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COMPARISON OF STATIC AND DYNAMIC LOAD TESTING: A REVIEW

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ABSTRACT: Engineers have used deep pile foundations to support heavy loads from multi-story structures. For engineers to compare the actual pile capacities from their designs, deep foundation testing has made it possible to determine the actual pile foundation capacity and its behavior with soil. Static and dynamic load testing are the primary load tests to determine pile capacities. Numerous authors have proven connections between static and dynamic load tests on piles since the 1980s. However, comparing both testing results, we see that both have different capacities and correlation criteria. Fifty-one (51) piles tested with static and dynamic load testing from previous research are used. The comparison of DLT and SLT results provided the outcome of an average DLT/SLT ratio of 0.9833. The literature review reveals good agreement between the two test results when compared. The literature review recommends comparing SLT capacities to the DLT's field capacities and those obtained using CAPWAP analysis. Moreover, instrumented SLT can also be compared to those from DLT, allowing for the utilization of skin resistance from both tests as an additional criterion for comparison.

Keywords: Static load testing, Dynamic load Testing, CAPWAP analysis, Deep foundation testing

1. INTRODUCTION

Piling foundations are currently among the most common solutions in densely populated urban areas [1]. Since the necessity for controlling settlements and supporting heavy loads increases, deep foundations are widely used in construction [2]. Engineers have various options when building a foundation system, including the maximum load per pile and pile size (type, length, and diameter). The foundation will move unacceptably or perhaps fail if the ultimate pile capacity is not sufficient to exceed the applied loads [3]. As a result of the rise in foundation service loads, geotechnical engineers and designers are following a global trend to measure the actual behavior of pile-soil interaction [4]. It is almost impossible to predict the soil's actual behavior using theoretical and iterative methods since it behaves significantly differently under loads applied over time. A more complicated phenomenon appears when the loads are transferred to the ground using a foundation. Interest in foundation behavior has grown since foundations were used to support ever-larger superstructures [5].

Accurately estimating pile-bearing capacity has always been a top priority for geotechnical engineers. Static design equations, in situ test methods, static load tests, and dynamic load tests may be used to estimate the axial bearing capacity of single piles when designing pile foundations. Currently, estimates by set and rebound (dynamic formulae), static load testing (SLT), and dynamic load tests (DLT) are used to verify this capacity for quality control and performance [6]. Meanwhile, the required pile capacity depends on the test method for verifying the pile capacity and the testing frequency [3].

Three tests can be performed: the vertical load test (compression), the lateral load test, and the pull-out test (tension). A vertical load test is typically conducted to evaluate the allowed load on a pile and establish the load-settlement relationship under compression. Initial testing and routine testing are the two sorts of tests that are typically performed on piles [7].

Dynamic and static load tests are the main load tests that estimate pile capacities [8-9]. Because typically only one procedure is employed per site, comparing the findings of various tests is frequently impossible. The Static Load Test (SLT), whether in compression or tension, is the primary test that may correctly forecast pile capacity and pile reaction for both driven and bored piles. However, a single SLT requires a costly, time-consuming, and sophisticated setup, and SLTs are rarely carried out. SLTs may typically only be economically justified on large-scale projects, and even then, the geotechnical conditions may be so variable that more than a few tests may be needed to fully understand the behavior of the pile over the project site [9-10].

On the other hand, due to its simplicity and solid theoretical foundation, DLT presents as a reasonable alternative to handle most of the challenges raised above (including pile capacity determination) [10]. The dynamic load (PDA) test has become the standard testing procedure for assessing pile capacity and integrity for driven and cast-in-situ piles.

Generally, there is a good agreement between the derived pile capacity and the static load-carrying capacity. The cost of the test is far lower than the cost of a typical static load test, and the test's brief duration is one of its most alluring benefits. Dynamic load testing delivers significant time, cost, and space savings over static pile loading tests [11].

Numerous authors have proven connections between static and dynamic load tests on piles since the 1980s; nevertheless, adequate load test execution is required for a satisfactory correlation. Signal matching can further analyze dynamic data to determine the distribution of soil resistance, toe resistance, quakes, and damping. The best feasible match between a computed pile top variable, such as the pile top force, and its measured equivalent serves as the basis for results [6,11-12]. However, these comparisons are based on the actual practice of completing just one CAPWAP analysis for each dynamic test run. When conducting CAPWAP analysis for all blows of the same test, confirming a better fit between the tests when comparing the DLT and the SLT (and not just one) is possible. This method accurately calculates the rupture load of the foundation element using the SLT or DLT [6].

Although numerous researchers proved a satisfactory correlation, it is still noted that different capacities and correlation criteria were used in comparing both testing results. Therefore, the authors gathered different studies to review the existing comparison of both tests as a reference and guide for future studies involving SLT and DLT.

2. RESEARCH SIGNIFICANCE

Deep foundations are crucial to the long-term performance of a structure because they sustain the entire structural system. Geotechnical engineers use deep foundation testing to determine actual pile foundation capacity and soil behavior. Static and dynamic testing methods were employed to define and validate each deep foundation's geotechnical capabilities. Furthermore, the larger the load the foundation supports, the more critical deep foundation tests such as SLT and DLT are. As a result, geotechnical engineers need to examine the existing comparison of static and dynamic load testing to determine actual foundation capability.

3. METHODOLOGY

This section provides a systematic overview of the related research in explaining, evaluating, and gathering data on the subject [13]. A keyword-based resource, such as Scopus (https://www.scopus.com), was used for the advanced search to gather relevant studies regarding the sources of the authors' interest and give a comprehensive list of literature. The authors select Scopus as the research database because it contains the most comprehensive citations researchers use [14]. The keywords "TOPIC" with the Boolean operators "AND" and "OR" were used by the authors to initiate the literature search. If the title of the articles appeared to be related to the literature review topic, the authors started gathering valuable data, such as the author, year, title, and abstract, which are for further analysis.

The objective was to identify existing research that discusses the following topics:
Topic 1: Discussion of static load testing and its testing methodology
Topic 2: Discussion of dynamic load testing and its testing methodology
Topic 3: CAPWAP analysis as a means of evaluating dynamic load testing capacities
Topic 4: Comparison of Static and Dynamic Load Testing result

The database search terms "STATIC PILE LOAD TEST," "DYNAMIC PILE LOAD TEST," and "COMPARISON" or "CORRELATION" are shown in Fig. 1 and produce 169 articles. The screening stage excluded 10 articles not written in English and 25 papers published before 2000. As a result, 134 potential articles were found. Papers unrelated to the research question (n = 84) and those uploaded without author information (n = 14) were also eliminated after the screening stage. Thirty-six (36) documents were chosen to be included in the literature review. Additionally, both standard test procedures for static and dynamic load testing issues by the American Society for Testing and Materials (ASTM) are included in the literature review.

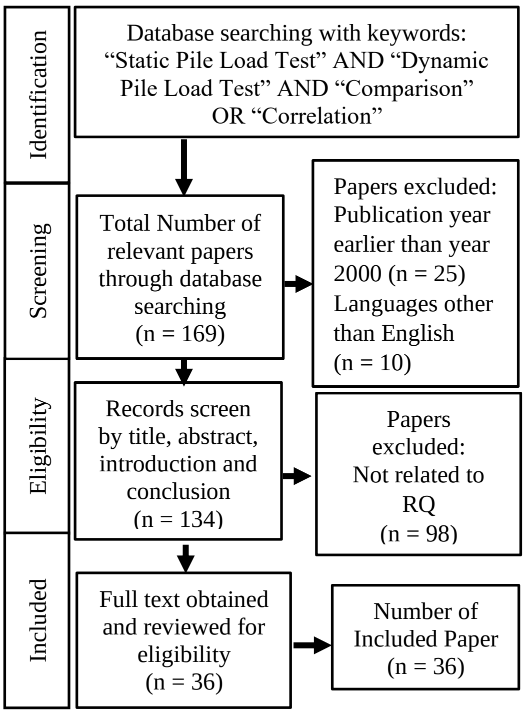

Fig.1 Flow Diagram of Systematic Review

4. DISCUSSION

4.1 Static Load Testing and Its Methodology

Many authors believe that static pile load testing is the sole method for testing piles and the best indicator of long-term pile performance, ultimate bearing capacity, settlement characteristics at working load (and beyond), and structural integrity [1,15]. The ability of the deep foundation to support structural loads at acceptable settlements would be best understood if all the foundation's piles were put through this test and if the test was carried out appropriately, that is, at the appropriate time, with accurate instruments and sufficient loading equipment [16].

Before 1970, piles were tested for large projects using an ASTM D1143 Standard for Static Load Test, which specified that the slowly applied load maintained over days was twice the design load. Per the site, only one static test was typically run, and these so-called "proof tests" seldom ever failed. Thus, even though the pile did not fail, the usual safety factor 2.0 was established due to the loading being only twice the design load. Standard failure load estimates were based on either a net movement limit after the load was removed (usually 0.25 to 0.75 inches) or some pile top movement limit (commonly 0.75 to 1.5 inches). The quick procedure static test method described in ASTM D1143 is increasingly popular due to the recent emphasis of the FHWA (1997). Its evaluation for failure or ultimate load uses the offset yield line method, which is typically among the most conservative failure definitions, and the loads are frequently carried to failure or to at least three times the design load in a test that lasts only a few hours. Foundation expenses can often be decreased when the ultimate failure load rather than just a proof load can be identified [3,17].

The kentledge or weighted box system was first used for static load tests – later, it became a reaction frame system. A hydraulic jack resting on the Kentledge girder or provision of reference beams is used to apply the load to evaluate pile load carrying capacity in compression. Under the appropriate weights, compression, uplift, and lateral static load tests can be performed to determine pile displacement (axial compression, tension, or lateral loads). The static system uses a load cell to measure the applied loads. According to the test standard, the load is applied to the pile in a succession of safe vertical downward incremental loadings. Dial gauges that are each evenly spaced around the piles and often held by datum bars on immovable supports are used to measure settlement on top of the pile. Meanwhile, dial gauges were replaced by wire vibration strain-reinforced bars in the interim due to several inaccuracies during testing [11,17-19]. Fig. 2 and 3 show the typical schematic diagram of the SLT using the Kentledge and reaction frame systems.

If only one or a few carefully chosen test piles are used, static load testing is cost- and time-effective. However, additional quality assurance and control methods are necessary due to the diversity of the site's geotechnical characteristics, potential structural damage problems with specific piles, unpredictable equipment behavior during installation, and other challenges. Such measures include comprehensive construction monitoring and supplementary dynamic loading tests [16]. Due to time and money restrictions, it is not feasible to statically test every pile; hence, such testing is generally restricted to a tiny sample of piles on any site (about 1% or less for significant

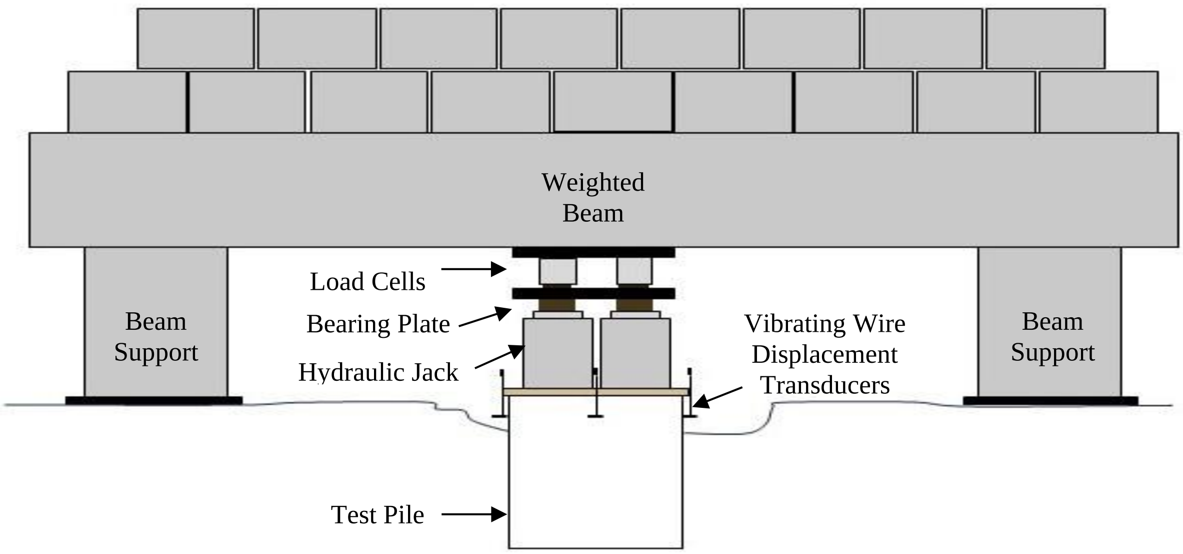

Fig. 2 Typical Schematic Diagram of SLT using Kentledge or Weighted Box System

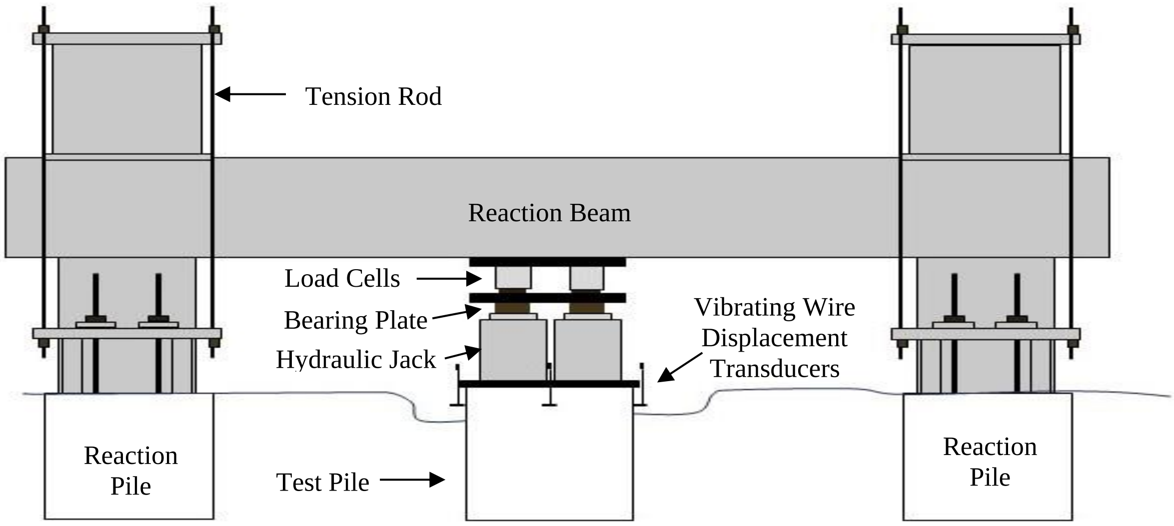

Fig. 3 Typical Schematic Diagram of SLT using Reaction Frame System

projects or only one per site, if any, for small projects).

Numerous factors can impact the accuracy of static testing. The measuring accuracy should be within 20% of the actual value when static testing is done correctly. If a recently calibrated load cell is specified, the accuracy of the results is increased.

However, depending on the evaluation method (such as Davisson, Chin, Butler-Hoy, double tangent, slope, D/10, etc.), interpretation of the resulting load-settlement graph might result in numerous distinct ultimate loads [3]. Designers are looking for an alternate approach for pile testing due to increasing time and cost, notably, the challenges of transporting static load testing accessories into crowded city centers and the need for more space on many sites. The trend is for contractors to mainly use dynamic approaches in addition to standard static tests [19].

4.2 Dynamic Load Testing and Its Methodology

Due to the possibility of considerable changes in the surrounding soil conditions during construction or installation, it is crucial to determine the pile capacity via a load test [20]. Weap analysis, PDA measurements, and CAPWAP analysis of measured data are generally referred to as "dynamic testing and analysis" in the abbreviated version. Dynamic testing and analysis have grown into an essential tool for the foundation engineer responsible for dealing with designing piles, pile installation, and pile foundations, as well as verifying a design and resolving issues that arise during construction since it has become available to the industry in the early 1970s [21]. Dr. G.G. Goble and his associates at Case Western Reserve University in Cleveland, Ohio, invented dynamic testing, a common technique for assessing pile capacity. To determine the behavior of the soil during dynamic testing, it is necessary to measure the pile force and velocity during hammer contact [3]. Dynamic load testing (DLT) is increasingly popular worldwide for testing cast-in-situ piles to determine their integrity and capacity in compression.
[19]. According to ASTM D4945, a Dynamic Load Test (DLT) or High Strain Dynamic Testing (HSDT) is carried out to assess the mobilized load at the pile-soil system [8,20,22-24].

Currently, most projects use the dynamic load test (DLT) on piles to assess the piles' structural integrity and static capacity using force and velocity measurements. The dynamic test determines the force and velocity induced in a pile during an axial impact event based on readings from strain or force, acceleration, velocity, or displacement transducers. The pile is pushed relative to the surrounding soil by the stress wave produced by the impact and travels down the pile. The dynamic load test involves striking the pile repeatedly while using force transducers and high-sensitivity accelerometers to measure deformation and acceleration values over time. To estimate soil resistance and distribution, the DLT measures force and velocity close to the top of a foundation struck by a hammer or drop weight. The total pile resistance (dynamic + static) can be calculated using force and velocity readings from strain gauges and accelerometers mounted to the pile. These sensors are linked to a device that stores, analyses, and presents data and outcomes, such as a pile driving analyzer. The most often used tool for gathering pile data is the Pile Driving Analyzer (PDA), which is manufactured by Pile Dynamics, Inc. Between 1.5 and 2.0 Diameters from the pile top, at least two transducers and one accelerometer are mounted [8,18,20,22,25-32]. Fig. 4 shows the typical schematic diagram of dynamic load testing.

Dynamic pile testing must be done after the concrete has sufficiently strengthened so a long enough wait is naturally achieved to allow the soil strength to recover from the installation process. The instrumentation and alignment are typically checked with a small initial impact. Then, blows with increasing drop height are applied until, whichever comes first: the stresses meet the pile's strength limits; the set per blow exceeds around 3 mm, activating the entire capacity; or the result reveals a capacity sufficiently more significant than the project requirements. For shafts built in clay soils or into rock, the advised drop weight is at least 1% of the needed ultimate capacity to be proven. The suggested proportion rises to at least 2% of the load to be tested for piles with more excellent estimated end-bearing contributions [3].

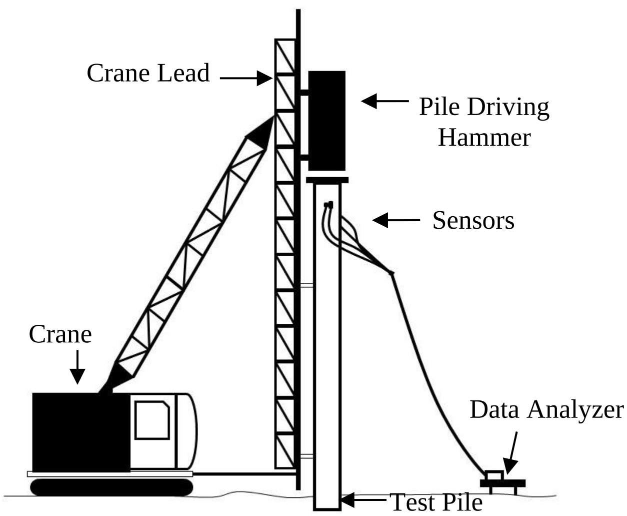

Fig. 4 Typical Schematic Diagram for DLT

In DLT, the dynamic impact is applied, signals are recorded, and after post-processing, the pile's static capacity, skin frictional resistance, and tip resistance are determined. DLT also provides information about pile driveability, pile integrity, and changes in cross-section, in addition to assessing the pile's static capacity (if any). DLT can test at least two bored and more driven piles in a single day, making it substantially faster and more cost-effective than static testing [20].

The engineer may interpret the gathered data using engineering principles and judgment to assess the pile's integrity, the impact mechanism's effectiveness, and the maximum compressive and tensile stresses present. Evaluations of the hammer system performance, pile driving compression and tension stresses, pile structural integrity, soil resistance distribution, and pile static load carrying capacity are made possible by real-time data processing of test findings. The measured data are evaluated with the CAPWAP software, which uses modern signal-matching techniques to assess the impacts of soil resistance. The CAPWAP results also contain soil quake and damping values in friction and end bearing and a simulated pile static test load-movement graph. Static resistance forces along the pile shaft (also known as skin friction) and at the pile toe (also known as end bearing) is an efficient method for determining the impacts of high rebound on the performance of the hammer, pile, and soil during pile installation is dynamic pile testing and accompanying data analysis. Dynamic pile testing during restrike provides long-term static pile load-bearing capacity and load-movement characteristics incorporating time-dependent geotechnical impacts [25-26,28,33].

4.3 CAPWAP Analysis as a Means of Evaluating Dynamic Load Test Capacities

The wave equation analysis offers a more reasonable method for estimating pile load-carrying capacity. A plot of measured force vs. measured displacement does not resemble the static load-settlement curve due to stress wave effects brought on by the quick loading of the pile. By eliminating the dynamic impacts of the pile and soil, the dynamic force must be converted to a static force to calculate the static load-settlement curve [23].

The CASE method was used to analyze the pile load-carrying capacity. Later, the static pile capacity was calculated using the recorded data and the computer software called CAPWAP. The correct CASE damping factor for the piles at the location was eventually determined by matching the PDA signals with CAPWAP analysis. The CAPWAP software, as defined by Goble, is typically used to analyze the force and velocity information received in dynamic loading testing. [9,11,18,34-36].

A modeled load-displacement curve produced by CAPWAP signal-matching analyses is equivalent to the static load test results as shown in Fig. 5. Dynamic load testing uses the standard approach, which involves applying hammer drops from lower to higher heights until a total displacement of D/60 is reached. More significant displacements allow for a higher end-bearing activation when the pile is tipped in a sand layer; hence, larger cumulative sets may be desirable depending on the geotechnical conditions at the pile toe. The software analyzes wave equations using the velocity records as pile-top boundary conditions. The side friction and end-bearing distribution (Fig. 6) may be estimated and predicted by resolving equations using the side and toe quakes, side and toe damping, and shaft and toe resistance as the unknowns [33,37]. CAPWAP enables the calculation of tensions and movements (elastic modulus and mass density) by dividing the pile into segments with known attributes. The wave equation, in which the ascending and descending forces are added, and the velocities are equal to their differences divided by the impedance of the pile in each segment, is used to superimpose the propagations of the descending and ascending waves ("Wave down" and "Wave Up") on one another. The basis for calculating the soil resistance is each pile segment's displacement and velocity [23,25].

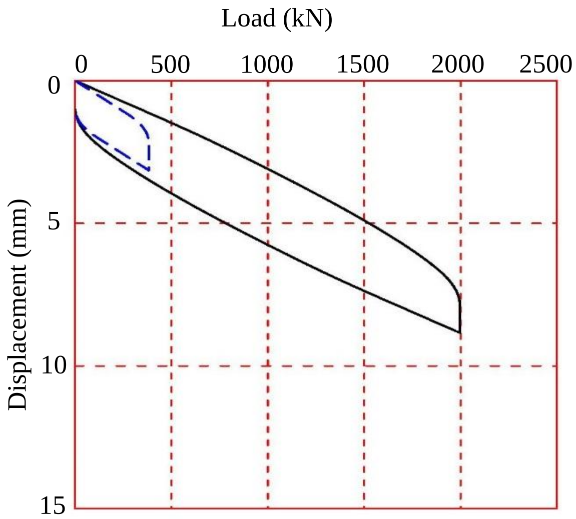

Fig. 5 Modeled Load-Displacement Curve from CAPWAP

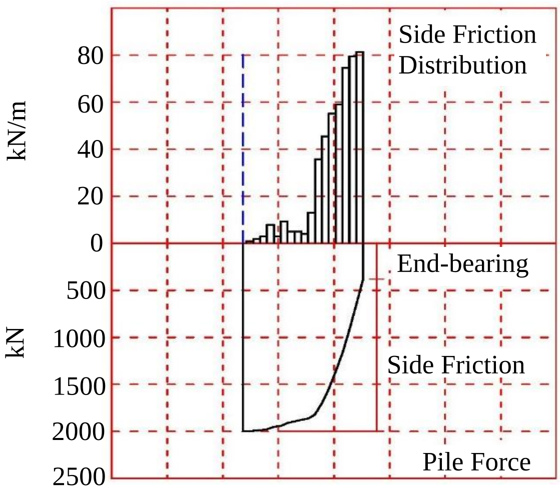

Fig. 6 Side Friction Distribution Graph from CAPWAP software

4.4 Static and Dynamic Load Testing Results Comparison

The authors compared DLT and SLT results on 51 piles from thirteen (13) different papers. DLT versus SLT results are presented in Table 1 and Fig. 7. The comparison result provided an average DLT/SLT ratio of 0.9833. Additionally, Fig. 7 shows the comparison of DLT capacities and SLT capacities. In most cases, the difference between the DLT and SLT capacities may be attributed to the testing time between tests. Higher DLT capacity may be due to a longer wait time after static load testing. Moreover, factors such as varying drop heights and heavier weight (exceeding the minimum of 1-2% of test load) of the impact hammer also contribute to the overestimation of DLT capacity. Besides, lower DLT capacity than SLT capacity may be due to insufficient soil strength recovery after static load tests, as the time between tests is shortened. These may happen most of the time due to the shortening of the project or construction timeline. Furthermore, DLT and SLT are important in foundation engineering as it evaluate actual soil properties and behavior [38]. Nevertheless, the comparative study shows that DLT and SLT agree in determining actual pile capacity.

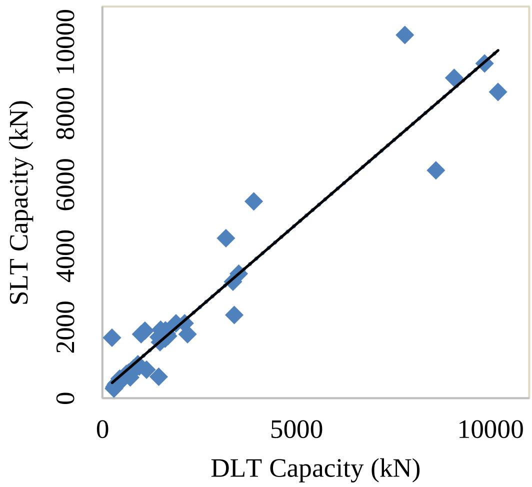

Fig. 7 DLT Capacity VS SLT Capacity

5. RESEARCH GAPS

The CAPWAP analysis results were used to calculate the static compressive capacities of piles tested by DLT. The static capacities determined by CAPWAP were compared to the axial compressive capacities determined by SLTs [9,11,23].

Meanwhile, [6,12,16,18-19,22,35,39-41] uses the dynamic results from the dynamic field testing. Since some researchers did not use CAPWAP analysis in comparing DLT and SLT results, [23,32] recommended that it is best to use both dynamic results in the field (CASE METHOD) and CAPWAP since by eliminating the dynamic impacts of the pile and soil, the dynamic force is converted to a static force to calculate the static capacity and produce load-settlement curve.

It is noted that some energy may be absorbed by the pile cushion during DLT; it should be emphasized that impact force is affected; thus, underestimation or overestimation of dynamic capacity happens [12,35]. Additionally, loads for dynamic testing are affected by different testing times. Therefore, capacities only represent estimation at the time of respective testing. In common practice, DLT is usually done after SLT. By increasing the wait time for DLT, the soil gaining strength can result in higher capacity determination [12,22,39,41].

Moreover, various failure criteria were used for static and dynamic tests [18], with the dynamic outcome usually agreeing with the Davisson criterion, which was applied to the static load-displacement curve and is typically considered conservative. The load-displacement curve from the dynamic test must be evaluated using the same standard or one that fits the static standard more closely [16].

6. CONCLUSIONS

DLT and SLT were used to estimate and verify the design pile capacity of the deep pile foundation. While SLT requires a costly and time-consuming setup, DLT has become the standard method of assessing pile capacities. This paper summarizes static and dynamic load testing and its methodology. This paper also discusses CAPWAP analysis as a means of evaluating DLT capacities. Fifty-one (51) piles tested with static and dynamic load testing from previous research are used. The authors' comparative study compares different pile capacities from both test methods. The literature review reveals good agreement between the two test results when compared.

Although some papers in the review, e.g., [12,40], show results with very low and very high DLT/SLT ratios, the comparative study still indicates a good correlation. The literature review recommends comparing SLT capacities to the DLT's field capacities and those obtained via CAPWAP analysis. In the SLT capacity versus CAPWAP analysis, [9] demonstrated a better DLT/SLT ratio than the field DLT capacity. This paper also suggests that future research works should better compare DLT and SLT results on the same pile. Future comparative studies should also consider comparing load-settlement curves from SLT and DLT. Moreover, instrumented SLT can also be compared to those from DLT, allowing for the utilization of skin resistance from both tests as an additional criterion for comparison. This literature review provided relevant information that can be used in future SLT and DLT research works.

Table 1 Result of static and dynamic test comparison

Authors	Pile No.	SLT (kN)	DLT (kN)	CW (kN)	DLT/SLT Ratio
[6]	E2(P24G)	2100		2124	1.011429
	Franki	3500	3520		1.005714
	CFA	1820	1660		0.912088
[9]	Test Pile 1	1670		1660	0.994
	Test Pile 2	1740		1690	0.971
[11]	Test Pile 1	10200		7800	0.764
	Test Pile 2	6400		8600	1.343
	Test Pile 3	8600		10200	1.186
[12]	SLT1	4492			0.709
	DLT1		3185		
	SLT2	5524			0.707
	DLT2		3906		
[16]	1	2340	3400		1.452
[18]	P121	9000	9071		1.007
	P126	9400	9852		1.048
[19]	TP1	585	718		1.227
	TP3	525	467		0.889
	TP5	680	621		0.913
	TP10	422	371		0.879
	TP11	549	508		0.925
	TP12	383	344		0.898
	TP4	395	371		0.939
	TP8	720	675		0.937
	TP9	720	687		0.954
	TP1-6	550	450		0.818
	S2-1	350	340		0.971
	S2-2	530	524		0.988
	S2-3	450	433		0.962
	S3-1	320	314		0.981
	S3-2	270	295		1.092
	S3-3	290	306		1.055
[22]	1	950	920		0.968
	2	940	920		0.978
	3	890	950		1.067
[23]	D1	840		800	0.952
	D2	670		700	1.044
	S3	1920		1500	0.781
	S4	1800		1000	0.555
[35]	T414-1	1570	1490		0.949
	T414-4	1765	1675		0.949
	T414-7	1715	1450		0.845
	T414-10	1905	1625		0.853
[39]	Pile 1	3275	3367		1.028
[40]	PP3A	800			1.426
	PP1B		1451		
	PP3B	600			2.418
	PP1A		1141		
[41]	1	1800	2200		1.222
	2	2100	1900		0.904
	3	1900	1100		0.578
	4	1700	250		0.147

Note: SLT = Static Load Test, DLT = Dynamic Load Test, CW = CAPWAP Analysis

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