

Tensile Capacity of Concrete Pile Foundation at the Surajaya Stadium Tribune in Lamongan

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ABSTRACT

The foundation of the Surajaya Stadium Tribune in Lamongan utilizes 772 concrete piles with specific tensile capacity requirements, necessitating reliable and efficient verification methods. This study aims to evaluate the effectiveness of substituting conventional static tensile tests with modified dynamic testing methods—namely Driving Record analysis combined with Pile Driving Analyzer (PDA) and CAPWAP—to determine the tensile capacity of the piles. Using a comparative analytical approach, three evaluation methods were applied: Minimum Bearing Capacity Factor (FDDmin), Average Bearing Capacity Factor (FDDavg), and direct CAPWAP Friction Bearing Capacity. The findings indicate that all three methods yield a safety factor (SF) exceeding the required minimum of 2, with average SF values of 2.73, 3.02, and 2.51, respectively, confirming the piles' structural safety. The adoption of these dynamic methods resulted in significant efficiencies, saving approximately 36 days and Rp 1,299,077,600 in costs compared to static testing. However, the study implies that the accuracy of dynamic testing is highly dependent on proper sensor installation and calibrated equipment, highlighting the need for experienced vendors. This research demonstrates that dynamic methods are a viable, cost-effective alternative for tensile capacity verification in similar projects, provided that stringent implementation protocols are followed.

Keywords: Tensile capacity, static test, dynamic test, cost efficiency

INTRODUCTION

The Foundation testing plays a crucial role in ensuring the structural safety and longevity of large public buildings, particularly stadiums that accommodate thousands of people. Globally, inadequate foundation assessment has led to catastrophic failures and significant economic losses (Aven, 2016; Bokiev & Samad, 2021; Hou et al., 2022). In Indonesia, compliance with national standards (SNI 8460:2017) mandates rigorous testing protocols for pile foundations to minimize structural risks. The proper verification of pile capacity is essential not only for meeting regulatory requirements but also for preventing potential disasters that could result from foundation inadequacies (Ansori & Radam, 2015; Bokiev & Samad, 2021; Feri et al., 2018; Novina et al., 2020; Yanto et al., 2017).

The number of concrete pile foundations in zone 3 is 453 points with a depth of 28 m and the allowable compression capacity requirement is: 80 tons. Of the 772 points, in zone 3 there are 44 Tensile piles with a allowable Tensile capacity is: 60 tons which need to be ensured that the length of the embedded pile is still able to withstand the required Tensile force. In the planning there are 4 (four) soil investigation points in the form of deep drilling, including: 1. West Zone: BH 01, 2. North Zone: BH 02, 3. East Zone: BH 03, 4. South Zone: BH 04.

In addition, static and dynamic testing is also carried out to verify the results of the Driving Record whether they have met the bearing capacity requirements. With the right testing method, the potential for structural failure can be minimized, so that the quality and safety of the structure supported by concrete piles are guaranteed. Dynamic testing and static testing are two commonly used techniques in testing concrete pile foundations. Each method has advantages and limitations related to effectiveness, time efficiency, and implementation costs.

Previous research has extensively examined the application of PDA and CAPWAP methods in pile foundation testing. Riyanda et al. (2023) compared static, dynamic, and PDA test results for pile foundations of the Peureulak Bridge, concluding that dynamic methods showed 15-20% deviation from static tests but remained within acceptable engineering tolerances. Sari and Amin (2024) evaluated the bearing capacity and settlement of bored piles using PDA testing at Universitas KH. Abdul Wahab Hasbullah Jombang, demonstrating that PDA results

correlated well with design specifications when properly calibrated. Kusuma and Lestari (2021) analyzed pile capacity for a coal conveyor project using multiple methods, finding that CAPWAP analysis provided more detailed information on friction and end bearing components compared to conventional approaches. Furthermore, Suharyanto and Sunarta (2021) conducted a comprehensive study on deep foundations for a seven-story building at Universitas Gadjah Mada, comparing theoretical calculations with field test results and highlighting the importance of soil investigation quality in prediction accuracy. These studies collectively emphasize the reliability of dynamic testing methods when implemented with proper protocols, while acknowledging the continued importance of static testing as a validation benchmark.

In construction practice, dynamic testing is often the main choice to verify the bearing capacity of concrete piles. One of the widely used methods is Pile Driving Analyzer (PDA), which is known to be effective, efficient, accurate in results, and more economical than other methods (Asfarina, Sharwanda, & Makarim, 2020). With further analysis using CAPWAP, the results of the ultimate bearing capacity can be separated into end bearing capacity and blanket friction. However, this method has limitations because it cannot be used to test the lateral bearing capacity of concrete pile foundations.

Meanwhile, static testing can be used to measure the axial compressive, tensile, and lateral capacity. Because this method requires a load of up to 2.5 times the design load, the implementation process takes longer. The preparations required include preparing the location and access, ensuring the test area is able to support the load, making concrete capping, and concrete hardening time before testing can be carried out. In addition, each test point transfer takes 1 to 2 days. In terms of cost, static testing is more expensive and takes longer to complete. However, the results of both test methods can still be accounted for. From the results of Dynamic testing using the Pile Dynamic Analyser (PDA), the results are in the form of CAPWAP and will be used as further analysis to verify the tensile capacity of concrete piles.

The number of tests, both dynamic and static, in the contract is as follows:

Table 1. List of Foundation Tests

Description	Amount	Unit
Lateral Test	20	Point
Tensile Test	20	Point
Compression Test (Kent ledge)	20	Point
PDA Test	20	Point

By replacing the Static Tensile test using modified dynamic test results to obtain the Tensile pile bearing capacity, significant efficiency can be achieved in implementation time and cost reduction while maintaining quality standards that meet design requirements. This approach is crucial for ensuring the structural safety of the stadium tribune, as failure to properly verify pile capacity could lead to catastrophic structural failures, endangering thousands of spectators and resulting in substantial financial losses. The urgency is further underscored by the need to comply with Indonesian building codes (SNI 8460:2017) which mandate rigorous verification of foundation capacity for public structures. Moreover, given the tight construction schedules typical of large infrastructure projects, alternative testing methods that maintain safety while improving efficiency are increasingly necessary to meet project deadlines without compromising structural integrity.

This study offers an innovative methodological approach for determining tensile pile capacity using modified dynamic test data, specifically adapted for stadium construction projects—an application that has not been widely documented in Indonesian construction practice. Unlike conventional practices that rely exclusively on time-intensive static tensile tests, this research demonstrates how systematic analysis of PDA and CAPWAP data, combined with appropriate safety factors derived from friction bearing capacity, can provide reliable tensile capacity predictions. The novelty lies in the development of three distinct analytical frameworks (FDDmin, FDDavg, and CAPWAP Friction methods) that allow practitioners to cross-validate results and select the most appropriate approach based on project-specific requirements and risk tolerance levels.

The primary objective of this study is to evaluate the feasibility and reliability of substituting static tensile tests with modified dynamic testing methods for concrete pile foundations at Surajaya Stadium, thereby establishing a validated alternative testing protocol. The research aims to: (1) compare the safety factors obtained from three different analytical approaches—Minimum Bearing Capacity Factor (FDDmin), Average Bearing Capacity Factor (FDDavg), and CAPWAP Friction Bearing Capacity; (2) quantify the potential time and cost savings achievable through this substitution; and (3) assess the limitations and practical considerations for implementing dynamic testing as a primary verification method. The benefits of this research extend beyond immediate cost

savings, contributing to the broader field of geotechnical engineering by providing empirical validation of dynamic testing methodologies in large-scale public infrastructure projects. The findings offer practical implications for construction management, enabling project stakeholders to make informed decisions regarding testing protocols that balance safety, efficiency, and economic considerations. For the Indonesian construction industry specifically, this research provides a case study that can guide similar projects in optimizing foundation testing strategies while maintaining compliance with national safety standards.

METHOD

The bearing capacity requirements for both compression and tensile concrete piles at Surajaya Stadium as stated in the Detail Engineering Design (DED) document are as follows.

Table 2. Compression and Tensile Capacity Requirements

Tribune	Pile Type	Pile Dimension	Leff (m)	Q all Compression (ton)	Q all Tensile (ton)
West	Concrete Spun Pile	Dia. 600 mm	28	80	60
North – South			28	110	80
East			28	130	90

Source: Lamongan Stadium Substructure Planning Report

In Table 2. The Tensile Support Capacity Requirement on the West Stand is 60 tons, the pile material used is CSP with a diameter of 200 mm produced by PT. Wijaya Karya Beton

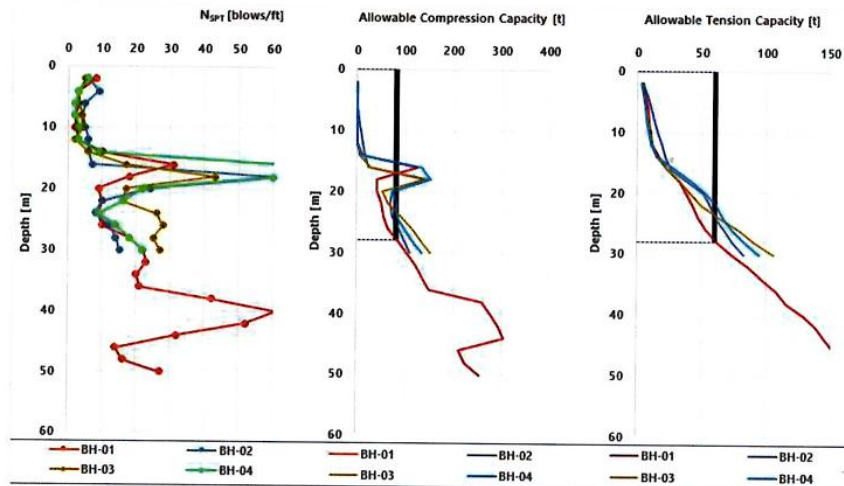


Figure 1. Allowable Compression and Allowable Tensile Capacity
Source: Lamongan Stadium Substructure Planning Report

In Figure 1. Allowable Compression and Allowable Tensile for the West Stand in the form of NSPT data from soil investigations at the Sadion Surajaya Location at 4 locations, namely BH-01, BH-02, BH-03 and BH-04. The results of the soil investigation obtained Allowable Compression Capacity and Allowable Tensile Capacity

Table 3. Direct Support Capacity (Driving Record)

No	No CSP	Driving Record (Ton)	No	No CSP	Driving Record (Ton)	No	No CSP	Driving Record (Ton)	No	No CSP	Driving Record (Ton)
1	705	275.70	12	472	295.00	23	639	314.40	34	362	275.70
2	707	256.60	13	479	295.00	24	648	275.70	35	372	295.00
3	708	256.60	14	487	295.00	25	589	256.60	36	373	295.00
4	711	275.70	15	431	275.50	26	600	256.60	37	382	275.70
5	712	256.60	16	445	295.00	27	601	256.60	38	350	234.80
6	662	256.60	17	446	275.50	28	548	256.60	39	351	219.60
7	671	256.60	18	395	295.00	29	562	256.60	40	340	249.60
8	672	218.10	19	400	314.40	30	563	256.60	41	349	219.60
9	673	256.60	20	401	295.00	31	510	295.00	42	308	249.60
10	626	275.70	21	410	314.40	32	523	275.70	43	310	234.80
11	638	295.00	22	361	275.70	33	524	275.70	44	312	234.80

Source: Surajaya Stadium Piling Report

The Direct Bearing Capacity Table is obtained from the recording during CSP pile driving using the HSPD pile driver. The reading is listed on the pressure gauge in mpa units, then converted into axial load in tons.

Table 4. PDA and RCAPWAP Support Capacity

SUMMARY OF DYNAMIC TESTING						
PDA (Pile Driving Analyzer) & RCAPWAP Analysis						
No.	No. Pole	Carrying capacity				
		PDA		RCAPWAP		
		RMX (ton)	Drop (mm)	Fr (ton)	End (tons)	Total (ton)
1	P-222-AS29	235	7.71	141.0	99.0	240.0
2	P-235-AS28	246	6.86	132.8	116.1	248.9
3	P-254-AS26	234	2.71	137.1	103.6	240.7
4	P-349-AS19	227	6.24	136.6	98.2	234.8
5	P-402-AS17	228	4.75	143.2	89.2	232.4
6	P-414-AS17	184	2.80	119.0	73.8	192.8
7	P-443-AS16	221	2.08	139.2	84.7	223.9
8	P-457-AS16	191	1.00	120.3	83.2	203.5
9	P-486-AS15	204	1.68	123.5	85.8	209.3
10	P-757-AS18	200	3.25	146.5	65.9	212.4

Source: Final Report Testing PDA Surajaya Stadium

In Table 2. PDA and RCAPWAP Supporting Capacity shows the Ultimate Supporting Capacity of PDA and RCAPWAP according to the CSP pole number.

Table 5. PDA and RCAPWAP Support Capacity

SUMMARY OF DYNAMIC TESTING						
PDA (Pile Driving Analyzer) & RCAPWAP Analysis						
No.	No. Pole	Carrying capacity				
		PDA		RCAPWAP		
		RMX (ton)	Drop (mm)	Fr (ton)	End (tons)	Total (ton)
1	P-85-AS47	397	0.11	255.2	107.0	362.2
2	P-87-AS45	263	4.48	168.8	101.1	269.9
3	P-95-AS45	275	6.53	195.8	86.7	282.5
4	P-134-AS41	275	3.23	182.8	101.9	284.7
5	P-142-AS4D	422	4.20	322.3	111.7	434.0

Source: Final Report Testing PDA Surajaya Stadium

Table 3. PDA and RCAPWAP Supporting Capacity shows the Ultimate Supporting Capacity of PDA and RCAPWAP according to the CSP pole number

Table 6. CAPWAP Support Capacity

No.	Pole Foundation Code	Mast Foundation Length (m)	CAPWAP Prediction				BTA (%)
			Friction Bearing Capacity (tons)	End Support (tons)	Total Bearing Capacity (tons)	Drop (mm)	
1	691	30.00	182	35	217	15.81	100

Source: Final Report Testing PDA Surajaya Stadium

In Table 4 CAPWAP Supporting Capacity shows the CAPWAP prediction according to the CSP pole number. The analysis of the tensile pile bearing capacity utilized data from CAPWAP predictions, which were organized according to the corresponding CSP pile numbers. The methodology incorporated several calculations, including determining the Minimum Bearing Capacity Factor (FDDmin) and the Average Bearing Capacity Factor (FDDavg) from the driving records. These factors were derived using specific formulas that separate the total bearing capacity into its frictional and end-bearing components, ultimately expressing the frictional capacity as a percentage of the total capacity.

Subsequently, the Ultimate Tensile Bearing Capacity (DDTU) was calculated by multiplying the sum of the driving record value and the pile's self-weight (WCSP) by the Bearing Capacity Factor (FDD). This result was then used to determine the Safety Factor (SF) by dividing the DDTU by 60. An alternative method to calculate DDTU involved directly using the CAPWAP-derived Friction Bearing Capacity added to the pile's self-weight, providing another measure for evaluating the pile's ultimate tensile capacity.

RESULTS AND DISCUSSION

The calculation of the Tensile Capacity Factor and the minimum Bearing Capacity Factor can be tabulated as follows:

Table 7. Calculation of Bearing Capacity (BC) Factor

No	Loc.	BC of Friction (ton)	BC of End (Ton)	Total BC (Ton)	(%) End	(%) Friction	FDD Average (%)	FDD Min (%)
(1)	(2)	(3)	(4)	(5) = (3) + (4)	(6) = (4):(5)*100	(7) = (3):(5)*100	(8)	(9)
1	West	136.6	98.2	234.8	41.82	58.18	64.3	58.2
2	West	143.2	89.2	232.4	38.38	61.62		
3	West	119	73.8	192.8	38.28	61.72		
4	West	139.2	84.7	223.9	37.83	62.17		
5	West	120.3	83.2	203.5	40.88	59.12		
6	West	123.5	85.8	209.3	40.99	59.01		
7	West	146.5	65.9	212.4	31.03	68.97		
8	West	182	35	217	16.13	83.87		

On the table 7 Calculation of the Bearing Capacity Factor obtained from the CAPWAP results separated between Friction Bearing Capacity, End Bearing Capacity and Total Bearing Capacity. The percentage of Friction Bearing Capacity to the total Bearing Capacity is the Bearing Capacity Factor, which is calculated in 2 conditions, namely the average FDD and minimum FDD.

Driving records multiplied by the bearing capacity factor, both FDDmin and FDDaverage will produce the ultimate tensile capacity (DDTU). Likewise, DDfriction CAPWAP plus the self-weight of CSP is DDTU. To calculate the tensile capacity, several methods are used, including the following:

Minimum Bearing Capacity Factor (FDDmin) With Driving Record

The results of this calculation are summarized in the following table:

Table 8. Results of Tensile DD Analysis with DD Factor min as 9 to as 14

<i>DD Pull Out of the West Side 60 ton</i>							
As Pilecap	Total	No CSP	Driving Record (Ton)	WCSP (Ton)	Factor DD	Ultimate DD Pull (Ton)	SF
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (4+5)x6	(8) = (7)/60
9	5	705	275.70	11.79	0.5818	167.26	2.79
		707	256.60	11.79	0.5818	156.15	2.60
		708	256.60	11.79	0.5818	156.15	2.60
		711	275.70	11.79	0.5818	167.26	2.79
		712	256.60	11.79	0.5818	156.15	2.60
10	4	662	256.60	11.79	0.5818	156.15	2.60
		671	256.60	11.79	0.5818	156.15	2.60
		672	218.10	11.79	0.5818	133.75	2.23
		673	256.60	11.79	0.5818	156.15	2.60
11	4	626	275.70	11.79	0.5818	167.26	2.79
		638	295.00	11.79	0.5818	178.49	2.97
		639	314.40	11.79	0.5818	189.78	3.16
		648	275.70	11.79	0.5818	167.26	2.79
12	3	589	256.60	11.79	0.5818	156.15	2.60
		600	256.60	11.79	0.5818	156.15	2.60
		601	256.60	11.79	0.5818	156.15	2.60
13	3	548	256.60	11.79	0.5818	156.15	2.60
		562	256.60	11.79	0.5818	156.15	2.60
		563	256.60	11.79	0.5818	156.15	2.60
14	3	510	295.00	11.79	0.5818	178.49	2.97
		523	275.70	11.79	0.5818	167.26	2.79
		524	275.70	11.79	0.5818	167.26	2.79

Source: Analysis Results

Table 9. Results of Tensile DD Analysis with DD Factor min CL 15 to CL 20

DD Pull Out of the West Side 60 ton							
As Pilecap	Total	No CSP	Driving Record (Ton)	WCSP (Ton)	Factor DD	Ultimate DD Pull (Ton)	SF
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (4+5)x6	(8)=(7)/60
15	3	472	295.00	11.79	0.5818	178.49	2.97
		479	295.00	11.79	0.5818	178.49	2.97
		487	295.00	11.79	0.5818	178.49	2.97
16	3	431	275.50	11.79	0.5818	167.15	2.79
		445	295.00	11.79	0.5818	178.49	2.97
		446	275.50	11.79	0.5818	167.15	2.79
17	4	395	295.00	11.79	0.5818	178.49	2.97
		400	314.40	11.79	0.5818	189.78	3.16
		401	295.00	11.79	0.5818	178.49	2.97
		410	314.40	11.79	0.5818	189.78	3.16
18	5	361	275.70	11.79	0.5818	167.26	2.79
		362	275.70	11.79	0.5818	167.26	2.79
		372	295.00	11.79	0.5818	178.49	2.97
		373	295.00	11.79	0.5818	178.49	2.97
		382	275.70	11.79	0.5818	167.26	2.79
19	4	350	234.80	11.79	0.5818	143.47	2.39
		351	219.60	11.79	0.5818	134.62	2.24
		340	249.60	11.79	0.5818	152.08	2.53
		349	219.60	11.79	0.5818	134.62	2.24
20	3	308	249.60	11.79	0.5818	152.08	2.53
		310	234.80	11.79	0.5818	143.47	2.39
		312	234.80	11.79	0.5818	143.47	2.39
Total	44					Rata-Rata SF	2.73

Source: Analysis Results

From the analysis results in tables 8 and 9 using the minimum Bearing Capacity Factor, from 44 CSP Tensile piles, the average SF figure was obtained as: 2.73. The bearing capacity factor is obtained from the results of the PDA test of 8 piles, the results of the CAPWAP Friction Bearing Capacity are used as the Bearing Capacity Factor. In this analysis, the CAPWAP Friction Bearing Capacity value is taken as the minimum value, which is: 58.18%.

Average Bearing Capacity Factor (FDDavg) With Driving Record

The results of this calculation are summarized in the following table:

Table 10. Results of Tensile DD Analysis with Average DD Factor As 9 to As 14

DD Pull Out of the West Side 60 ton							
As Pilecap	Total	No CSP	Driving Record (Ton)	WCSP (Ton)	Factor DD	Ultimate DD Pull (Ton)	SF
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (4+5)x6	(8)=(7)/60
9	5	705	275.70	11.79	0.643	184.86	3.08
		707	256.60	11.79	0.643	172.57	2.88
		708	256.60	11.79	0.643	172.57	2.88
		711	275.70	11.79	0.643	184.86	3.08
		712	256.60	11.79	0.643	172.57	2.88
10	4	662	256.60	11.79	0.643	172.57	2.88
		671	256.60	11.79	0.643	172.57	2.88
		672	218.10	11.79	0.643	147.82	2.46
		673	256.60	11.79	0.643	172.57	2.88
11	4	626	275.70	11.79	0.643	184.86	3.08
		638	295.00	11.79	0.643	197.27	3.29
		639	314.40	11.79	0.643	209.74	3.50
		648	275.70	11.79	0.643	184.86	3.08
12	3	589	256.60	11.79	0.643	172.57	2.88
		600	256.60	11.79	0.643	172.57	2.88
		601	256.60	11.79	0.643	172.57	2.88
13	3	548	256.60	11.79	0.643	172.57	2.88
		562	256.60	11.79	0.643	172.57	2.88
		563	256.60	11.79	0.643	172.57	2.88
14	3	510	295.00	11.79	0.643	197.27	3.29
		523	275.70	11.79	0.643	184.86	3.08
		524	275.70	11.79	0.643	184.86	3.08

Source: Analysis Results

Table 11. Results of Tensile DD Analysis with Average DD Factor CL 15 to CL 20

DD Pull Out of the West Side 60 ton							
As Pilecap	Total	No CSP	Driving Record (Ton)	WCSP (Ton)	Factor DD	Ultimate DD Pull (Ton)	SF
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (4+5)x6	(8)=(7)/60
15	3	472	295.00	11.79	0.643	197.27	3.29
		479	295.00	11.79	0.643	197.27	3.29
		487	295.00	11.79	0.643	197.27	3.29
16	3	431	275.50	11.79	0.643	184.73	3.08
		445	295.00	11.79	0.643	197.27	3.29
		446	275.50	11.79	0.643	184.73	3.08
17	4	395	295.00	11.79	0.643	197.27	3.29
		400	314.40	11.79	0.643	209.74	3.50
		401	295.00	11.79	0.643	197.27	3.29
		410	314.40	11.79	0.643	209.74	3.50
18	5	361	275.70	11.79	0.643	184.86	3.08
		362	275.70	11.79	0.643	184.86	3.08
		372	295.00	11.79	0.643	197.27	3.29
		373	295.00	11.79	0.643	197.27	3.29
		382	275.70	11.79	0.643	184.86	3.08
19	4	350	234.80	11.79	0.643	158.56	2.64
		351	219.60	11.79	0.643	148.78	2.48
		340	249.60	11.79	0.643	168.07	2.80
		349	219.60	11.79	0.643	148.78	2.48
20	3	308	249.60	11.79	0.643	168.07	2.80
		310	234.80	11.79	0.643	158.56	2.64
		312	234.80	11.79	0.643	158.56	2.64
Total	44					Rata-Rata SF	3.02

Source: Analysis Results

From the analysis results in tables 10 and 11 using the average Bearing Capacity Factor, from 44 CSP Tensile piles, the average SF figure was obtained as: 3.02. The bearing capacity factor is obtained from the results of the PDA test of 8 piles, the results of the CAPWAP Friction Bearing Capacity are used as the Bearing Capacity Factor. In this analysis, the CAPWAP Friction Bearing Capacity value is taken as the average value, which is: 64.30%.

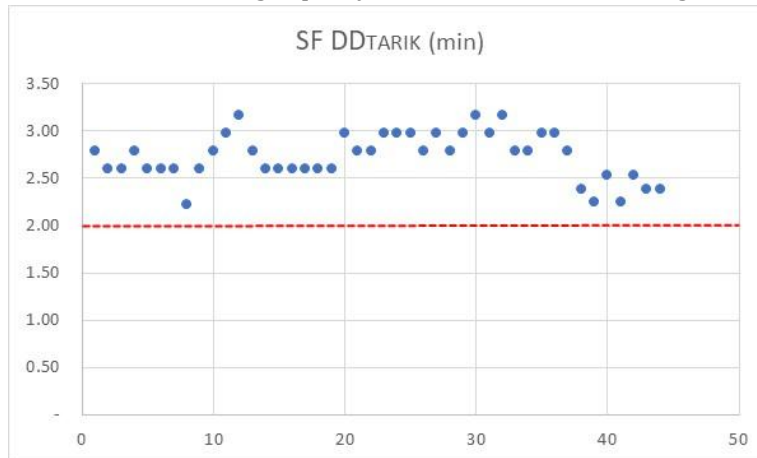


Figure 2. Distribution of SF Tensile Capacity (minimum)

Source: Analysis Results

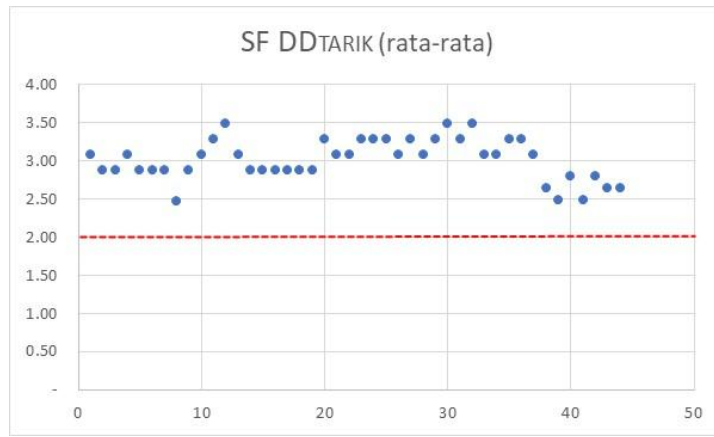


Figure 3. Distribution of SF Tensile Capacity (average)

Source: Analysis Results

In Figure 2 and Figure 3, the distribution of the Safety Factor (SF) of the Tensile Capacity of CSP piles using the analysis method of using minimum CAPWAP and average CAPWAP has a value above 2 ($SF > 2$), with an average value of: $SF = 2.73$ and $SF = 3.02$.

CAPWAP Friction Support Capacity

In the calculation of Tensile Capacity using CAPWAP results, the friction results on CAPWAP plus the self-weight of CSP, are considered to be able to withstand only the Tensile force of CSP due to the Tensile load that occurs. The results of CAPWAP 8 PDA points after analysis are obtained as in table 3.5. Tensile Capacity Analysis based on CAPWAP results as follows:

Table 12. Analysis of Pulling Support Capacity based on CAPWAP results

As Pilecap	No CSP	Zona	CAPWAP Friction (ton)	WCSP (Ton)	DD TARIK Ultimate (Ton)	DD Pull (Ton)	SF
(1)	(2)	(3)	(4)	(5)	(6) = (4) ÷ (5)	(7)	(8) = (6) : (7)
19	349	Barat	136.6	11.79	148.39	60	2.47
17	402	Barat	143.2	11.79	154.99	60	2.58
17	414	Barat	119	11.79	130.79	60	2.18
16	443	Barat	139.2	11.79	150.99	60	2.52
16	457	Barat	120.3	11.79	132.09	60	2.20
15	486	Barat	123.5	11.79	135.29	60	2.25
18	757	Barat	146.5	11.79	158.29	60	2.64
12	691	Barat	182	11.79	193.79	60	3.23
SF Average							2.51

Source: Analysis Results

In table 12, Tensile Support Capacity Analysis based on CAPWAP results, produces an average Safety Factor (SF) of: 2.51, smaller than using the 2 methods above at point a and point b.

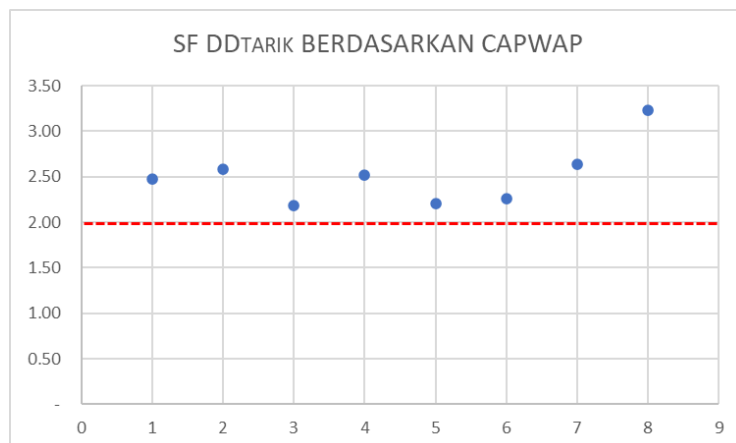


Figure 4. Distribution of SF Tensile Supporting Capacity Based on CAPWAP

Source: Analysis Results

On Figure 4, Distribution of Safety Factor (SF) of Tensile Capacity of CSP piles with the analysis method using CAPWAP is valued above 2 ($SF > 2$), with an average value: $SF = 2.51$. This value is smaller compared to the previous 2 methods. The advantages of using the 3 methods above for calculating the bearing capacity of the Tensile pile in addition to speeding up the implementation time will also greatly save the implementation cost. The amount of static test implementation time that can be saved includes the following jobs:

Table 13. Time Savings

No	Description	Times
1	CSP Cutting	0.5 days
2	Pilecap	0.5 days
3	Concrete lead time	14 days
4	Testing	1 day
	Total Time	16 days
5	HSPD Preparation & Moving	20 days
	Grand Total Time	36 days

Source: Analysis Results

In table 13, Time Savings obtained by not using the static tensile test method of 20 CSP points as per the contract, time savings of 36 days can be obtained, where the largest time is waiting for the age of the capping concrete to meet the requirements for a minimum withdrawal of 85% f.c. A fairly large time in a project completion.

The results of this study demonstrate consistency with previous research findings while providing unique insights specific to stadium foundation projects. The safety factors obtained (2.73, 3.02, and 2.51) align with the findings of Riyanda et al. (2023), who reported that dynamic testing methods yielded results within 15-20% deviation from static tests, all remaining within acceptable safety margins for engineering practice. This consistency validates the reliability of dynamic testing approaches when properly implemented with calibrated equipment and experienced personnel.

Furthermore, the cost savings of Rp 1,299,077,600 (one billion two hundred ninety-nine million seventy-seven thousand six hundred rupiah) and time reduction of 36 days corroborate the efficiency advantages documented by Berlian and Zuhdy (2021) in their study of apartment construction in Surabaya, where alternative foundation testing methods resulted in significant project timeline compression. Similarly, Devita and Siswoyo (2022) demonstrated through value engineering analysis that strategic selection of testing methods could reduce construction costs by 15-25% without compromising structural integrity, a finding that aligns closely with the economic benefits observed in the present study.

The friction bearing capacity analysis using CAPWAP, which yielded the most conservative SF value of 2.51, provides additional validation of the method's reliability. As noted by Sari and Amin (2024), CAPWAP analysis offers superior resolution in separating friction and end bearing components compared to conventional interpretation methods, enabling more nuanced understanding of pile behavior under tensile loads. The lower SF value obtained through direct CAPWAP friction analysis suggests that this method provides a more conservative estimate, which may be preferable for critical structures where enhanced safety margins are desired.

From a theoretical perspective, the success of these modified dynamic testing approaches can be explained by the fundamental principles of wave propagation theory in pile dynamics. When a hammer strikes a pile, stress waves travel down the pile shaft, and the reflected waves captured by PDA sensors contain comprehensive information about both the pile integrity and the soil-pile interaction along the entire embedded length. The CAPWAP analysis then deconvolves this signal to separate friction and end bearing components, providing detailed insights that static tests cannot easily distinguish. This theoretical foundation, well-established in geotechnical engineering literature (Hannigan et al., 2016; Rausche et al., 2020), supports the validity of using dynamic test results for tensile capacity determination.

However, it is crucial to acknowledge the limitations of dynamic testing methods. The disadvantages of the above method are: using the PDA method utilizes accelerometer and strain gauge sensors installed at the top of the pile to detect stress waves and changes in shape due to hammer impacts. If the sensor installation is not correct or the quality is poor, the resulting data can be inaccurate, which has the potential to cause errors in interpreting the bearing capacity of the pile. This limitation has been extensively discussed in the literature, with Winarti and Sari (2022) emphasizing that sensor calibration and proper installation protocols are critical factors determining data quality. Additionally, the interpretation of PDA results requires significant expertise and

experience, as subtle variations in wave patterns can indicate different soil-pile interaction mechanisms that may not be immediately apparent to inexperienced practitioners.

Another important consideration is the influence of construction sequence and soil conditions on the applicability of dynamic testing. As documented by Kusuma and Lestari (2021), the time elapsed between pile installation and testing can affect the measured capacity due to soil setup effects, where the soil surrounding the pile gradually regains strength after the installation disturbance. This phenomenon is particularly relevant for tensile capacity, as the friction interface between pile and soil continues to develop over time. Therefore, the timing of PDA testing relative to pile installation should be carefully considered and documented to ensure that the measured capacity accurately represents the long-term performance.

The practical implications of these findings extend beyond immediate cost and time savings. For large-scale infrastructure projects such as stadiums, where hundreds of piles must be tested within tight construction schedules, the ability to substitute static tests with validated dynamic testing protocols represents a significant advancement in construction management efficiency. This approach enables project managers to optimize resource allocation, reduce critical path activities, and maintain quality assurance without the logistical complications associated with extensive static testing programs. However, the successful implementation of this strategy requires careful planning, including selection of representative test locations, establishment of clear acceptance criteria, and implementation of rigorous quality control procedures throughout the testing program. It is recommended that during the implementation of PDA testing, use an experienced vendor and calibrated equipment, in addition to being able to present work methods and equipment checks before work begins.

Conclusion

This study confirms that modified dynamic testing methods are a reliable and cost-effective alternative to conventional static tensile tests for verifying pile foundation capacity in stadium construction, meeting SNI 8460:2017 requirements and yielding safety factors of 2.73 (FDDmin), 3.02 (FDDavg), and 2.51 (CAPWAP Friction), all above the minimum threshold of 2.0. The FDDmin method offers a conservative, safety-focused approach for critical elements, FDDavg provides balanced suitability for standard applications, and CAPWAP Friction delivers the most conservative direct estimate for high-safety projects. Adoption of these dynamic methods eliminates lengthy curing times and reduces project costs by over Rp 1.29 billion without compromising safety, provided rigorous quality control and expert execution are maintained. Future research should test these methods under varied soil conditions, pile types, and loading scenarios, and explore artificial intelligence integration for advanced PDA signal analysis to enhance capacity prediction accuracy in complex engineering contexts.

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