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Deterministic Modelling of Hydraulic Static Pile Driver Productivity for Rectangular and Triangular Shaped Piles in Silty Soil

Joko Y.E. Warsito, Jati D.U. Hatmoko, Rusdi H. Ataf

Abstract: ***Various piles driving equipment can be used for piling in building projects. In densely populated urban area, more environmentally friendly pile driving equipment, such as hydraulic static pile driver (HSPD) is therefore needed. There are important factors influence the HSPD productivity that are implied in treatment of pile in soil, such as soil type, driven pile size, piling depth, and cycle time. While some methods are available to estimate construction productivity, each method has limitations, such as unreliable prediction and difficult implementation. In present research, HSPD productivity in construction project has been estimated by deterministic modelling, so produced the chart model of HSPD productivity of rectangular and triangular shaped piles in silty soil. Data were collected through site observation from five building projects in three cities of Indonesia, i.e. Semarang, Pati, and Solo. A deterministic model has been designed utilizing data of 180 piling points from the five projects and simulation, so was obtained the chart model of HSPD productivity. Validation of the outputs of the model shows a valid result with an average validity value of 95.6% and standard deviation of 3.3%. Sensitivity analysis of these outputs shows an average sensitivity value of 88.25%. The productivity chart is valuable to plan and to estimate time related to the use of HSPD in construction projects.***

Keywords: productivity; HSPD; piles; deterministic; chart

I. INTRODUCTION

Rapid urban growth along with population density has caused an increase of infrastructure and building construction projects in recent years in terms of project scale and number. Many of which certainly involve the construction of deep foundation, including pile foundation. Pile foundation has been used in building constructions, bridges, and others structure since before the time. Various piles driving equipment is available. Compared to other types of piling equipment, the operation of HSPD has no vibration, emits low pollution, and produces low noise [1 – 2]. The use of this tool can reduce the loss of complaints from affected communities so that contractors' benefits are maintained [3].

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***** Correspondence Author
Joko Y.E. Warsito*, Doctoral of Civil Engineering, Diponegoro University Semarang, Indonesia
Jati D.U. Hatmoko, Department of Civil Engineering, Diponegoro University Semarang, Indonesia
Rusdi H. Ataf, Department of Civil Engineering, Lambung Mangkurat University, Banjarbaru, Indonesia

HSPD uses press-in method to insert driven pile in soil, and can merge grip and push or pull technique. The press-in method offers an alternative technique of pile installation to the urban area, which allows pile installation with minimal noise and vibration [4]. The operation of HSPD involves 3 major steps, i.e. preparing driven pile, pressing driven pile and moving to other piling point. In certain case, it needs welding joint.

Estimating equipment productivity is both an art and a science. An accurate prediction of the productivity is one of the prerequisites for construction project control and planning [5]. There is a lack of HSPD productivity research.

HSPD productivity has been studied in an apartment project [6 –7] and a showroom project [8]. Each studies limited on one site, one pile type, one soil kind, and one piling depth. The studies used cycle time data, which then was analyzed with statistic non-parametric to obtain a productivity value on the site. This value cannot be generalized on other sites due to different conditions they may have. In the method, labor performance has not been considered. In the other hand, a study of equipment productivity has been done by model to produce a productivity chart, i.e. a study of bored pile productivity has been done by various modelling [9], a study of continuous flight auger (CFA) as drilling technique has been done by deterministic method [10], a study of horizontal direction drilling (HDD) as trenchless technology has been done by deterministic method [11]. The chart can be used to plan next project. Therefore, HSPD productivity needs further study to obtain a chart that can be used to plan project.

The pile installation and pile driving equipment productivity is affected by a large number of factors relating to subsurface obstacles, operator experience, and site planning difficulties [12]. The site pre-investigation usually consist of statistical samples around the foundation area that do not cover the entire area. Soil types differ from site to site due to cohesion or stiffness, natural obstacles, and surface infrastructure construction obstacles. Operator skill differs from the one to the others due to experience. HSPD mechanical and piling problems must be considered for site planning. All these problems, no doubt, greatly affect the HSPD productivity on site. A large number of factors greatly affect the HSPD productivity, which is impossible to consider all of them in one study. Based on studies of pile foundation and literature, there are important factors influence the HSPD productivity that are implied in treatment of pile in soil [13], such as soil type, driven pile size, piling depth, and cycle time.

Therefore, this study assesses the HSPD productivity considering the above factors.

HSPD productivity requires certain techniques to analyze the problem and to determine the optimal solution. Some methods are available to estimate construction productivity, such as; deterministic, simulation, regression, and Artificial Neural Network (ANN) [14 – 15]. Each method has limitations, such as unreliable prediction and difficult implementation [14].

Due to above-mentioned factors and methods, it is difficult for the researcher to evaluate HSPD productivity in one study. There is lack of research in studying HSPD productivity.

Therefore, it is necessary to use certain techniques to analyze the problem. Warsito *et al.* [16] has studied HSPD productivity using ANN method to produce a good HSPD productivity chart.

This chart is valuable for practitioners to plan and to estimate time related to the uses of HSPD for a construction project. In this study, deterministic method is used to assess HSPD productivity, because it is a simple calculation [14], easy to apply [17], and no need many data.

The aim of this research is to study HSPD productivity in construction projects using deterministic method. The objective is to produce charts model of HSPD productivity of rectangular and triangular shaped piles in silty soil.

II. MATERIALS AND METHOD

A. Data Collection

The data consists of CPT (Cone Penetration Test) data for soil classifying, driven pile size, piling depth, and cycle time. Data were collected through site observation from 5 building projects in 3 cities of Indonesia, i.e.

Semarang, Pati, and Solo. Piling in this zone can be generalized for piling in other zone, because has similar characteristic in same soil category. Collected data was divided into 3 main data sets based on soil type, 2 sub main data sets based on driven pile size, 1 set for each size. Within each set, data are classified into 3 categories according to piling depth attributes.

Each category has least 30 data point to indicated cycle time. The data were collected for driving triangular 32 cm and for driving rectangular 25 cm, whereas soil bearing capacity data were collected through CPT.

The cycle time (CT) consist of determined and undermined time. Determined time covers preparing time, welding time, and moving time to next piling point. Determined time has fixed value in all soil type.

Undetermined time is pressing time. Pressing time is not fixed, because depend on soil bearing capacity. Pressing time data were separated each 6 m piling depth and identified its soil bearing capacity (q_c) so that got 8 data groups.

Pressing time and soil bearing capacity data each group were plotted on a chart, for example is shown in Fig. 1, so that got 8 linier equations as shown in Table 1. The CPT data were analized to obtain soil composition.

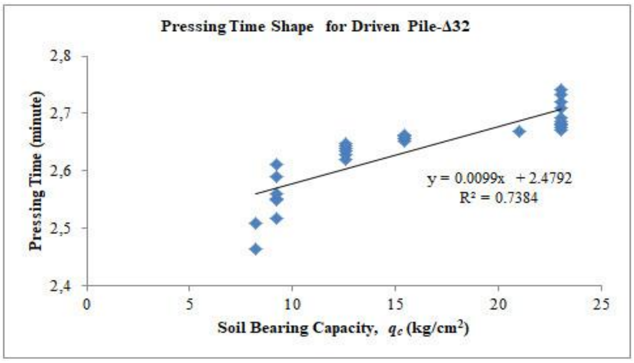


Fig. 1. Shape of pressing time

Table 1. Pressing time equation

Site/Soil Type	Piling Depth (m)	Description	Soil Composition	q_c (kg/cm^2)			Pressing Time Equation ($x = q_c$)
				Min	Average	Max	
1 / Sand	0 – 6	t_p-DP-□25	Sand 50% + Silt 50%	23	49	115	y=0.0039x+ 3.2989
2 / Sand	0 – 6	t_p-DP-Δ32	Sand 83% + Silt 17%	34	68	97	y=0.0158x+ 2.2752
6 / Silt	0 – 6	t_p-DP1-Δ32	Silt 67% + Clay 17% + Sand 16%	8	16	23	y=0.0099x+ 2.4792
	6 – 12	t_p-DP2-Δ32	Sand 67% + Silt 33%	19	39	118	y=0.0032x+ 2.8684
7 / Clay	0 – 6	t_p-DP1-□25	Clay 67% + Silt 33%	12	16	29	y=0.0227x+ 2.3429
	6 – 12	t_p-DP2-□25	Clay 50% + Sand 33% +Silt 17%	24	58	118	y=0.0034x+ 3.2661
8 / Clay	0 – 6	t_p-DP1-Δ32	Clay 67% + Silt 33%	8	14	30	y=0.0564x+ 2.2178
	6 – 12	t_p-DP2-Δ32	Sand 50% + Silt 33% + Clay 17%	10	66	116	y=0.0049x+ 3.1813

Note: tp = pressing time, DP = Driven Pile, DP1 = First Driven Pile, DP2 = Second Driven Pile

Some other data of cycle time were obtained from simulation based on Table 1. This simulation was used to get data based on the relationship between q_c and pressing time of observed project sites. This equations were used to simulated the presing time on the other soil bearing capacity. The choosing of equation depends on the similarity of soil bearing capacity and the same size of driven piles. The determined time from observation is collected and chosen randomly, then undetermined time from observation and simulation are added to get the cycle time. There is 180 data of piling point for 2 driven pile size section and 3 piling depth. The collected data sets are split randomly into two data subsets: 70% for modelling and 30% for validation.

Fig. 2. The conceptual uses the piling process activities duration of HSPD as input.

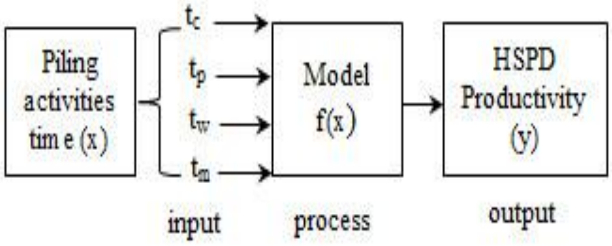


Fig. 2. Conceptual model of deterministic modelling.

The determined and undetermined time are required to construct a driven pile has to be determined before productivity assessment. The design of the deterministic model of HSPD productivity considers the following steps:

(a) Driven pile pressing time determination

Pressing pile has 4 sub-activities: clipped the driven pile by grip of HSPD, pressing the driven pile, loose of grip clipped, and push up of grip. Piling depth has to be divided into equal small depth segment (d_i) appropriate driven pile length as shown in Fig. 3. Pressing time at the beginning of the depth segment is different from that at the end of the segment. Therefore, the segment depth (d_i) has to be so small that the pressing time difference between the upper and lower segment's edges is small. It is assumed that the pressing time does not change inside each depth segment, so that each average pressing time on the center of depth segment can be used to represent the pressing time through the entire segment [18]. Then, based on Fig. 3, the pressing time (t_p) one segment can be calculated using Equation (1).

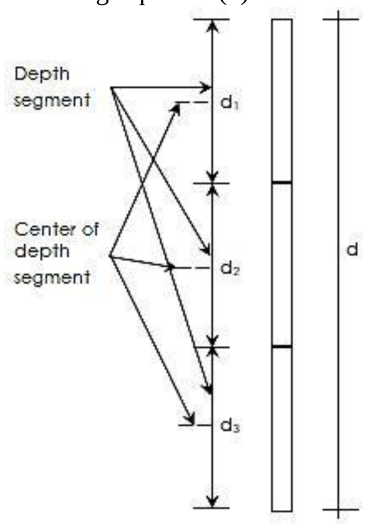


Fig. 3. Piling depth segment.

$$t_p = \left(\frac{d}{h_t}\right)\sum_{d=1}^{b}\sum_{j=1}^{a} t_{dj} \quad \text{(minute)} \qquad (1)$$

where t_p is the pressing time, d is the depth segment, h_t is pressing length, a is amount of the maximum sub-activities, b is amount of the maximum segment, j is the sub-activity, and t_{dj} is the time sub-activity j on the segment d_i.

(b) Other activities' time determination

Other activities' time consist of preparing time (t_c), welding time (t_w), and moving time to next piling point (t_m). Crane machine prepare of driven pile and stickpress. Welding machine welds of driven pile joint. HSPD move its self to next piling point. Based on the above explaining, the other activities' time (OAT) can be expressed in Equation (2).

$$OAT = t_c + t_w + t_m \quad \text{(minute)} \qquad (2)$$

(c) Piling cycle time determination

Piling cycle time is the sum of piling activities's time that is the pressing time (t_p) and the other activities' time (OAT). Hence, based on Equations (1) and (2), the piling cycle time (CT) can be calculated by Equation (3).

$$CT = t_p + OAT = t_p + t_c + t_w + t_m \quad \text{(minute)} \qquad (3)$$

(d) Normal piling cycle time determination

Skill, effort, conditions, and consistency in each labors are different. A performance rating (PR) value has to be applied for resulting normal time based on Westinghouse Performance Rating is shown in Table 2 [20]. Average activities' time was adjusted to PR value for resulting normal time each activity. Then, the normal piling cycle time (CT_n) can be calculated using Equation (4).

Table 2. Westinghouse rating system [19]

SKILL		EFFORT		CONDITIONS		CONSISTENCY	
+ 0.15 A1	Superskill	+ 0.13 A1	Excessive	+ 0.06 A	Ideal	+ 0.04 A	Ideal
+ 0.13 A2		+ 0.12 A2					
+ 0.11 B1	Excellent	+ 0.10 B1	Excellent	+ 0.04 B	Excellent	+ 0.03 B	Excellent
+ 0.08 B2		+ 0.08 B2					
+ 0.06 C1	Good	+ 0.05 C1	Good	+ 0.02 C	Good	+ 0.01 C	Good
+ 0.03 C2		+ 0.02 C2					
0.00 D	Average	0.00 D	Average	0.00 D	Average	0.00 D	Average
- 0.05 E1	Fair	- 0.04 E1	Fair	- 0.03 E	Fair	- 0.02 E	Fair
- 0.10 E2		- 0.08 E2					
- 0.16 F1	Poor	- 0.12 F1	Poor	- 0.07 F	Poor	- 0.04 F	Poor
- 0.22 F2		- 0.17 F2					

$$CT_n = t_p.PR_p + t_c.PR_c + t_w.PR_w + t_m.PR_m \quad \text{(minute)}$$
(4)

where CT_n is the normal cycle time, PR_p is the normal pressing time, PR_c is the normal preparing time, PR_w is the normal welding time, and PR_m is the normal moving time to next piling point.

(e) Productivity model determination

Productivity can be determinated after calculating the CT_n in normal distribution statistic. The outcome is the number of piling point that can be constructed per hour, whereas CT_n in minutes, so the time has to be converted to hour using 60 minutes/hour. The one cycle of piling result one piling point. Therefore, to calculating productivity, the working time per hour (60 minutes/hour) has to be devided by the CT_n.

The realistic productivity must consider: equipment operation condition, machine maintenance, and operator efficiency. The matters are considered by correction factor (CF) for getting actual productivity estimation [19]. CF is suggested for using Table 3 [21] and Table 4 [22]. Productivity can be calculated using Equation (5).

Table 3. Job efficiency [20]

Equipmen Operation Condition	Machine Maintenance				
	Very good	Good	Average	Poor	Very poor
Very good	0.83	0.81	0.76	0.70	0.63
Good	0.78	0.75	0.71	0.65	0.60
Average	0.72	0.69	0.65	0.60	0.54
Poor	0.63	0.61	0.57	0.52	0.45
Very poor	0.52	0.50	0.47	0.42	0.32

Table 4. Operator efficiency [21]

Operator Skill	Operator Efficiency
Very good	1.00
Average	0.75
Poor	0.60

$$AP_{EM} = \frac{60}{CT_n}\, CF \qquad (5)$$

B. Deterministic Validation

Good quality plagiarism software/ tool (Turnitin / iThenticate) will be used to check similarity that would not be more than 20% including reference section. In the case of exclusion of references, it should be less than 5%. Deterministic Validation

Validation model was done by comparing the estimation actual productivity and the actual productivity to check the validity percent. The validity factor (VF) and the average validity percent (AVP) term are used to represent the validity of the develop models. The VFs are found expression in fitness percent. Furthermore, the number of VFs that more than a certain limitation was calculated and divided by the number of data from this was got fitness percent. The AVP shows average validity percent of model. The VF and AVP are determined using the Equation (6) and (7) that be modified from [13, 19], respectively:

$$VF = \frac{AP_{EM}}{AP}\,.\,100\% \qquad (6)$$

$$AVP = \left(\textstyle\sum_{i=1}^{n} VF\right)/n \qquad (7)$$

where i is number of data, and n is maximum number of data.

C. Sensitivity Analysis

The sensitivity analysis checks consistency and stability model outcome. This test was done with changing model input that is the amount driven pile each piling point (ADP). The changing ADP influences pressing time. All pressing time data for sensitivity test were simulated adjusting length driven pile change whereas the other driving activities time are same with modelling data. The new cycle time was used to calculate the productivity for getting new model as applied model (AM). The applied model was compared with the initial model to know its deviation and pattern.

If the models show the same pattern, its mean that the model is consistent and stable. The deviation can be calculated to determine a model confidence degree that is found expression in sensitivity percent. The sensitivity degree can be calculated by Equation (8) that be modified from Bayes Theorem [23].

$$R = (1 - C)^{\frac{1}{n+1}}\,.\,100\% \qquad (8)$$

where R is model sensitivity degree, C is confidence degree, and n is maximum number of data.

D. Data Processing

Pressing time and q_c of 5 building project were processed. Relationship between q_c and pressing time give a new form in piling process, which result an equation that represents data collection of piling depth (Table 1). The equation in Table 1 can be used to simulate pressing time the other site. Equation selection based on almost similar soil composition and q_c. This method gave robust result.

CPT data every sites were plotted on chart service [24] until was known its soil composition, one of them shows in Fig. 4, reflecting the soil composition of 6%-33% clay soil, 44%-81% silt soil, and 11%-42% sand soil, which is categorized as silty soil. Soil composition and q_c value each 6 m depth determine pressing time equation based on Table 1. The result pressing time equation simulation for silty soil is shown in Table 5. Its q_c value enter in the equation so obtain pressing time value. The determined time and the pressing time are added up to get the cycle time, it agrees with Equation (3). The productivity can further be calculated from this cycle time.

Table 5. Simulation of pressing time equation

Site/Soil Type	Piling Depth (m)	Description	Soil Composition	q_c (kg/cm²)			Pressing Time Equation ($x = q_c$)
				Min	Average	Max	
3 / Silt	0 – 6	t_p-DP-□25	Silt 50% + Clay 33% + Sand 17%	7	48	120	y=0.0034x+ 3.2661
	0 – 6	t_p-DP-Δ32					y=0.0032x+ 2.8684
6 / Silt	0 – 6	t_p-DP1-Δ32	Silt 67% + Clay 17% + Sand 16%	8	16	23	y=0.0227x+ 2.3429
	6 – 12	t_p-DP2-□25	Sand 67% + Silt 33%	19	39	118	y=0.0039x+ 3.2989
10 / Silt	0 – 6	t_p-DP1-□25	Clay 67% + Silt 33%	2	6	11	y=0.0227x+ 2.3429
	6 – 12	t_p-DP2-□25	Silt 67% + Clay 33%	8	25	48	y=0.0227x+ 2.3429
	12 – 18	t_p-DP3-□25	Sand 67% + Silt 33%	51	79	112	y=0.0034x+ 3.2661
	0 – 6	t_p-DP1-□25	Clay 67% + Silt 33%	2	6	11	y=0.0564x+ 2.2178
	6 – 12	t_p-DP2-Δ32	Silt 67% + Clay 33%	8	25	48	y=0.0564x+ 2.2178
	12 – 18	t_p-DP3-Δ32	Sand 67% + Silt 33%	51	79	112	y=0.0032x+ 2.8684

Note: tp = pressing time, DP = Driven Pile, DP1 = First Driven Pile, DP2 = Second Driven Pile, DP3 = Third Driven Pile

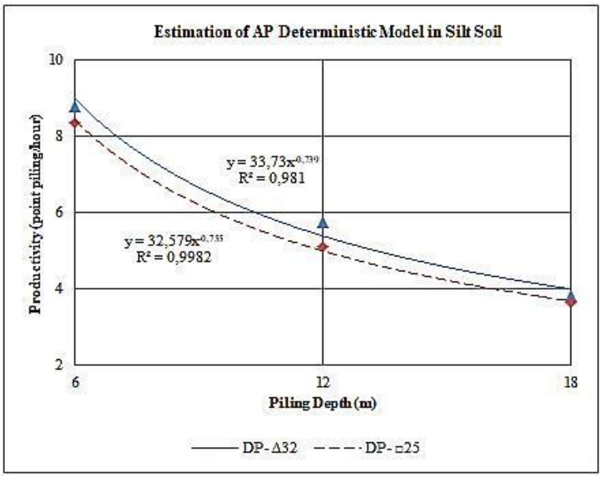


Fig. 5. HSPD productivity chart in silty soil.

Data processing in this study has not been done in previous study, in HSPD [6 – 8] or drilling system [9 – 11] study. Relationship between q_c and pressing time gave a new form in piling process. It resulted an equation that represented data collection in a part of piling depth. The equation was used to simulate other site which has almost similar soil composition and q_c. This method gave robust result.

E. Deterministic Model

Cycle time (CT) consist of determined and undetermined time. Determined time was obtained from 5 building project. Undetermined time or pressing time was obtained from observation and simulation. Determined time or other activities' time was calculated with Equation (2).

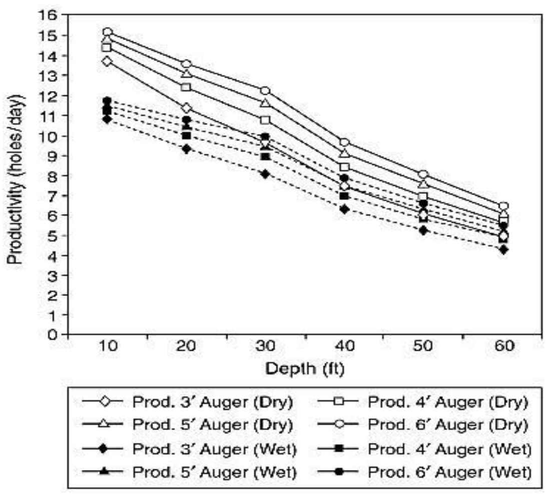
Cycle time can be calculated with Equation (3). Operators have certain skill, effort, condition, and consistency, so need PR to correct the CT. PR value in Table 2 is used for determining normal piling cycle time by Equation (4) for obtaining a normal productivity. CF in Table 3 and Table 4 is used 0.83 in this study. It is based on certain consideration along the observation, so actual productivity can be calculated with Equation (5).

The deterministic model was done for 2 types of driven pile, i.e. triangular Δ32x32x32 cm and rectangular □25x25 cm. Each types of driven pile were calculated for 6 m, 12 m, and 18 m piling depth. The actual deterministic outputs is shown in Fig. 5. The deterministic outputs of actual productivity of model estimation (AP_{EM}) is summarised in Table 6. Fig. 5 shows that a power trend regression type has been suitably used for the equation with R^2 values of 0.981 and 0.988. The productivity decreases along with the increasing piling depth. The variation of driven pile section sizes also influences the productivity value, that the bigger the section size, the lower level of the productivity.

Table 6. The AP_{EM} deterministic model (piling point/hour)

Piling depth (m)	Driven pile section size (cm)	
	Δ32x32x32	□25x25
6	8.77	8.36
12	5.75	5.09
18	3.83	3.63

The chart of HSPD productivity is different from bore pile productivity in previous study [19] as shown in Fig. 6. The different is caused by work and approachment method difference. HSPD work method is pressing until end bearing each piling depth part, which pressing time is influenced by soil bearing capacity and soil friction, whereas change of its productivity is not linier. In the other hand, approachment method uses power trend regression type from observation and simulation data whereas result is the warped chart. Bor pile work method is boring, usually in soft soil, which boring time is influenced by soil hardness and soil friction, whereas change of its productivity is linier. In the other hand, approachment method uses linier line from questionnaire, site interview, and telephone call data whereas result is the linier chart. Similarities of them are productivity turn down along with depth increase and the chart useful for planning in next project.



[1] **Fig. 6. Chart of bore pile productivity in clay soil [19]**

The result of research adds a new knowledge about HSPD productivity chart and a media for learning of productivity. The HSPD productivity chart and its equation can easy apply on site for estimating of productivity on construction project. Furthermore, it can determine project cost. If unit price of equipment rent, labor pay, and materials are known, then project cost will be known too.

F. Model Validation

Validation is so important because a model cannot be used in practice unless it is valid. The outputs of model in Table 6 have to be validated by validation subset data so that it can be used for productivity estimating. There is 54 data to validate that outputs, 9 validation data each output. The validation factor (VF) can be obtained from Equation (6). If the model provides close numbers to the validation data, it is valid and can be used to represent this process in the real practice. In addition, the average validity percentage (AVP) is calculated using Equation (7), as well as standard deviation (SD) of VF, at 95% and 85% level of validity of data fitness. On VF > 95% of the model output has 70.4% data fitness and on VF >85% of the model output has 100% data fitness, it means that the model is valid to HSPD productivity estimating. The AVP shows a high value (95.6%) and small SD (3.3%), it means that the model is a good model.

G. Model Sensitivity

The model has been built using composition of ADP: 1, 2, 3 in order following the piling depth. The composition of ADP changes to 2, 3, 4 as model input, which causes the productivity to change due to the amount of welding activities. The new data was used for modelling to produce a new productivity known as applied model (AM). Both AM and AP_{EM} points were compared to get deviation to obtain sensitivity degree using Equation (7). From the calculation R = 88.98% for driven pile Δ32x32x32 cm and R = 87.59% for driven pile □25x25 cm. Pattern of AM and AP_{EM} charts are shown in Fig. 7. The pattern and R values showed good condition, it means that the model is consistence and stable.

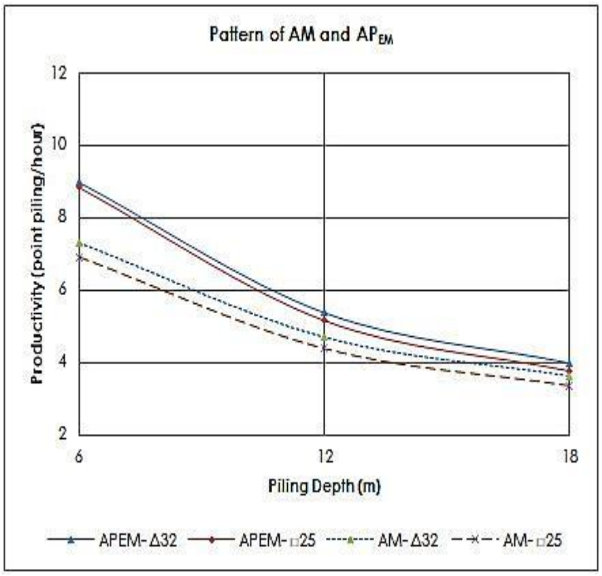


Fig. 7. Pattern of AM and AP_{EM}. 5

H. Model Validation

This model has advantages, i.e. the model is simple, the program easy to apply, the chart is easy used and to modify. This model has limitations, however, that the CF is difficult to determine and the model does not explain actual productivity base on real situation, as actual data of loose productivity and delay time is difficult to collect.

III. CONCLUSION

The silty soil in this study has composition: 6%-33% clay soil, 44%-81% silt soil, and 11%-42% sand soil. The deterministic output is known as actual productivity of model estimation (AP_{EM}) that is: on driven pile triangular ∆32x32x32 cm, respectively is 8.77, 5.75, 3.83 piling point/hour at 6, 12, 18 m piling depth; and on driven pile rectangular □25x25 cm, respectively is 8.36, 5.09, 3.63 piling point/hour at 6, 12, 18 m piling depth.

The deterministic outputs have been validated by comparing with validation collected data. The VF and AVP concepts have been designed to check the fitness degree of the designed deterministic. The value of AVP = 95.6% and SD = 3.3%, which are fairly good and acceptable. Sensitivity analysis has been done by changed input model so that was resulted an applied model (AM). Both AM and AP_{EM} points resulted the same pattern, it means that the model is consistence and stable.

This research has produced a chart of HSPD productivity in silty soil using rectangular and triangular shaped piles. This chart is a novelty of knowledge as innovation of bore pile productivity chart in previous study. HSPD is a new kind of pile driver in this last decade, which is a lack of HSPD productivity research, so result of this research is that of beginning base for completing gap of HSPD productivity chart. The deterministic method developed in the research is potentially useful for other researchers to construct a new productivity model on other types of HSPD. For practitioners, this chart is valuable to plan and to estimate time related to the use of HSPD in construction projects. Future research can be done on developing productivity chart for different pile driving type, pile sizes and piling depths.

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