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Case Studies on Environmental Emissions of Machinery and Material Use due to Bored Pile Construction

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Abstract: Irrespective of the large impact exerted by the building sector on the environment because of intensive resource and energy utilization, much less attention has been paid to understanding the emission contributions due to machinery and resource consumption in pile foundation construction. Four piling sites were selected in Sri Lanka to estimate and compare the contribution on Global Warming Potential (GWP) caused by heavy machinery and material use for in-situ bored pile construction, based on the Intergovernmental Panel on Climate Change (IPCC) methodology. Accordingly, machinery and material related data were collected. In parallel, soil conditions as assessed by SPT-N values were used to characterizes oil, which displayed loose sand to very dense clayey or silty sand in the selected sites. The average Green House Gas (GHG) emission due to machinery used for each project revealed that the GHG emission of pile boring varied from 7.4 to 20.48 $kgCO_{2-e}$ per m^3 of pile bored across the project sites, the project in Mannar recording the lowest while the project in Kandy recording the highest. Compared to machinery emissions, materials had a higher emission contribution to the total, varying in the range of 86% to 93% across the project sites. Analysis of GWP attributable to piling machinery revealed that the highest contributions were from boring rigs compared to excavators and cranes. Further, statistical analysis of forcing factors for machinery emissions revealed that operator experience and engine capacity have significant impacts on emissions. This study helped to recognize high-emitting bored piling machinery work and enhance environmental and economic sustainability of bored pile construction.

Keywords: Boring rig, Crane, Construction material, Excavator, Global warming potential, Greenhouse gas

1. Introduction

Generally, foundation construction is responsible for one-third to half of the entire project working cycle and cost [1]. Pile foundation is a commonly used foundation type in most tall building construction, as well as in other infrastructure projects. Piling construction tends to utilize more machinery than other foundation types.

Boring rigs, crawler cranes, truck cranes and excavators serve as the primary machinery employed during pile-boring activities. The boring rig machines are used to bore the pile in to the bedrock or desired depth in the soil layer, while crawler cranes or truck cranes are used to place and remove temporary casings, steel cage installations, and concrete funnel movements [2]. Additionally, generators are employed to provide power to the various on-site construction operations mentioned above. Excavators play versatile roles in backfilling, loading excavated materials, moving equipment within the site, and small demolition work [2]. The environmental impact of construction machinery, particularly during piling work, has raised concerns regarding the significant emissions it generates [1]. The environmental impact of pilling works is mainly due to direct and indirect Green House Gas (GHG) emissions arising from the use of energy and construction material [3]. However, much less work has been carried out to assess the Global Warming Potential (GWP) from the piling construction owing to the material and machinery emissions globally.

Estimation and analysis of emissions is the first approach to reduce environmental impact. Accurate estimation and assessment of the

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emissions due to piling work are crucial for developing effective environmental mitigation strategies and ensuring sustainable construction practices. Most of the building life cycle assessment exercises during the construction phase notably focus on the calculation of environmental impact because of material usage, energy, and water usage of superstructure while much less attention has been given to the emission due to construction equipment used during the substructure construction as well as demolition stages. This may be mainly because of the complicated nature of the piling activities and the lack of data availability [4].

Different approaches of direct emission estimation methods, such as real-time monitoring, activity-based estimations, etc., indirect methods such as emission factors, modelling, etc., and hybrid approaches are used to estimate environmental emissions from vehicle and machinery operations [5]. Among the available methods, indirect emissions are more appropriate for investigating the emission reduction opportunities during the design stage of construction considering the upstream emissions. Direct emissions are important to investigate emission reduction opportunities at the implementation stage of construction. It is worth noting that the choice of approaches depends on factors such as the level of accuracy required, available data and resources, and the specific context of the machinery operation [5]. Selecting an appropriate approach is essential to ensure a reliable and representative estimation of environmental emissions from machinery operations.

During preliminary research conducted by Fan [4], factors affecting heavy-duty diesel construction equipment were studied and equipment conditions, maintenance, operations, and equipment operating conditions were considered. Lyu et al. [6] compared CO_2 emissions originating from both machines and materials of precast and in-situ piles and they found that material emissions exceeded the machine emissions. In a separate study, Sandanayake et al. [7] evaluated GHG and non-GHG emissions in two case studies of cast bored piles and raft foundations in Australia using process-based and hybrid methods of Life Cycle Assessment (LCA). Process-based methods estimate the environmental emissions considering the activities while the hybrid method is a combination of methods. It is generally acknowledged that hybrid LCA, which combines input-output models with process-based LCA for a full system boundary, is a more accurate method than process-based LCA with a partial system boundary [8]. According to Sandanayake et al. [7], a process-based approach was utilized to assess the environmental emissions of two case studies by comparing the two methods. According to the study, the average distribution of emissions is 66% from materials, 19% from equipment, and 15% from transportation. A related study by Sandanayake et al. [1], evaluated the environmental emissions of construction machinery in 54 bored piles of750 mm diameter and found the highest emission was from concrete pumping trucks and boring rigs.

Irrespective of the studies mentioned above, there is still a lack of studies concerning the estimation of environmental emissions related to different types of machines used in piling work with respect to different pilling processes. In many studies, emissions from machines and materials are mostly focused on CO_2 only, while other GHGs are mostly omitted [6]. Further, the effects of soil conditions on the emissions due to piling machinery during piling work have not been studied in depth.

Thus, this paper aims to assess the GWP associated with the machinery and materials utilized in bored pile construction. The assessment considered four projects in Sri Lanka and adopted the IPCC Tier 1 methodology, complemented by an analysis of the embodied carbon of materials used in piling work to calculate the emissions.

Hence, the objectives of the study are to:

- Conduct a data collection survey to identify the resource (material and machinery) utilization during piling work at 4 selected piling sites in Sri Lanka.
- Estimate the GWP due to machinery and material emissions during piling work.
- Compare and analyze the GWP related to pile foundations considering the material and machinery utilization to identify the emission hot spots in bored pile construction.

2. Methodology

Emissions arising from the utilization of both material and machinery usage in bored pile work were assessed by collecting process base data from four different piling sites. This study focused on the main sources of emissions caused by basic piling materials and the associated machinery used during the pile construction process. As such, C30 concrete,

bentonite powder, and reinforcement steel were considered as the main materials used in pile construction while machines involved in activities in pile boring to reinforcement cage installation were considered according to the site observations. This is in par with Lyu et al. [10] who considered C25 concrete, reinforcement, stirrup, and water for comparing material emissions. Transportation of concrete and other materials to the site and pile concreting process were considered out of the system boundary because the environmental impact of these activities heavily relies on outside variables, such as the location of concrete batching plants, raw material sourcing, transit routes, etc. Hence, they were not included in the system boundary to ensure the accuracy and relevance of the data as they can differ greatly between different sites.
The process flow diagram for bored pile construction with the system boundary is as shown in Figure 1.

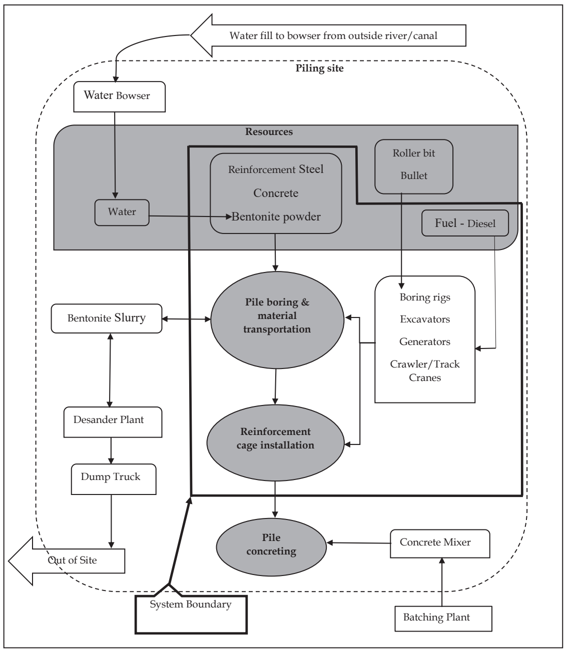


Figure 1 - Process Flow Diagram for Bored Pile Construction Indicating the System Boundary

2.1 Site Selection

Four piling sites were selected considering the availability of documented data (Table 1). Among the projects, project 1 consisted of pile construction for an international airport terminal building with piers while project 2 was for constructing pile foundations for wind turbines for a wind power plant. Projects 3 and 4 consisted of pile foundations to support a 350 MW liquid natural gas combined cycle power plant and road flyover, respectively. Projects 1 and 4 were in the Western province while projects 2 and 3 were in the Northern province and Central province in Sri Lanka, respectively. The project details with locations are given in Table 1.
As shown in Table 1, projects 1 to 4 had a total of 465 bored piles with pile diameters varying from 600 to 1500 mm. Project 1 had the largest number of piles, 228 with 5 different sizes of pile diameters (600, 800, 1000, 1200, and 1500 mm). Project 2 had 68 piles with 900 mm diameter while project 3 had 27 piles with 1000, 1200, and 1500mm diameter. Project 4 had a total number of 142 piles with 600mm and 900mm diameters. It should be noted that all piles were bored down to bedrock and the average pile length at project 1 varied from 14-32 m. The pile lengths of the other three sites were shallower than project 1 and were in the range of 12-27 m.

2.2 Data Collection

2.2.1 Machinery-Related Data

Consistent with the research conducted by Fan [4], machinery usage data was collected from all four project sites. This data encompassed machinery details about Boring rigs, Excavators, Cranes, and Generators. Information was collated based on daily fuel usage for each type of machinery, machine operation hours (machine hours), machinery information (machine type, manufacturer, fuel type, engine power), and operator details (experience and age). Machines and vehicles used for the transportation of materials were excluded from the data collection process and not considered for the calculations.

2.2.2 Material-Related and Other Data

The data collection process focused exclusively on primary construction materials used in piling operations, namely, concrete volume (m^3), rebar weight (tons), and bentonite volume (m^3), using the bill of quantities of each project [6]. Additionally, critical parameters such as pile diameter, pile length, and subsurface soil profile data about specific projects were collected from each project site.
Subsurface soil profile characterization of project sites 1-4 involved the utilization of average standard penetration test (SPT) values derived from site investigation borehole reports as per the methodology outlined in Al-Ani et al. [9]. SPT values were taken from the ground level at depth intervals ranging from 0.5m – 1m.

2.3 Estimation of GWP of Pile Foundation due to Machinery and Material Usage

The study encompassed an assessment of the GWP of piling work due to machinery and material usage. Four types of major machinery such as boring rigs, truck/crawler cranes, and excavators used in piling work were considered for emission calculations. The analysis was extended to investigate the impact of parameters such as soil condition (using SPT N values), engine power, machine age, operator experience, and operator age on machinery emissions to pinpoint emission hotspots.

2.3.1 GWP due to Machinery Use

The calculation of GWP entailed an analysis of GHG gases such as CO_2, CH_4, and N_2O due to fuel usage by considering major machinerysuch as boring rigs, truck/crawler cranes, and excavators adhering to the methodology outlined in the IPCC Tier 1 approach [10].

For ease of comparison, GWP was estimated per operation hour for each machine type.

$$Total\ GWP\ per\ machine\ hour = \frac{Total\ GWP\ (kgCO_{2\text{-}e})\ due\ to\ fuel\ usage}{Total\ operation\ hours} \quad \text{Eq. 1}$$

2.3.2 GWP of Materials

GWP of i^{th} materials was calculated using Eq.2 below. The emission factors based Environmental Product Declaration (EPD) were obtained from literature [12-14]. Accordingly, GWP of C30 concrete, rebar, bentonite powder was 270 kg $CO_{2\text{-}e}/m^3$, 860 kg $CO_{2\text{-}e}$/t and 0.031 kg $CO_{2\text{-}e}$/kg, respectively.

$$GWP\ due\ to\ i^{th}\ material\ consumption\ (in\ kgCO_{2\text{-}e}) = i^{th}\ material\ quantity \times Emission\ factor\ (GWP)\ of\ i^{th}\ material \quad \text{Eq. 2}$$

2.3.3 Estimation of GWP of Different Diameter Piles

Based on Eq. 1, the total GWP due to machinery usage was calculated for each project site.

GWP due to machinery use per 1 m^3 of piles excavated was made to ensure consistency in comparing environmental impacts across various excavation activities. This approach aligns with common practices in life cycle assessment (LCA) studies, where functional units (such as m^3 of material processed) are defined to provide a standardized basis for analysis. Using 1 m^3 of excavated material as the functional unit ensures that the results are scalable and comparable across projects of varying sizes.

Hence, the total pile volume for each project site was calculated by considering the pile diameters and the lengths of piles, and considering the total number of piles. The average GWP potential of 1 m^3 of pile excavation was estimated as per Eq. 3.

$$Average\ GWP\ of\ 1\ m^3\ of\ pile\ excavation = \frac{Total\ GWP\ due\ to\ machinery\ used}{Total\ volume\ of\ the\ pile\ excavation} \quad \text{Eq. 3}$$

2.4 Statistical Analysis

The statistical analysis was conducted by using the IMB SPSS software [11] to identify the key factors influencing GHG emissions. The multiple regression analysis by stepwise method was used to identify relationships between GHG emissions (dependent variable) and factors such as engine power, operator experience, machine age, and operator age (independent variable).

3. Results and Discussion

3.1 Resource (Machinery and Material) Utilization During Piling Work at Four Selected Project Sites

Among the four sites studied, machinery usage details, such as machine type, year of manufacturing, operator details, and engine power for each main machine, are presented in Table 2. Engine power of the boring rigs used in the piling work varied from 205 - 225 kW. All the machines used at project 3 ranged in operation age from 10 to 22 years. Engine power of truck cranes and crawler cranes were in the range of 132-250 kW while the power of excavators varied from 63-77 kW. All types of machinery were operated using diesel fuel. Machine operators' ages varied between 26 - 47 years and their experience varied between 1 - 12 years.

3.1.1 Comparative Analysis of GWP and Identification of the Environmental Hot Spots

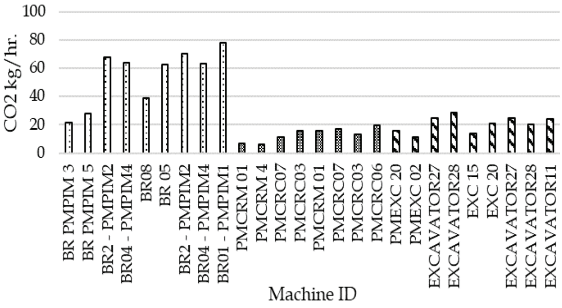
Figure 2 a-d shows the emission rates (in kg/hr.) of CO_2, N_2O, CH_4, and GWP in $kgCO_{2\text{-}e}$ respectively, of different machine types indicated in Table 2, which were considered at the four piling projects. GWP is highest in the boring rigs compared to the excavators and cranes in all four projects. Boring rigs can be considered as the main machinery used in pile foundation construction and it does the most amount of work towards constructing in-situ piles, thereby producing high amounts of GHG emissions compared to other machinery.

Table 1 - Details of the Selected Projects

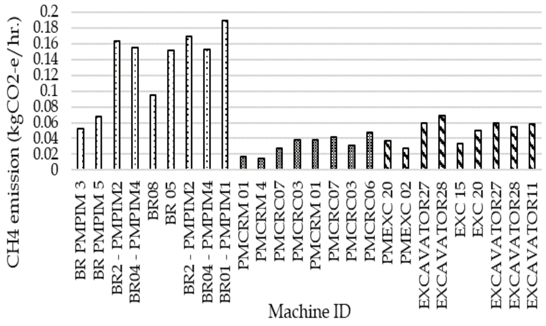
Project No	Project name	Pile diameter (mm)	Number of piles	Considered project duration	Location Details
1	Bandaranayake International Airport Construction Phase 2	600 800 1000 1200 1500	20 16 43 72 77 Total = 228	Seven months	Katunayake, Gampaha. 7°10′N 79°53′E
2	Mannar wind power plant construction	900	68 Total = 68	Two months	Nadukkuda, Mannar island. 9°03′N 79°47′E
3	Flyover construction - Gatambe	1000 1200 1500	4 16 7 Total = 27	Three months	Gatambe junction, Kandy.
4	Proposed 350 MW liquid natural gas combined cycle - Yugadanavi	600 900	114 28 Total = 142	Four months	Kerawalapitiya, Gampaha. 7°01′N 79°53′E

Table 2 - Details of Major Equipment Used for Construction

Machine type	Machine ID	Manufactured year	Operator's age to the date 05/09/2022	Operator's experience years to the date 05/09/2022	Engine capacity (kW)	Project No.
Boring rig	BR PMPIM 3	2012	35	12	205	2
	BR PMPIM 5	2012	35	12	205	2
	BR08	2001	32	5	170	3
	BR 05	2012	35	12	205	3
	BR2 - PMPIM2	2006	41	8	205	1,4
	BR04 - PMPIM4	2012	43	11	205	1,4
	BR01 - PMPIM1	2006	41	11	225	1
Truck crane	PMCRM 01	2012	32	1	250	2,3
	PMCRM 4	2006	27	1.5	165	2
Crawler crane	PMCRC07	2012	29	9	154	1,4
	PMCRC03	1996	47	12	132	1,4
	PMCRC06	2012	41	10	154	1
Excavator	PMEXC 20	2011	28	8	72	2
	PMEXC 02	1999	37	6	63	2
	EXC 15	2014	26	5	77	3
	EXC 20	2011	28	8	72	3
	EXCAVATOR27	2013	33	10	72	1,4
	EXCAVATOR28	2013	30	8	72	1,4
	EXCAVATOR11	2006	31	6	63	1



(a)



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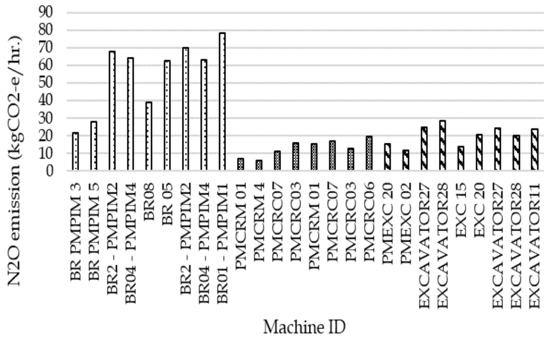

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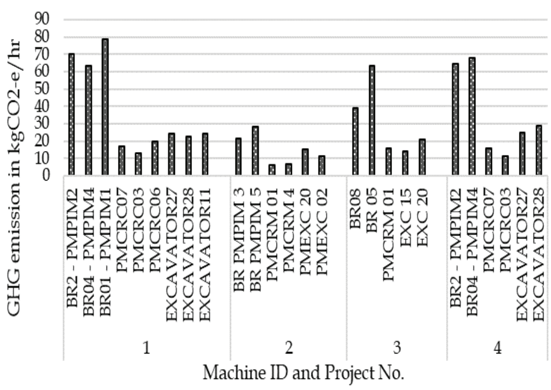

(d)

Figure 2 - a) CO_2 emission; b) CH_4 emission; c) N_2O emission; d) Total GHG emission of Different Piling Equipment

The average GWP per hour of operation of boring rig machines were 211, 49, 102 and 132 in projects 1 to 4, respectively, (Fig. 2(d)). The boring rig machines of project 1 displayed the highest average GWP while boring rig machines of project 2 recorded the lowest average. Guggemos and Horvath [16] also noted that heavy-duty machinery used in foundation work significantly contributes to GHG emissions due to prolonged operational hours.

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As per Table 1, project 1 has approximately 3 times higher number of in-situ piles in contrast with project 2. This could be the reason for the lower GWP observed in project 2.

The present observations are on par with the similar work done by Sandanayaka etal. [1], which mentioned that a 328 kW boring rig emitted 232.75 CO_2 kg/hr. Emissions due to the use of generators at the four projects were considered only for the total equipment GHG emission calculation (Table 3) due to the lack of individual pile-related fuel consumption records from generators [16, 17].

3.2 Effect of Soil Condition on Machinery Emissions

According to the weighted average SPT N values of site borehole investigation reports, the average soil conditions were assessed as shown in Table 3. It can be seen that the ground profile of all the projects comprised loose sand to very dense clayey or silty sand.

Table 4 shows the analysis of total onsite boring volumes of different pile diameters of each project and their total GHG emissions attributable to total machinery usage such as boring rigs, cranes, excavators, as well as generators. Boring volumes of piles of different diameters were calculated considering the pile diameter and the length. All the pile diameters in project 3 were 1000 mm or greater.

This corresponds with the highest GWP per m^3 of pile bored observed at project 3. Further, the average GHG emission for boring 1 m^3 of pile (across all pile diameters in that specific site) calculated for each project revealed that the GHG emission of pile boring varied from 7.4 to 20.48 $kgCO_{2\text{-}e}$ per m^3 of pile bored across the project sites. Project 2, recorded the lowest GHG emission of 7.40 $kgCO_{2\text{-}e}$ per m^3 of pile bored while project 3, recorded the highest

GHG emission of 20.48 $kgCO_{2-e}$ per m^3 of pile bored. Considering the total emissions from all the sites and the total pile volume bored, the estimated average GWP per m^3 of pile bored was 13.63kg CO_{2-e}. Figure 3 shows the distribution of GWP of piles of different diameters caused by piling machinery usage at four project sites estimated based on the average emission due to machinery usage for each site. The variation observed among the sites was primarily due to the variation of total pile numbers leading to varying emission quantities.

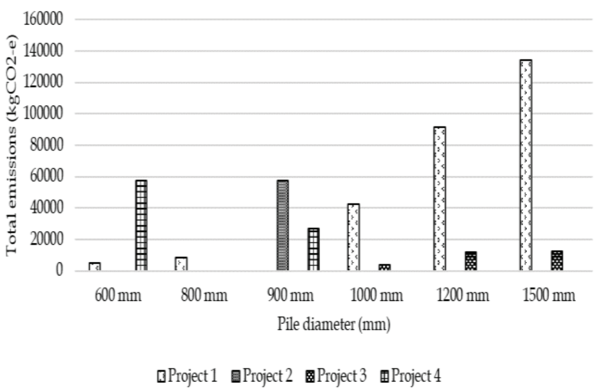

Figure 3 - Comparison of Estimated GWP of Piles of Different Diameters (16, 17]

3.3 Comparative Analysis of GWP due to Material and Machinery Usage

Figure 4 illustrates a comparison of GWP (in $kgCO_{2-e}$) attributed to material and equipment across four projects. Remarkably, concrete and steel are the predominant contributors to GWP in all projects, rather than equipment. Concrete and steel account for 88.94%, 92.66%, 88.22%, and 86.33% of the total GWP of pile construction in projects 1 to 4, respectively. Although project 1 has a higher number of piles, it is notable that project 2 exhibits a higher percentage of material quantity compared to other projects because of the least equipment emissions.

Of the materials used, bentonite has the least contribution towards GWP, ranging from a mere 0.06% to 0.19%, in contrast to concrete and steel. Projects 1 to 4 contributed 11%, 7.27%, 11.59%, and 13.6% of the total GWP due to equipment usage emissions, respectively, with the highest in project 4. The outcomes of this research closely align with those reported by Lyu et al. [6], where a similar investigation into material, equipment, and transportation emissions indicated the material-related emissions over those stemming from equipment. Accordingly, carbon emission from concrete, rotary drills, and cranes caused 69.8%, 1.1%, and 1.8%, respectively, by drilling 1897 piles [6].

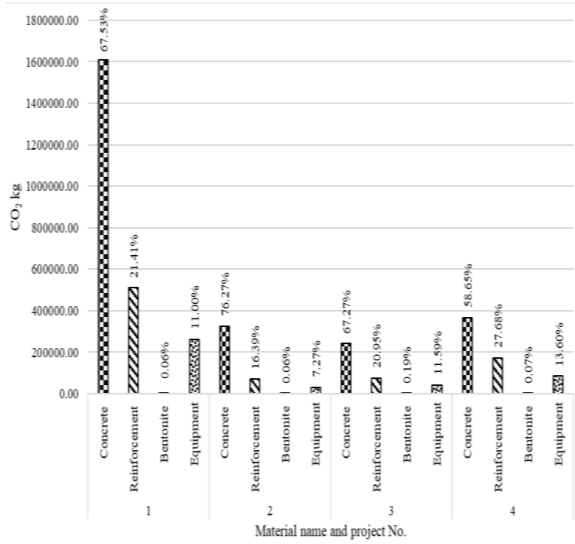

Figure 4 - Comparison of GHG Emission of Material and Equipment among Four Projects

3.4 Analysis of Parameters Influencing Machinery GHG Emissions

Various studies have been conducted to find the factors influencing GHG emissions other than the soil condition [4, 15, 16, 17]. The effect of engine power (kW), the experience of the operator (in years), age of the operator (in years), and machine age on GHG emission were analyzed. The number of replicates (machines) was 26 and the basic statistics of the four exploratory variables and the dependent variable are as shown in Table 6.

3.4.1 Basic Statistics of Variables Affecting GHG Emissions

Table 5 indicates that the observed GHG emission varies from 6.02 $kgCO_{2-e}$ / hr. (min) to 78.52 $kgCO_{2-e}$ / hr. (maximum) with a mean of 30.38 and a Standard Deviation (SD) of 22.29. Of the five variables, GHG emission has the highest Coefficient of Variation (CV) of 73.37% and the age of the operator has the lowest variability. It varies from 26 years to 47 years with an average of 34.5 years and SD of 6.01.

Pearson correlation of each pair was computed to find the association among variables, and the correlation matrix is shown in Table 6. Table 6 exhibits that GHG emission is significantly correlated ($p < 0.05$) solely with engine power. In contrast, the correlations between GHG emissions and factors such as the operator's experience and age are relatively weak. These results demonstrate that there is a moderately favourable association between machine engine power, operator experience, and operator age with GHG emissions. Furthermore, the analysis reveals that the machine age shows a very weak relationship with GHG emission denoted by a correlation coefficient of -0.047.

Among the explanatory variables, a significant correlation was found between operator age and experience ($r = 0.589$, $p < 0.05$) and between operator age and machine age ($r = 0.495$, $p < 0.05$). A Stepwise selection procedure in IBM SPSS software [11] was used to identify the most affecting factors of GHG emission.

3.4.2 Multiple Linear Analysis

The result of the final coefficients identified by the stepwise selection method is shown in Table 7. It was found that the regression model is significant ($p < 0.05$), and the two parameters of the model are significantly different from zero. The fitted model indicates that when engine power increased by one-unit, GHG emission increased by 0.158 when operator experience was fixed. Also, with fixed engine power, when operator experience decreased by 1-unit, GHG emission increased by 2.65 (R^2 = 35.9 and adjusted R^2 = 30.3%). However, the model can explain about 35.9% of the variability of the dependent variables (engine power and operator experience). The results obtained by Fan [4], in a study on wheel loaders indicated that engine power, operator skill, and equipment age affect 0.647, -0.285, and 0.189 times on GHG emissions, respectively.

All the machines used in all projects were subject to regular inspection such as, changing the oil filter with engine oil every 250 hours, changing fuel filters and air filters every 500 hours., changing gear oil 1000 hours, and every changing hydraulic oil with filters 3000 hours, ensuring good working conditions. There was a weak correlation shown between machine age and GHG emissions. Therefore, it can be suggested that regular machine services have led to minimizing the impact of the machine age on GHG emissions.

Moreover, based on standardized coefficients among significant variables, the impact of engine power on GHG emissions is higher than the impact of operator experience on GHG emissions. Notably, the variables of the machine age and operator age are not included in the model as significant variables; it can be inferred that those two variables do not have a significant impact on GHG emissions.

The pattern of influencing external factors on total GHG is the same as that of CO_2, N_2O, and CH_4. In other words, the engine power and operator experience mostly influence the total GHG as well as CO_2, N_2O, and CH_4 gases separately.

The analysis was extended to investigate whether there is any significant correlation between the total GWP ($kgCO_{2\text{-}e}$) due to machinery use of bored piles and the weighted average SPT value as shown in Table4. However, it was seen that there was no strong correlation (R^2=0.1029) implying that the soil condition of sites did not influence machinery emissions significantly. As none of the sites had encountered large rock boulders during drilling, this observation could be justifiable.

However, a comparative assessment of the machinery capacities for the above-mentioned projects revealed that project 1 utilized higher engine capacity machinery than project 3 as detailed in Table 3. This observation aligns with the statistical analysis of the factors affecting the GWP emission, revealing that engine capacity and operator experience have a major contribution concerning the GHG emission for pile foundation construction. In summary, these findings underscore the significant influence of pile quantity, machinery capacity, and operator skills on GWP emissions in the context of bored pile foundation construction, with project 1 exhibiting noteworthy characteristics in each of these aspects [1, 16, 17].

4. Conclusion

This study undertook a comparative analysis of material and equipment emissions in pile foundation construction, showing the highest emissions are from materials compared to equipment. The study reiterated the predominant emissions contribution due to construction materials such as concrete and steel which alone contributed to 86% – 93% of the total emissions of the sites studied. The study also showed that the soil condition did not significantly impact the machinery emissions (indicated by the weak correlation of R^2=0.1029), most probably when there are no or minimum encountering of large rock boulders during drilling.

This study further verified that the factors such as engine power and operator experience become predominant factors impacting the GHG emissions due to machinery usage, compared to operator age and machine age.The average GHG emission for boring 1 m^3 of pile (across all pile diameters) calculated for each project revealed that the GHG emission of pile boring due to machinery use varied from 7.4 to 20.48 kg $CO_{2\text{-}e}$ per m^3 of pile bored across the project sites with an average value of 13.62 CO_2e per m^3.

Further studies will elaborate on the availability of closely monitored data encompassing the material use and machine fuel consumption in pile construction.

Table 3 - Subsurface Characteristics of Selected Sites

Project No. / Depth (m)	1	2	3	4
Ground level-0.5	Landfill	Loose clayey Sand	Landfill	Very loose sand
0.5-5	Medium dense clayey sand	Medium dense clayey sand	Medium dense clayey sand	Loose sand
5-10	Medium dense clayey sand	Dense clayey sand	Medium dense clayey sand	Medium dense clayey sand
10-15	Dense clayey sand	Very dense clayey sand	Medium dense clayey sand	Medium dense to very dense clayey sand
15-20	Very sense silty sand	Very dense clayey sand	Very dense silty sand	Very dense clayey sand

Table 4 - Pile Boring Volumes of Different Pile Diameters and Total GWP due to Equipment Usage for Different Projects

Project No.	Boring volume (m^3) of different pile diameters (mm)						Total GWP due to machinery use ($kgCO_{2-e}$)	Weighted average SPT
	600	800	900	1000	1200	1500		
1	344.9	612.3	-	3119.2	6717.5	9862.0	265096.9	29.28
2	-	-	4210.9	-	-	-	31170.5	41.25
3	-	-	-	266.9	868.6	901.9	41715.0	25.53
4	4198.2	-	1983.8	-	-	-	85248.7	31.65

Table 5 - Descriptive Statistics

Variable	Minimum	Maximum	Mean	SD	CV (%)
GHG emission ($kgCO_{2-e}$ / hr.)	6.02	78.52	30.38	22.29	73.37
Engine power (kW)	63.00	250.00	148.31	64.81	43.70
Operator experience (years)	1.00	12.00	8.25	3.38	40.97
Operator age (years)	26.00	47.00	34.46	6.01	17.44
Machine age (years)	8.00	26.00	13.15	5.42	41.22

Table 6 - Pearson Correlations Matrix

	GHG emission (kg CO_2e / hr.)	Engine power (kW)	Operator experience (years)	Operator age (years)	Machine age (years)
GHG emission ($kgCO_{2-e}$ / hr.)		.445*	.385	.344	-.047
Engine power (kW)			-.037	.328	-.042
Operator experience (years)				.589**	.038
Operator age (years)					.495*
Machine age (years)					

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 7 - Properties of the Estimators of Regression Model for GHG Emission

Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Significance
	B	Std. Error	Beta		
(Constant)	-14.913	13.201	-	-1.130	0.270
Engine power (kW)	0.158	0.057	0.460	2.750	0.011
Operator experience (years)	2.650	1.102	0.402	2.406	0.025

(R^2 = 35.9 and Adjusted R^2 = 30.3%)

It can improve research, yielding a more comprehensive understanding of GHG emissions of the pile construction process.

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