753.0 mins) is not competitive to the one of bored pile method (37671.9 mins). Thanks to the mobilisation features of robotic excavator, if more sets of resources (2 sets, 3 sets) for robotic-dug method are given, the productivity performance using robotic-dug method (44851.8 mins, 29901.2 mins) is able to outperform its excavation performance to that of bored pile method. This productivity characteristic enables robotic-dug method to be effective and competitive for tiny construction site commonly found in Hong Kong. The research team envisioned that the productivity of using robotic method will be further improved by refining the mechanical configurations of the robotic excavator (Mark II version) for caisson construction.

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7 References

Buildings department, 2009. *Practice note for authorised persons, registered structural engineers, and registered geotechnical engineers*. Buildings department, 12/F Pioneer Centre, 750 Nathan Road, Mong Kok, Kowloon, Hong Kong.

Chong, W.K. and Chou, J.S., 2006. Examining productivity of foundation construction. *Foundation Analysis and Design: Innovative Methods* (GSP 153), pp 300-307.

Chong, W.K., O'Connor, J.T., Chou, J.S. and Lee, S.H., 2005. *Construction Research Congress* 2005, pp 1-10.

Civil engineering and development department, 2004. *Technical circular, no. 35/2004*. Civil engineering and development department, Civil engineering and development building, 101 Princess Margaret Road, Kowloon, Hong Kong.

Guan, D., Yang, N., Lai, H.K., Siu, M.F., Jing, X.J. and Lau, C.K., 2021. Kinematic modeling and constraint analysis for robotic excavator operations in piling construction. *Automation in Construction*, 126 (2021) 103666

Jiradamkerng, W., Thongmai, S. and Pongpatanasuegsa, N., 2011. Studying and preparing of basic time for piling works by synthetic equations. *Engineering Journal*, 15 (4), pp 1-10.

Occupational Safety and Health Council, 1993. *Code of Safe Working Practices for Hand-dug Caissons.* Occupational Safety & Health Council, Hong Kong, 42 p.

Siu, M.F., 2018. Collaboration Proposal for Development of a robotic system for robotic-dug caisson construction in Hong Kong., unpublished

The Hong Kong Institution of Engineers, 1981. *Guidance notes on hand-dug caissons.* Hong Kong Institution of Engineers, Hong Kong, 15 p.

Zayed, T.M., 2005. Productivity and cost assessment for continuous flight auger piles. *J. Constr. Eng. Manage.*, 2005, 131(6), pp 677-688.

Zayed, T.M. and Halpin D.W., 2001. Simulation of bored pile construction. *Proceedings of the 2001 Winter Simulation Conference*, pp 1495-1503.

Zayed, T.M. and Halpin D.W., 2005a. Deterministic models for assessing productivity and cost of bored piles. *Construction Management and Economics*, 2005, 23, pp 531-543.

Zayed, T.M. and Halpin D.W., 2005b. Pile construction productivity assessment. *J. Constr. Eng. Manage.*, 2005, 131(6), pp 705-714.