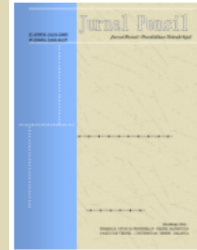


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COMPARATIVE ANALYSIS OF ANALYTICAL RATIONAL METHOD IN CALCULATING BEARING CAPACITY OF PILE FOUNDATION BASED ON N-SPT DATA AGAINST CAPWAP TEST RESULTS PDA

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Abstract

This research aims to analyze the comparative value of analytical rational methods in calculating the bearing capacity of pile foundations based on N-SPT data. The results of calculating the bearing capacity of pile foundations by analytical methods (Luciano Decourt & Quaresma, Meyerhof, Nakazawa, Terzaghi & Peck, Reese O'Neil, and Vesic & Tomlinson) will be compared to the results of CAPWAP analysis of PDA (Pile Driving Analyzer) tests. The results of this study show that the Meyerhoff (1956) method provides the highest tip bearing capacity values, while the Nakazawa (2000) method produces the highest blanket bearing capacity and total bearing capacity values compared to other methods. Comparison of the ratio of total bearing capacity to CAPWAP showed a range of values from 0,82 to 1,64 with the Terzaghi & Peak (1948) methods providing the highest ratio. The methods with the smallest to largest average comparison values are Nakazawa (2000), Meyerhoff (1956); Luciano Decourt (1982) & Quaresma (1978); Vesic (1977) and Tomlinson (1977); Reese O'neil (1999); Terzaghi & Peak (1948) with average comparison values against CAPWAP of 0.81; 0.88; 1.14; 1.56; 1.57; 1.64 respectively. The comparison of the total bearing capacity of the analytical method to the CAPWAP analysis that is closest to 1 is the Meyerhoff (1956) and Luciano Decourt (1982) & Quaresma (1978) method. Therefore, the most effective analytical methods in calculating the total bearing capacity of piles are Meyerhoff (1956) and Luciano Decourt (1982) & Quaresma (1978) methods.

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Keywords: foundation bearing capacity, pile foundation, analytical method, N-SPT, Pile Driving Analyzer

Introduction

Along with the times, people's needs for public facilities are also increasing (Putri and Rahardjo, 2019). Public facilities in the construction sector play an important role in supporting the progress of the times. A construction generally consists of substructure and superstructure buildings (Candra, 2017). Superstructure is the upper structure of a construction while substructure is the lower structure of a construction or also known as the foundation (Hidayah, 2021). The foundation is a crucial component of the substructure, responsible for supporting and transferring the load from the superstructure to the ground. (Febriantoro, Cahyo and Ridwan, 2018; Hartanto *et al.*, 2018; Al-Mosawi and Khan, 2022). For its crucial role, the foundation needs to be calculated properly, in order to maintain building stability and avoid building damage due to soil shear collapse (Candra, 2017; Schipper, 2021). The main factors in planning foundation requirements include soil characteristics, working loads, foundation shape, and bearing capacity calculation methods (Ridar and Khatib, 2015; Lailiya *et al.*, 2023). If the load acting on the foundation is relatively large and no hard soil layer is found at a shallow depth, then the deep foundation type is the best choice in that case (Gazali, Perdana and Rachman, 2021). One example of deep foundation is pile foundation (Widojoko, 2015; Gazali, Perdana and Rachman, 2021).

Pile foundation is a deep foundation that uses piles made from certain materials and embedded in the ground (Suwarno, Siswanto and Wahyudiono, 2018). There are various types of pile foundations that can be used according to construction needs, including wood, prestressed concrete, and steel piles (Khomaeni, 2020; Gazali, Perdana and Rachman, 2021). The selection of the right type of pile is very important to ensure the strength and durability of the foundation being built (Syafei, 2016). This foundation system is the main choice for construction in areas with unstable or soft surface soil characteristics, where the use of shallow foundations is considered inadequate to support building loads (Khusnah, Respati and Huda, 2021). The implementation of piles is done by hitting or pressing the pile using heavy equipment until it reaches a layer of soil that is hard enough to support the structure (Jawat, 2016). Piles play an important role in channeling building loads to deeper soil layers, while providing protection against various threats such as groundwater pressure, horizontal forces, and earthquake vibrations (Lamansari, Balamba and Manaroinsong, 2019; Mardianti, Nuklirullah and Dwina, 2022; Raja, Endayanti and Hutahean, 2022). This system also serves to maintain the stability of excavated soil and prevent the possibility of landslides (Winarti and Indah Sari, 2022). Overall, pile foundations are an effective solution to ensure the stability and robustness of buildings, especially in unfavorable soil conditions (Widojoko, 2015).

The bearing capacity of pile foundations is typically determined through analytical methods. (Badan Standardisasi Nasional, 2017). The widely used and standardized analytical methods are Meyerhof, Reese, Vesic, and Terzaghi methods (Hardiyatmo, 2011; Ulfa, 2019). One of the most common methods is the Meyerhof method, which calculates the bearing capacity of piles based on the shear force and cohesion of the soil around the pile (Khairi, Sundry and Gunawan, 2021). In this method, soil parameters such as soil layer depth and soil shear angle that affect the bearing capacity of the pile are also taken into account (Triastuti and Indriasari, 2019). Another method is the Nakazawa method which adapts soil parameters based on SPT and CPT test data to determine the bearing capacity of piles more accurately (Lestari, Propika and Puspasari, 2020). However, the value of pile bearing capacity obtained from the calculation of the analytical method is quite diverse (Ahmad and Surahman, 2016; Hekmatyar *et al.*, 2017). Therefore, it is essential to conduct tests on the piles that have been installed in the field to determine the actual bearing capacity of the piles. (Santoso and Hartono, 2020; Rosyada and Indianto, 2021). Dynamic testing is one of the tests that can be conducted to obtain the actual value of the bearing capacity of a pile (Faruha and Ridwan, 2018).

A commonly used dynamic testing method to evaluate pile bearing capacity, pile structural integrity, and piling efficiency is the Pile Driving Analyzer (PDA) testing method (Sagita, Fahriani and Apriyanti, 2020). This test is conducted by utilizing a device equipped with accelerometer and

strain gauge sensors mounted at the top of the pile (Tarigan, 2020). When the pile is struck by a driving hammer, the sensors measure the resulting acceleration and force, which are then analyzed to determine the dynamic and static characteristics of the pile (Luthfi and Suhardi, 2024). The advantages of this method are its ability to provide fast test results and is more economical than static load tests, and can be applied to a variety of soil conditions. In addition, PDA is also used to monitor the piling process in real-time, thus preventing potential damage to the pile during installation. However, in order to obtain accurate results, the analysis must consider various factors, including soil characteristics and the type of pile being used (Simanjuntak and Suita, 2017). The results of the Pile Driving Analyzer tests will be processed using CAPWAP software to determine the tip, friction and ultimate bearing capacity of the piles (Khomsianti, Jirna and Setyawan, 2019).

Previous research conducted by Fadilla & Pradiptiya (2022) regarding the comparison of pile bearing capacity based on SPT test results and dynamic testing against the results of the PDA test results (Fadilla and Pradiptiya, 2022). The study used 4 analytical methods namely Static, Meyerhof, Briaud & Taucker, and L. Decourt. The results of this study, there is an average difference between each method on the results of the PDA test of 39.83% less than the PDA value, with the smallest difference found in the L. Decourt equation of 4.2%. Another study was conducted by Rus et al. (2021) who conducted a comparison test of bearing capacity using SPT, laboratory, and CPT data against the PDA test results. The study results show that there is an average difference of 66.74% between the analytical method and the PDA results (Rus, Sunarno and Irwaniansyah, 2021). Research conducted by Septianto et al. (2023) which analyzed the bearing capacity of piles using 3 different methods with an average difference of 55.89% against the PDA test results (Septianto, Yani and Sarie, 2023). From some of the research that has been done before, there is a significant difference between the analytical rational method and the Pile Driving Analyzer test results.

This research aims to analyze the comparison of pile foundation bearing capacity calculation using analytical rational method to the CAPWAP analysis result of PDA test. This research will calculate the bearing capacity of piles using analytical methods [Luciano Decourt (1996) & Quaresma (1978), Meyerhoff Meyerhoff (1956), Nakazawa (2000), Terzaghi & Peck (1948), Reese O'neil (1999), and Vesic (1977) & Tomlinson (1977)]. The results of each method will be compared with the results of the CAPWAP analysis of PDA testing. So that it can be seen the most effective method in calculating the bearing capacity of piles from the resulting comparative value.

Research Methods

The research method employed in this study is quantitative, utilizing a comparative approach to evaluate and contrast the results of pile foundation bearing capacity calculations derived from various analytical methods with those obtained from field tests. The research will be conducted by collecting secondary data required for analysis. The secondary data used is obtained from several construction projects around Surabaya that use pile foundations. The secondary data includes N-SPT data, foundation plans, and test plans along with Pile Driving Analyzer (PDA) test results.

Before determining the bearing capacity, it is essential to conduct a thorough analysis of the data (Choi, Kim and Kim, 2016; PUPR, 2019). The data analysis is to correct the N-SPT value and correlate it to the required soil parameters. The N-SPT value for pure sand soil must be corrected for overburden pressure using equation 1.

$$(N_1)_{60} = N_M \times C_N \times C_E \times C_B \times C_R \times C_S \quad (1)$$

$$C_N = \frac{2,2}{1,2 + \frac{\sigma'_{vo}}{Pa}} \quad (\leq 1.70)$$

N_M is the N-SPT value while the C_E , C_B , C_R , and C_S values are correction factors obtained from SNI 4153: 2008. N-SPT located below the water table needs to be corrected to MAT which can be done by using the formulation of Terzaghi and Peck in equation 2.

$$N^* = 15 + \frac{1}{2} \times (N-15) \quad (2)$$

N_M is the N-SPT value while the C_E , C_B , C_R , and C_S values are correction factors obtained from SNI 4153: 2008. N-SPT located below the water table needs to be corrected to MAT which can be done by using the formulation of Terzaghi and Peck in equation 2.

The parameters needed in calculating the bearing capacity of the analytical method are soil plasticity index, soil cohesion (C_u) and soil specific gravity (soil γ). Plasticity index can be found using the correlation between NSPT and α value (PUPR, 2019). The correlation of N-SPT values to soil parameters depends on the soil type. If the soil is cohesive, the correlation proposed by Terzaghi & Peck (1967) can be used, while for non-cohesive soil, the correlation proposed by Mochtar (2009) can be used.

After all the required data are complete, the calculation of foundation bearing capacity will be carried out using six analytical methods namely Luciano Decourt & Quaresma, Meyerhof, Nakazawa, Terzaghi & Peck, Reese O'Neil, and Vesic & Tomlinson methods. Specifically, the six methods can be seen in Table 1.

Table 1. Analytical method of bearing capacity calculation

Method	Supportability Equation			Description
	End (Qp)	Friction (Qs)	Total (Qu)	
Meyerhoff (1956)	$m \cdot N_p \cdot A_p$	$n \cdot \bar{N} \cdot A_s$	$Q_p + Q_s$	<ul style="list-style-type: none"> m = 40 n = (sandy loam = 0,2; clayey soil = 0,5) N_p = Average NSPT value at the tip of the pile (NSPT about 1D below and 4D above the base of the pile) \bar{N} = Average N price of the soil layer around the embedded pile.
Luciano Decourt (1982) & Quaresma (1978)	$\alpha \cdot k \cdot N_p \cdot A_p$	$\beta \cdot (\frac{NS}{3} + 1) A_s$	$Q_p + Q_s$	<ul style="list-style-type: none"> N_p = Average of N values at 4D above to 4D at the base of the pile tip. K = soil coefficient at the end of the foundation. N_s = Average of N values along the pile depth ($3 \leq N \leq 50$). α = pile base coefficient β = pile friction coefficient
Nakazawa (2000)	$q_d \cdot A$	$U \cdot \Sigma li \cdot fi$	$Q_p + Q_s$	<ul style="list-style-type: none"> q_d = Bearing capacity of soil at pile tip (ton/m²) A = Pole tip area (m²) U = Pole circumference (m) li = Depth of soil layer (m) fi = Frictional force of soil with pile wall (ton/m²)
Reese O'neil (1999)	$9C_{ub}A_p$ (Cohesive)	$\alpha C_u Li P$ (Cohesive)	$Q_p + Q_s$	C_{ub} = Undrained Cohesion at pile tip (ton/m ²)

Method	Supportability Equation			Description
	End (Qp)	Friction (Qs)	Total (Qu)	
	7NbAp (Non-Cohesive)	0.32NLiP (Non-Cohesive)		Nb = Average N-SPT (8D above - 4D below pile tip) Cu = Undrained cohesion of soil (ton/m ²) α = Coefficient of soil adhesion with the pile.
Terzaghi dan Peck (1948)	ApCbNc	∑αCuAs	Qp + Qs	Cb = Soil cohesion at base of pile (t/m ²) Nc = Bearing capacity factor
Vesic (1977) dan Tomlinson (1977)	qp·Ap	∑αCuPΔL	Qp + Qs	P = Pole circumference (m) ΔL = Depth of soil layer (m) qp = Ultimate end bearing capacity (ton/m ²)

The calculation results of each analytical method will be compared to the CAPWAP test results. This comparison will result in a percentage difference between the analytical method and the field test results. Next, a statistical analysis will be conducted to determine the accuracy of each analytical method. The results of this analysis will show which analytical method provides results closest to the actual conditions in the field based on the CAPWAP test results. The conclusion of this study will provide recommendations on the most effective analytical method for calculating the bearing capacity of pile foundations based on N-SPT data.

Research Results and Discussion

The PDA data in the field needs to be analyzed using the CAPWAP application in order to obtain the actual value of the bearing capacity of the friction, tip and total bearing capacity of the tested pile. A recapitulation of the analysis results of the bearing capacity of several projects that have been collected can be seen in Table 2.

Table 2. CAPWAP analysis results PDA test

No. Pile	Cross section (cm)	Depth (m)	Bearing capacity of PDA (ton)	CAPWAP Analysis Results (ton)		
				Friction	End	Ultimate
88-IP9	35x35	35.2	246	226.2	68.1	294.3
14-IP2	35x35	23.2	194	155.6	54.5	210.1
SP 19 ^{a)}	Ø40	24	136	133	44	177
SP 40	Ø40	24	90	93	31	124
SP 56	Ø40	21	197	178	68	246
SP 73	Ø40	24	75	54	29	84
SP 76 ^{a)}	Ø40	24	146	112	44	157
SP 92 ^{a)}	Ø40	24	156	164	44	209
85	Ø50	30	-	122	24	146
161	Ø50	30	-	160	29	189
261	Ø50	30	-	248	31	279

The N-SPT data shown in Table 3 and Table 4 were first analyzed by calculating the correction value and finding the Cu value and soil volume weight by correlating the corrected N-SPT values.

Table 3. N-SPT data for points 88-IP9, 14-IP2, 261, 85, and 161

depth (m)	88-IP9		14-IP2		261		85 and 161	
	Soil Type	NSPT	Soil Type	NSPT	Soil Type	NSPT	Soil Type	NSPT
0		0		0		0		0
2		4		3	Silt	3	Silt	4
4	Clay	3	Clay	3		2	Silt	3
6	Sand	12	Sand	9	Silt	2	Sand	3
8	Clayey Sand	3		4		2		2
10		3		2	Silt	2	Silt	2
12		3	Clay	3		2		2
14	Soft, Clay	4		3		4		3
16		4		4	Silt	5	Silt	4
18		4	Clay	8	Sand	12	Silt	14
20		12		25	Silt	15	Clay	15
22	Clay	17		16		19		16
24	Sandy Silt	74	Clay	17		23		17
26		1		14		22	Silt	23
28		18		13	Silt	21		26
30	Clay	19		19		22		28
32		21		19		13		
34		16	Clay	16		17		
36		17		18				
38	Clay	16		17				
40		17		18				

Table 4. N-SPT data for points SP19*), SP40, SP56, SP73, SP76*), and SP92*)

depth (m)	SP 19*), SP 40		SP 56		SP 73, SP 76*), SP 92*)	
	Soil Type	NSPT	Soil Type	NSPT	Soil Type	NSPT
0		0		0		0
1.5	Clay	8	Clay	7		9
3	Fine Sand	9		8	Clay	10
4.5	Clay	10	Fine Sand	11		10
6		3	Clay	5		16
7.5	Soft, Grey, Clay	14		12	Fine Sand	19
9	Fine Sand	13	Fine Sand	14		21
10.5		14		16	Fine Sand	19
12		16		17		18
13.5	Silty Clay	18		17		21
15	Sandy Silt	36		21		25
16.5		22		23		27
18		18	Silty Clay	25		22
19.5		16		26	Silty Clay	23
21	Silty Clay	17		21		20
22.5		18		24		21
24		19		21		23
25.5		20		24		25
27		22		26		25
28.5	Silty Clay	23	Silty Clay	22	Silty Clay	27
30		24		25		28

An example of the N-SPT data analysis results can be seen in Table 5. The N-SPT value used in the calculation of foundation bearing capacity is found in the Corrected N column.

Corrected N values are used in finding Cu and gama values by correlating them. The correlation results are found in the Cu and Saturated volume weight columns.

Table 5. Corrected N-SPT for Point No. 88-IP9

Soil Type	depth (m)	N-SPT	N Corrected	Cu (t/m ²)	Saturated volume weight (t/m ³)
Gragal + Sirtu	0	0	0	0	1.6
	1	0	0	0	
CLAY	2	4	4	2.50	1.85
	3	3.5	3.5	2.18	
	4	3	3	1.85	
	5	7.5	7.5	4.69	
	6	12	12	7.86	
fine SAND	7	7.5	8.48	0.00	1.7
	8	3	3.39	0.00	
clayey SAND	9	3	3.18	0.00	1.36
	10	3	3.18	0.00	
CLAY	11	3	3	1.85	1.93
	12	3	3	1.85	
	13	3.5	3.5	2.18	
	14	4	4	2.50	
	15	4	4	2.50	
	16	4	4	2.50	
	17	4	4	2.50	
	18	4	4	2.50	
CLAY	19	8	8	5.00	1.96
	20	12	12	7.86	
	21	14.5	14.5	9.64	
	22	17	16	10.67	
sandy SILT + gravel	23	45.5	30.25	20.00	1.93
	24	74	44.5	20.00	
CLAY	25	44.5	29.75	19.83	1.93
	26	15	15	10.00	
	27	16.5	15.75	10.50	
	28	18	16.5	11.00	
	29	18.5	16.75	11.17	
	30	19	17	11.33	
sandy SILT	31	20	17.5	11.67	1.95
	32	21	18	12.00	
CLAY	33	18.5	16.75	11.17	1.92
	34	16	15.5	10.33	
	35	16.5	15.75	10.50	
	36	17	16	10.67	
	37	16.5	15.75	10.50	
	38	16	15.5	10.33	
	39	16,5	15.75	10.50	
	40	17	16	10.67	

The bearing capacity calculation using the analytical rational method for the piles is based on the analyzed N-SPT data from the location nearest to the pile. A summary of the pile bearing capacity calculation results is provided in Table 6 through Table 8.

Table 6. Calculation result of pile end bearing capacity

No. Pile	Analytical Method End Support (ton)						CAPWAP (ton)
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)	
88-IP9	59.7	17.8	24.8	8.8	5.6	8.3	68.1
14-IP2	60.6	18.0	24.8	8.8	5.6	7.1	54.5
SP 19*)	62.1	31.1	27.2	9.3	5.9	7.5	44.0
SP 40	67.9	34.0	29.7	10.2	6.5	8.2	31.0
SP 56	74.0	37.0	31.2	10.3	6.5	8.0	68.0
SP 73	70.1	35.0	30.7	10.5	6.7	8.3	29.0
SP 76*)	67.8	33.9	29.7	10.2	6.4	8.0	44.0
SP 92*)	72.2	36.1	31.6	10.8	6.9	8.6	44.0
85	93.0	46.5	42.4	14.3	9.0	11.0	24.0
161	119.9	59.9	54.6	18.4	11.7	14.2	29.0
261	120.4	60.2	53.9	18.8	11.9	14.9	31.0
Average	78.9	37.2	34.6	11.9	7.5	9.5	42.4

From Table 6, it can be seen that the average tip bearing capacity values produced are below the CAPWAP analysis results, except for the Meyerhoff (1956) method. This can be clearly seen in Figure 1. The figure also shows that the Meyerhoff (1956) method has the highest average tip bearing capacity value compared to other analytical methods. This statement is supported by previous research conducted by Santoso and Hartono (2020), which resulted in the largest tip bearing capacity in the Meyerhof equation.

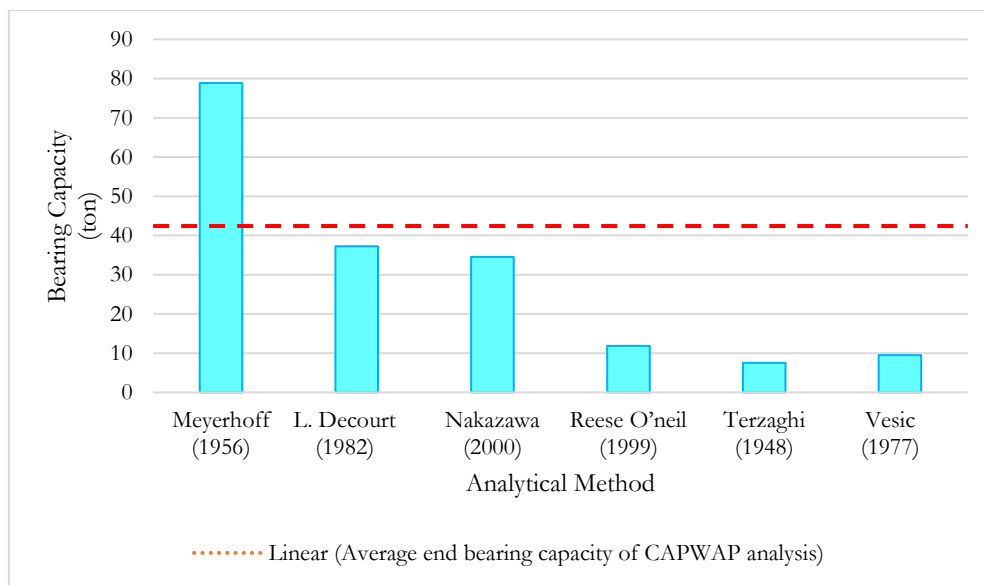


Figure 1. Average end bearing capacity value

Table 7. Calculation results of pile friction bearing capacity

No. Pile	Analytical Method Friction Bearing Capacity (ton)						CAPWAP (ton)
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)	
88-IP9	205.9	183.7	280.4	152.8	145.2	173.1	226.2
14-IP2	77.9	82.7	123.8	60.5	71.3	93.9	155.6
SP 19*)	136.7	128.5	192.2	113.1	102.2	120.5	133

No. Pile	Analytical Method Friction Bearing Capacity (ton)						CAPWAP (ton)
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)	
SP 40	149.5	140.6	210.3	123.7	111.8	131.8	93
SP 56	128.9	118.0	178.4	104.2	98.6	116.0	178
SP 73	149.0	146.0	197.4	129.9	101.7	79.2	54
SP 76*)	144.1	141.2	191.0	125.7	98.3	76.6	112
SP 92*)	153,4	150,3	203.3	133.8	104.7	81.5	164
85	122.4	111.0	183.4	88.5	109.0	101.4	122
161	157.7	143.0	236.4	114.0	140.5	130.6	160
261	176.7	166.3	262.0	131.1	153.5	170.9	248
Average	145.6	137.4	205.3	116.1	112.4	115.9	149.6

The results of the recapitulation of the calculation of the bearing capacity of the pile friction by analytical method can be seen in Table 7. From Table 7, it can be seen that the average friction bearing capacity value produced is below the CAPWAP analysis results, except for the Nakazawa (2000) method. This can be clearly seen in Figure 2. The figure also shows that Nakazawa (2000) method produces the highest average value of friction bearing capacity compared to other analytical methods.

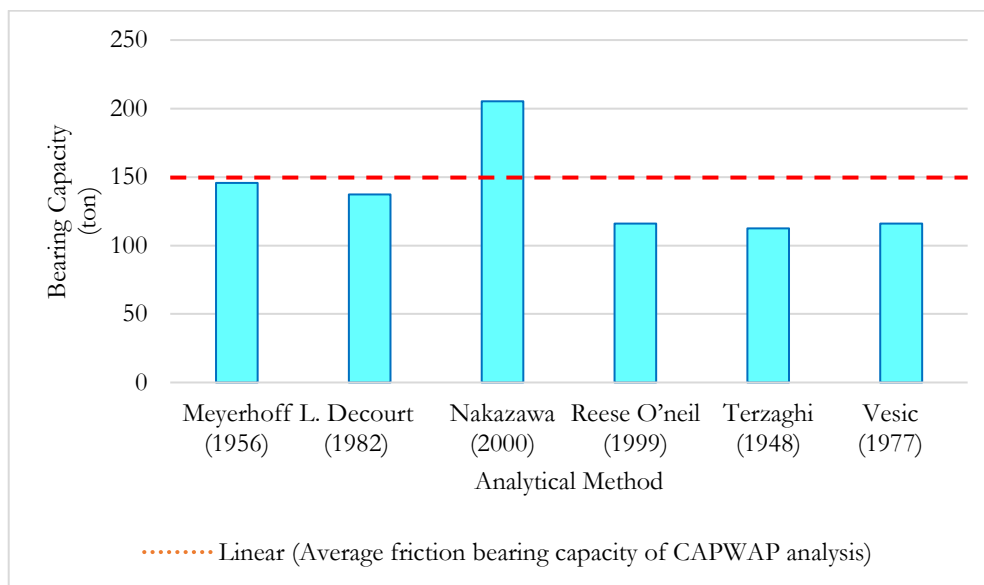


Figure 2. Average friction bearing capacity

Table 8. Calculation results of total bearing capacity of piles

No. Pile	Analytical Method Total Bearing Capacity (ton)						CAPWAP (ton)
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)	
88-IP9	265.5	201.5	305.2	161.6	150.8	181.4	294.3
14-IP2	138.5	100.6	148.6	69.3	76.9	101.0	210.1
SP 19*)	198.8	159.6	219.4	122.4	108.1	128.0	177.0

No. Pile	Analytical Method Total Bearing Capacity (ton)						CAPWAP (ton)
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)	
SP 40	217.5	174.6	240.0	133.9	118.2	140.0	124.0
SP 56	202.8	154.9	209.6	114.5	105.1	124.1	246.0
SP 73	219.1	181.0	228.1	140.4	108.3	87.5	83.0
SP 76*)	211.9	175.1	220.6	135.9	104.8	84.6	156.0
SP 92*)	225.6	186.4	234.8	144.6	111.5	90.1	208.0
85	215.4	157.5	225.7	102.8	118.1	112.4	146.0
161	277.6	203.0	290.9	132.5	152.2	144.9	189.0
261	297.1	226.4	315.8	149.9	165.4	185.8	279.0
Average	224.5	174.6	239.9	128.0	119.9	125.4	192.0

The summary of the analytical method for calculating the pile friction bearing capacity is presented in Table 8. From Table 8 it can be seen that the average value of the total bearing capacity produced is below the CAPWAP analysis results, except for the Meyerhoff (1956) and Nakazawa (2000) methods. This can be clearly seen in Figure 3. The figure also shows that the Nakazawa (2000) method has the highest average value of total bearing capacity compared to other analytical methods.

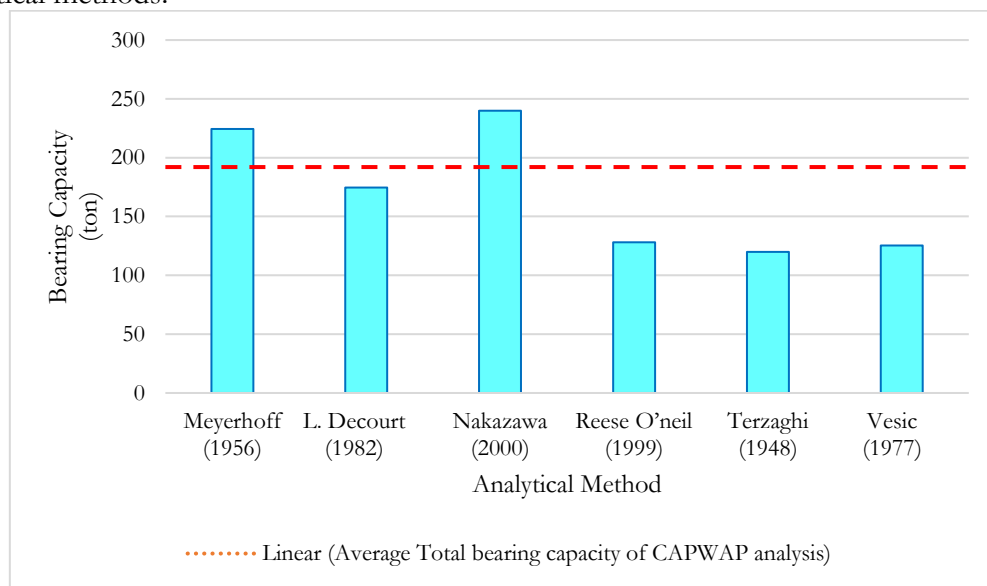


Figure 3. Average total bearing capacity

The comparison between the results of the bearing capacity of piles using the analytical rational method and the CAPWAP results of the PDA test can be seen in Table 9 to Table 11. The comparison value is obtained by dividing the value of the bearing capacity of the CAPWAP analysis by the bearing capacity of the analytical method.

Table 9. Comparison of end bearing capacity of analytical method to CAPWAP analysis

No. Pile	Comparison of Analytical Method End Bearing Capacity					
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)
88-IP9	1.14	3.82	2.75	7.73	12.21	8.24
14-IP2	0.90	3.04	2.20	6.19	9.77	7.63
SP 19*)	0.71	1.42	1.62	4.72	7.46	5.84

SP 40	0.46	0.91	1.04	3.04	4.80	3.76
SP 56	0.92	1.84	2.18	6.58	10.40	8.46
SP 73	0.41	0.83	0.95	2.76	4.36	3.49
SP 76*)	0.65	1.30	1.48	4.33	6.83	5.47
SP 92*)	0.61	1.22	1.39	4.07	6.42	5.14
85	0.26	0.52	0.57	1.68	2.65	2.17
161	0.24	0.48	0.53	1.58	2.49	2.04
261	0.26	0.52	0.58	1.65	2.60	2.08
Average	0.60	1.44	1.39	4.03	6.36	4.94

Table 9 shows the values of the end bearing capacity comparison of the analytical method against the CAPWAP analysis. The average value of the comparison that is closest to 1 is the Nakazawa (2000) method with an average comparison value against CAPWAP of 1,39. The method with the smallest average comparative value is Meyerhoff's (1956) method with a comparative value of 0,60. Meanwhile, the methods with the largest average comparative value is Terzaghi & Peak (1948) with a comparative value of 6,36.

Table 10. Comparison friction bearing capacity of analytical method to CAPWAP analysis

No. Pile	Comparison of Analytical Method Friction Bearing Capacity					
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)
88-IP9	1.10	1.23	0.81	1.48	1.56	1.31
14-IP2	2.00	1.88	1.26	2.57	2.18	1.66
SP 19*)	0.97	1.03	0.69	1.18	1.30	1.10
SP 40	0.62	0.66	0.44	0.75	0.83	0.71
SP 56	1.38	1.51	1.00	1.71	1.81	1.53
SP 73	0.36	0.37	0.27	0.42	0.53	0.68
SP 76*)	0.78	0.79	0.59	0.89	1.14	1.46
SP 92*)	1.07	1.09	0.81	1.23	1.57	2.01
85	1.00	1.10	0.67	1.38	1.12	1.20
161	1.01	1.12	0.68	1.40	1.14	1.22
261	1.40	1.49	0.95	1.89	1.62	1.45
Average	1.06	1.12	0.74	1.35	1.34	1.30

Table 10 shows the values of the comparison of the friction bearing capacity of the analytical method to the CAPWAP analysis. The average value of the comparison that is closest to 1 is the Meyerhoff (1956) method with an average comparison value against CAPWAP of 1,06. The method with the smallest average comparative value is the Nakazawa (2000) method with a comparative value of 0,74. Meanwhile, the methods with the largest average comparative value is Reese O'neil (1999) with a comparative value of 1,35.

Table 11. Comparison of total bearing capacity of analytical method to CAPWAP analysis

No. Pile	Comparison of Analytical Method Total Bearing Capacity					
	Meyerhoff (1956)	L. Decourt (1982)	Nakazawa (2000)	Reese O'neil (1999)	Terzaghi (1948)	Vesic (1977)
88-IP9	1.11	1.46	0.96	1.82	1.95	1.62
14-IP2	1.52	2.09	1.41	3.03	2.73	2.08
SP 19*)	0.89	1.11	0.81	1.45	1.64	1.38
SP 40	0.57	0.71	0.52	0.93	1.05	0.89
SP 56	1.21	1.59	1.17	2.15	2.34	1.98
SP 73	0.38	0.46	0.36	0.59	0.77	0.95
SP 76*)	0.74	0.89	0.71	1.15	1.49	1.84

SP 92*)	0.92	1.12	0.89	1.44	1.87	2.31
85	0.68	0.93	0.65	1.42	1.24	1.30
161	0.68	0.93	0.65	1.43	1.24	1.30
261	0.94	1.23	0.88	1.86	1.69	1.50
Average	0.88	1.14	0.82	1.57	1.64	1.56

Table 11 shows the values of the comparison of the total bearing capacity of the analytical method to the CAPWAP analysis. The average value of the comparison that is closest to 1 is found in the Meyerhoff (1956) and Luciano Decourt (1982) & Quaresma (1978) methods with an average comparison value against CAPWAP of 0,88 and 1,14 respectively. The method with the smallest average comparative value is the Nakazawa (2000) method with a comparative value of 0,82. Meanwhile, the methods with the largest average comparative values is Terzaghi & Peak (1948) methods with a comparative value of 1,64.

The comparison value closest to 1 indicates that the value of the analytical method bearing capacity calculation is more similar to the CAPWAP analysis results of the PDA test. For comparison values greater than 1, the value of the analytical method calculation is smaller than the CAPWAP value, and vice versa.

The comparative values of the previously calculated bearing capacity calculations will be compared to previous studies, in order to analyze the differences. The comparison can be seen in Table 12.

Table 12. Average Comparative Total Support Capacity Analytical Method Previous Research

Analytical Method	Results of this study	Fadilla & Pradiptiya (2022)	Santoso & Hartono (2020)	Septianto et al. (2023)
Meyerhoff	0.88	1.43	0.92	2.10
L. Decourt & Quaresma	1.14	1.04	0.87	-
Nakazawa	0.82	-	-	-
Reese O'neil	1.57	-	-	1.90
Terzaghi dan Peak	1.64	-	-	-
Vesic dan Tomlinson	1.56	-	-	-

From Table 12, it can be seen that the comparative values that have been carried out by several previous authors have differences from the results of this study. These differences can be influenced by the year of the formulation used, the condition of the pile in the field, and the heterogeneous soil conditions at the test location.

Conclusion

The resulting average tip bearing capacity values are below the CAPWAP analysis results, except for the Meyerhoff (1956) method. The Meyerhoff (1956) method has the highest average tip bearing capacity compared to the other analytical methods. The resulting average blanket bearing capacity values are below the CAPWAP analysis results, except for the Nakazawa (2000) method. The Nakazawa (2000) method produced the highest average value of blanket bearing capacity compared to the other analytical methods. The resulting average total bearing capacity values are below the CAPWAP analysis results, except for the Meyerhoff (1956) and Nakazawa (2000) methods. The Nakazawa (2000) method has the highest average value of total bearing capacity compared to the other analytical methods.

The methods with the smallest to largest average comparison values are Nakazawa (2000), Meyerhoff (1956); Luciano Decourt (1982) & Quaresma (1978); Vesic (1977) and Tomlinson (1977); Reese O'neil (1999); Terzaghi & Peak (1948) with average comparison values against CAPWAP of 0.82; 0.88; 1.14; 1.56; 1.57; 1.64 respectively. The comparison of total bearing capacity of the analytical method to CAPWAP analysis that is closest to 1 is Meyerhoff (1956) Method and Luciano Decourt (1982) & Quaresma (1978) Method. Therefore, the most effective analytical methods in calculating the total bearing capacity of piles are Meyerhoff (1956) and Luciano Decourt (1982) & Quaresma (1978) Methods.

Based on the results of the analysis that has been carried out, several important points can be suggested for the calculation of pile bearing capacity. In the practice of pile bearing capacity calculation, it is highly recommended to use Meyerhoff Method (1956) or Luciano Decourt Method (1982) & Quaresma (1978), considering that these two methods show the closest results to the CAPWAP analysis with comparative values of 0,88 and 1,14 respectively. To improve the accuracy of the calculations, it is strongly recommended to verify using at least two of these analytical methods. Thus, a more reliable range of bearing capacity values is obtained. It is suggested that future research can provide a correlation equation between the bearing capacity of the analytical method and the results of field testing. So as to obtain more accurate results in foundation planning, especially pile foundations.

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