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Can a Pile Load Tested to 'Failure' be Used as a Working Pile?

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ABSTRACT: There are a few available loading test methods to obtain a load-settlement curve of a pile. Likewise, there are many definitions to determine the 'ultimate' pile capacity from a load-settlement curve. Although pile load tests have been widely used over the past decades, there are still many questions regarding its practice and interpretation. Frequently asked questions include: when does a pile test considered to have failed? From an economic point of view, a failure in pile loading test can cost quite a lot of money. To what load can the pile be loaded till it is considered to have failed? Can a pile loaded to failure still be used as a working pile? What is a bidirectional pile load test (BD-test)? When should a BD-test be used? Can a pile tested with a BD be used as a working pile? What are the differences between kentledge or reaction piles static loading test with the bidirectional test? Do the different pile tests produce the same results? This paper aims to shed light on these questions, one case history where the pile tested to 'failure' and later used as working piles is presented.

KEYWORDS: Pile static load test, Bidirectional test, Ultimate pile capacity, Fail Pile

1. INTRODUCTION

Foundation piles have been used for over one hundred years. There are many methods to construct the piles. Likewise, there are also many methods to test the pile capacity. In Indonesia, foundation piles are very common, and engineers in Indonesia are willing to adopt state-of-the-art testing methods. From the common kentledge loading test, static load test with reaction piles, dynamic loading test (also known as PDA - pile driving analyzer), to the more recent one, bidirectional test (BD-test). Although these testing methods have been widely adopted in Indonesia, there are still questions regarding these testing methods. Often, engineers have different perspective on the practice of these testing methods. This paper aims to shed light to the following frequently asked questions:

- A pile load test should not be determined as failure as the project owner has spent thousands or tens of thousands of US dollars for it. So, in what scenario does a pile load test considered to have failed?
- Can a pile tested to "failure" still be used as a working pile?
- What is a bidirectional load test or O' Cell? When is it necessary to apply this test method?
- Can a pile tested by bidirectional load test still be used as a working pile?
- Will a pile tested by kentledge load test, static load test by reaction pile, and bidirectional test give the same results?

The paper first discusses what "ultimate" pile capacity is, the principles of each pile tests, followed by answers to the above questions.

2. ULTIMATE PILE CAPACITY

Eurocode 7 (BS EN 1997-1, 2004) defines ultimate pile capacity, also known as ultimate limit states, as compressive or tensile resistance failure of a single or piles system. However, according to Fellenius (2017), "Ultimate pile capacity" is a very imprecise concept in most soil conditions. This can be seen from a typical load-settlement curve shown in Figure 1. As shown in Figure 1, pile "capacity" continues to increase the further it is loaded. So, when does a pile fail? Figure 2 shows the 3 types of load-settlement curves that can be obtained in the field. The first type is a general failure, which as stated previously, the pile capacity continues to increase with pile settlement. The second type is punching failure with a relatively constant capacity, in which pile continues to move under constant load. The third type is punching failure with a reduction in capacity. Geotechnical pile failure only occurs when type 2 or type 3 occurs. For types 2 and 3, a true "ultimate" capacity can be defined. It is important to differentiate the peak and ultimate capacity for type 3. These three types of curves obtained can be explained with ultimate shaft resistance and toe resistance.

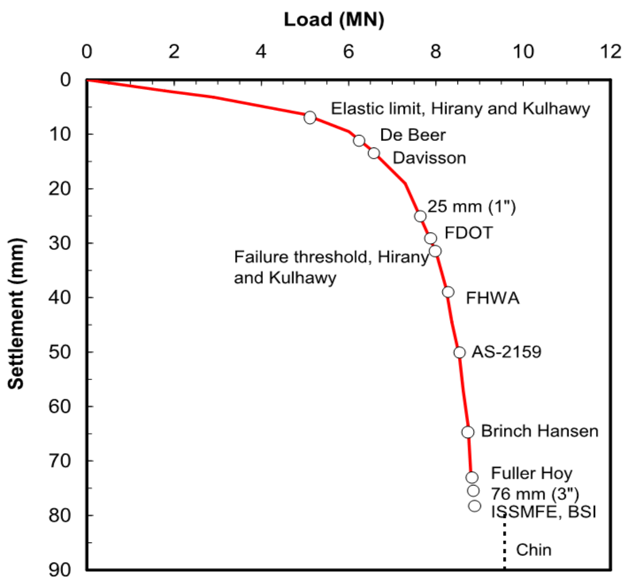

Figure 1 Typical load-settlement curve from a pile-load test in medium dense sand (Zhang and Tang, 2001)

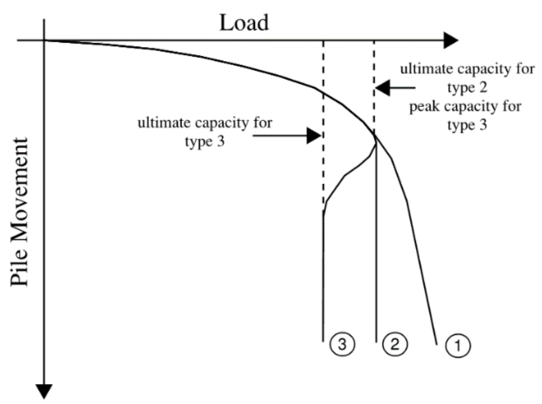

Figure 2 Three types of load settlement curve: 1 – general failure, 2 – punching failure with constant capacity, 3 – punching failure with reduction in the pile capacity

2.1 Ultimate Shaft Resistance

Development of shaft resistance is the consequence of relative movement between the pile and soil. If the pile settles more than the soil, a positive shaft resistance is generated. Whereas, when the soil settles more than the soil, a negative shaft resistance is generated. To fully mobilize shaft resistance, very small relative movement is required, often only a few millimeters (Fellenius, 2017). The relative movement required is independent of pile size but depends on soil type and roughness of the pile.

Shaft resistance is a function of the magnitude of relative movement and soil type as observed from direct shear test results shown in Figure 3. At first, the shear stress vs. movement increases more or less linearly, then, for loose sand or normally consolidated clay, after some magnitude of movement has been reached, the slope gets flatter and, finally, the shaft resistance becomes approximately constant. For dense sand or overconsolidated clay, the shaft resistance usually reaches a peak value, thereafter it decreases with movement to a residual strength. Some will define the ultimate shaft resistance as the peak value, others prefer to define it as the residual strength.

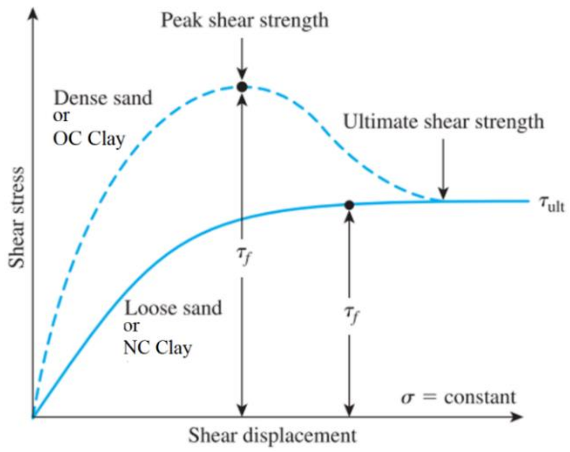

Figure 3 Shear stress versus shear displacement on dense and loose sand (Modified after Das, 2014)

2.2 Toe Resistance

Unlike shaft resistance, toe resistance does not have an ultimate value. The load-movement of pile-toe is a function of the stiffness and effective stress of the soil. Figure 4 shows an example of load versus pile toe movement measured in a 1.5 m and 1.8 m diameter piles. Even after a large movement of 150 mm, which is nearly 10% the pile diameter, the load-movement curve does not indicate reaching "failure".

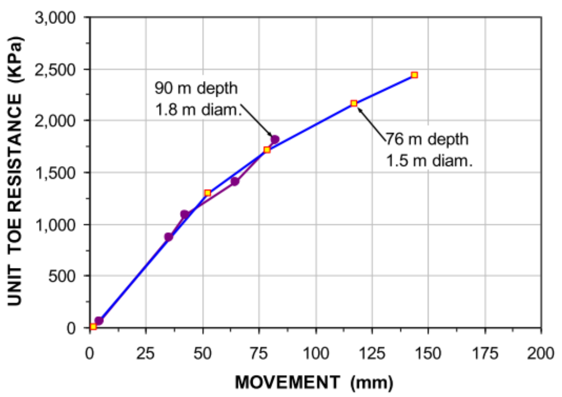

Figure 4 Unit toe resistance measured on a 1.5 and 1.8 m diameter bored pile constructed in silty sandy clay and clayey sand (Fellenius, 2017)

2.3 Failure in Pile

The three types of failure shown in Figure 2 can be explained from the ultimate shaft and toe resistance. For general failure, although ultimate shaft resistance has been mobilized, the toe resistance can continue to develop resistance as load is added. A Type 3 punching failure can occur, when the shaft resistance reduces more than the increase of toe resistance. Punching or plunging failure with relatively constant capacity or with reduced resistance is rather rare. For general failure, there is no obvious pile capacity. If a capacity value is necessary, a specific definition must be used and agreed on by the parties involved in the evaluation of the static loading test.

2.4 Failure Criterion

For pile which experience general failure, specific criterion to derive pile capacity is needed. In the early days (1960s-1970s), pile capacity is defined by identifying the initial relatively gentle part of the curve and the latter steeper part of the curve. Examples include Hansen 80% and 90% criteria (1963), Chin-Kondner extrapolation (Chin, 1971; Kondner 1963), DeBeer intersection load (1968), and many others.

A straighter forward method to define a pile capacity is by taking the pile load under certain displacement, usually based on the pile diameter. Eurocode 7 defines pile capacity as the load that resulted in a movement equal to 10% of the pile-toe diameter (BS EN 1997-1, 2004). Indonesian standard applies similar criterion, in which pile capacity is taken as the load that produced 25 mm movement in a pile with a diameter smaller than 800 mm, and a movement equal to 4% pile diameter for piles with a diameter larger than 800 mm (SNI 8640:2017).

There is also pile capacity derivation which includes elastic shortening of pile from the axial load. This method is adopted by Davisson (1973), AS2159 (2009), Ng et al. (2001), etc.

From the numerous different approaches available, many different pile capacities can be derived. As shown in Figure 1, the difference can be more than 150%! Naturally different approach also has their own respective accepted factor of safety. Engineers should abide by their respective local standards, unless for special reasons stricter settlement is required.

Before understanding the different types of pile load tests, an engineer needs to understand the basis of determining pile capacity. In essence, the capacity does not exist until it is defined. With this appreciation, one can have a clearer picture of the advantages and disadvantages of each testing methods, as well as their appropriateness in different situations.

3. THE STATIC LOADING TEST

A static loading test is a test whereby tested pile is loaded axially, either using dead-weights (kentledge) or reaction piles/frames. The choice of pile tested is usually based on the pile installed in the most adverse soil conditions. This is to ensure that the obtained results are most conservative and that there is no overestimation of pile capacity in other areas.

The main purpose of the static loading test is to obtain load versus movement relationship of the test pile. The pile capacity can be derived from the results based on the specific criterion. Some also assess a creep response of movement versus time under constant load. Another useful information that can be obtained through a static load test is the rebound behavior, when the pile tested is unloaded (BS EN 1997-1, 2004). More useful information can be obtained by using instrumented piles, e.g. separating shaft and toe resistance (Fellenius, 2017). In the next sections, the procedure of static loading test by kentledge and reaction piles are discussed.

3.1 Kentledge System

Figure 5 and 6 shows a schematic diagram and photograph of static load test with kentledge system, respectively. A pile capacity can range from a hundred of kN to thousands of kN. To load a pile to that level, a sufficient reaction force is required. One method to provide the reaction force is by kentledge, where blocks of concrete are placed on a platform to act as a reaction to loading of the pile. ASTM D1143 states that the total weights should at least be 10% larger than the maximum load that is going to be applied. The center of the cross beams needs to be in the center of the pile to prevent eccentric loading. Only 1% eccentric loading and an eccentric distance of 25 mm is allowed. To stabilize the cross beams, temporary support of the platform, such as timber or concrete cribs, need to be built. Care must be taken in determining the clear distance between the pile to the cribs. The distance is important because the kentledge load is transferred to the soil underneath the cribs adding stress to the ground and the supports must be placed far enough to not let the change of vertical stress affect the shaft resistance of tested pile. As a general guideline, ASTM D1143 states that the clear distance should not be less than 1.5 m.

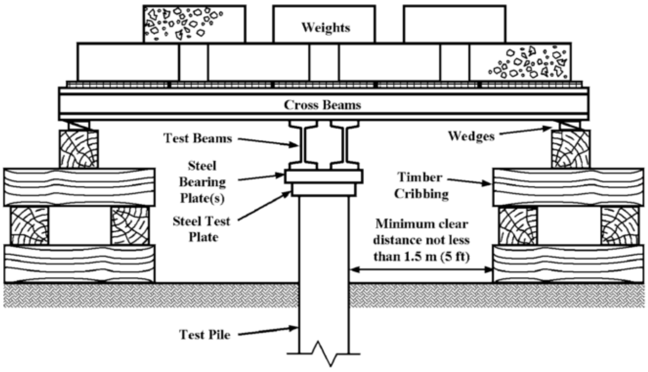

Figure 5 Schematic diagram of static load test with kentledge system (ASTM D 1143, 2007)

Figure 6 Photograph of static load test with kentledge system (Courtesy of Khmer D&C Technical Consultant, 2018)

3.2 Reaction Piles or Anchors

Alternative to kentledge, reaction piles or anchors can be used to provide the reaction force for pile loading. Figure 7 and 8 shows a schematic diagram and photograph of reaction pile system. Care must be taken to ensure sufficient resistance from anchors or reaction piles. Movement of anchors or reaction piles also must be measured to calculate the net movement of the tested pile. Another thing to note is the different requirements in clear distance between the tested pile and its anchors or reaction piles. ASTM D1143 states that the required clear distance is 5 times the largest pile/anchor diameter (can be the test pile or reaction pile) or 2.5 m, whichever is larger. The required clear distance is larger than the kentledge system, because for the kentledge system, the larger the load applied on the test pile, the lower the load on the cribs. However, when reaction piles or anchors are used, the larger the load applied on the test pile, the larger the opposite load acts on the reaction piles or anchors.

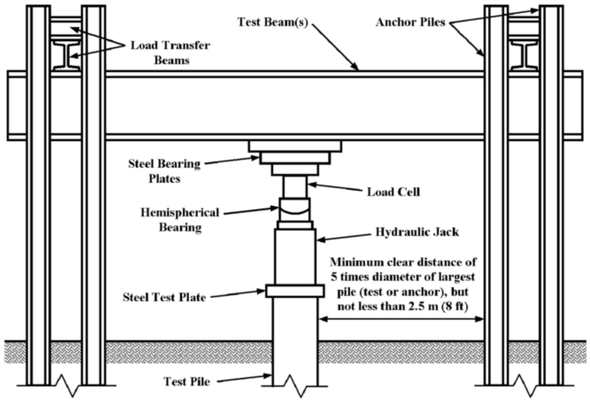

Figure 7 Schematic diagram of a static load test with anchored reaction frame (ASTM D 1143, 2007)

Figure 8 Photograph of static load test with reaction piles (Courtesy of Structville, 2018)

3.3 Loading Procedure

Ideally, the load applied should reach a "failure" that reflects the axial static compressive capacity of the pile. Care must be taken that the load applied does not exceed the axial structural strength of the pile. As pile capacity changes with time (setup effect, when strength is gained; relaxation, when strength decreases) a qualified engineer should specify the waiting period before testing. Moreover, for a cast-in-place pile or a bored pile, sufficient time should be given for the concrete to gain adequate strength.

ASTM D1143 lists 7 loading procedures that can be adopted for static loading tests. In Indonesia, the most commonly used loading procedure is the maintained test (ASTM D1143, 2007). The test pile is loaded to a minimum of 200% design load in 25% increments, the pile is then unloaded in four or five equal decrements. When higher capacity is anticipated, the pile can be reloaded to a higher load level. Figure 9 shows an example of a test pile loaded to 100%, 200% then 300% design load performed by the authors.

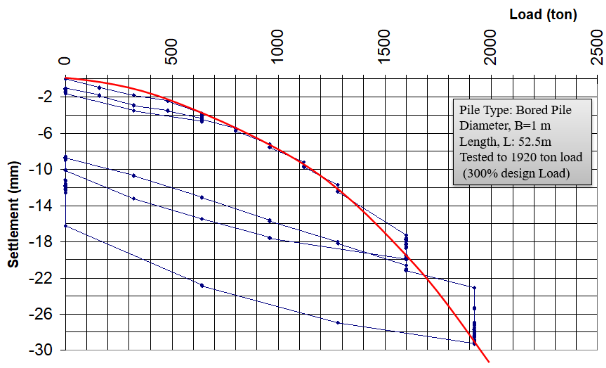

Figure 9 Static loading test result

3.4 Results, Failures in Execution of Static Load Test

Results from a non-instrumented pile static loading test comes in the form of load-settlement curve (an example is shown in Figure 1 and 9). From the load-settlement curve, the pile capacity can be determined using a definition based on local national standards. However, without any geotechnical instrumentation, it is not possible to separate the shaft or toe resistance. The importance of instrumentation is discussed in the next section.

Failures in the execution of static loading tests cost a lot of time and money. Causes of failures include bearing capacity failure of the concrete block supports/cribs, e.g. in Figure 10; instrumentation errors; insufficient reaction force; support platform located too close to the pile. These failures can be prevented and should not be allowed to occur.

Figure 10 Failure of kentledge system before loading (Courtesy of Profound BV, 2017)

3.5 Importance of Instrumentation

The most common instrumentation installed in a pile are strain gages. Strain gages provide the load distribution along the pile shaft, e.g. in Figure 11. From the axial load distribution, it is possible to derive the shaft resistance by differentiating the curve. It is also possible to estimate the toe resistance from the bottom-most strain gage. From the results, design can be verified, and optimization can be carried out.

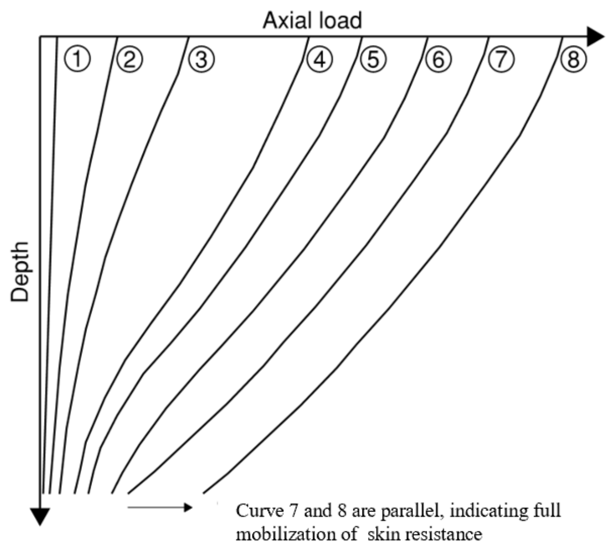

Figure 11 Development of axial load distribution with load steps

4. BIDIRECTIONAL TEST

The bidirectional test (BD-test) was first used in the 1980s in Brazil and the USA (Fellenius, 2017), and widely accepted internationally from 1990 onward (Osterberg, 1998). Because of Dr. Jorj Osterberg's pioneering work, the bidirectional cell (BD-cell) is also known as the Osterberg Cell test, or O-cell test. Figure 12 shows a schematic diagram of a bidirectional test. The BD-cell is in principle a hydraulic jack placed at some depth within the pile shaft. The cells are sacrificial, as they cannot be retrieved after the test completion. When pressure is applied to the O-cell, the cell expands, pushing the upper part of the test pile upward, and the lower part downward. The BD test can be used for both cast-in-place and precast piles.

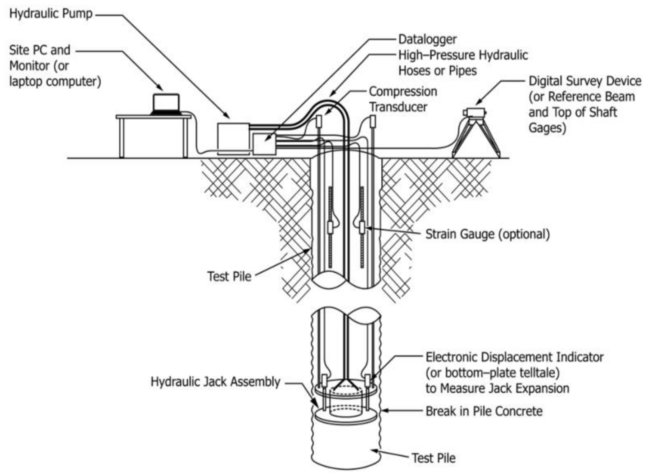

Figure 12 Schematic diagram of a bidirectional test (ASTM, 2018)

4.1 O-cell Test Apparatus, Instrumentation and Installation

Currently, there is no guideline available for bidirectional tests in the Indonesian Standard. For guideline, one can refer to ASTM D8169 (2018). For an O-cell test, the only apparatus required are the O-cell itself and hydraulic pump. Required instruments are pile head measuring device, e.g. digital survey, or reference beam with dial gauges, the BD-cell top, and bottom plate movement measuring device which are in the form of either electronic displacement indicators or telltales. Optional instrumentation are strain gauges along the pile shaft.

For cast-in-place pile, the reinforcement cage is separated into 2 sections. The first section is welded onto the top bearing plate of BD-cell, while the second section is welded onto the bottom bearing plate (see Figure 13). The bearing plate needs to have sufficient spacing to allow grouting to flow through.

For precast pile, the BD-cell can be prefabricated with the pile. Alternatively, the precast pile can be separated into two segments, that are spliced in the field with the segments attached to one of the BD-cell's bearing plates (Figure 14). The installation of precast pile with BD-cell attached is the same as normal precast piles.

4.2 Loading, Measurement of O-cell and Results

The BD test is carried out by applying hydraulic pressure using a hydraulic pump at the ground surface (refer to Figure 12). The applied pressure expands the BD-Cell, pushing the upper shaft upward, and the lower downward.

Figure 15 shows the typical results from a BD test. During the initial loading phase, the BD-cell shows zero movement as it has to overcome the buoyant weight of the upper length of the pile, as well as any residual load. As the BD-cell is further loaded, the shaft and toe resistance start to get mobilized until either the shaft or toe ultimate resistance is reached. The difference between the pile head movement and the top bearing plate movement is the shortening of the upper length of the pile. From the measurements, one can obtain a load-movement curve for both the pile shaft and pile toe. Therefore, the shaft and toe resistance can be evaluated separately.

Figure 13 Reinforcement cage welded onto bearing plates of BD-cell (Courtesy of Foundation Alliance, 2018)

Figure 14 Installation of BD-cell in precast pile (Courtesy of YJack, 2018)

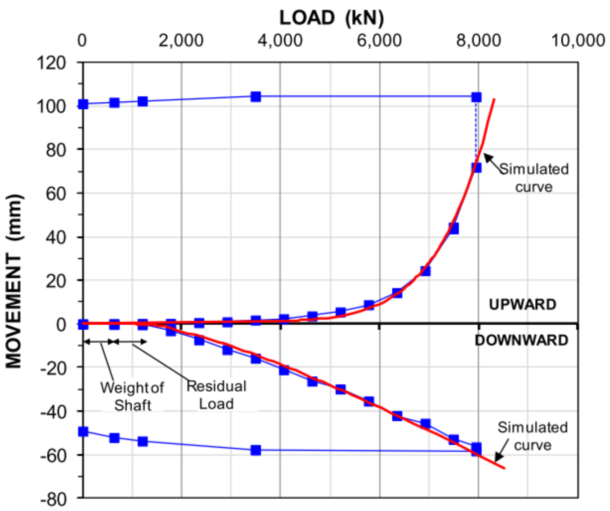

Figure 15 Typical result of a BD-cell test (Fellenius, 2017)

4.3 Failures in Execution of BD-cell test

Ideally, the BD-cell should be placed at a level that allows full mobilization of the upper length of the pile, and as much toe resistance as possible. Therefore, in most cases, the BD-cell is placed either at the pile toe, or very close to the pile toe. However, in cases where the pile sits on very soft soil, and depends mostly on the shaft resistance, it may be necessary to place the BD-cell higher up the pile.

5. CASE HISTORY

The case history is based on the authors' work at a project in the central business district area of Jakarta, the capital city of Indonesia. Two bored piles of 1.0 m diameter and embedded to 52.5m depth below ground were tested up to 300% of its design load. The design load is 6400 kN. The subsoil condition is as shown in Table 1 below.

Table 1 Subsoil Layers and Their Properties

Depth (m)	SPT N blow/ft	γ kN/m^3	w_n %	PI %	C_u kPa	E' MPa	OCR -
0							
	Reddish Brown Silty Clay (CH)						
	5 - 11	16.9	50	54	70	5	5
-8	Groundwater Table						
	Light Brown Silty Clay (CH)						
	3 - 12	16.0	60	54	50	5	1.8
	Bored pile 1m Dia, 52.5m depth						
-15							
	Brownish Grey Clayey Silt (MH)						
	10-20	17.0	60	45	70	17	1.5
-23							
	Greyish Brown Clayey Silt with cementation (MH)						
	24	18.0	40	45	100	20	1.4
-45							
	Greyish Brown Clayey Silt with cementation (MH)						
	24	18.2	40	30	100	20	1.2
-54							
	Grey Silty Clay with cementation (CH)						
	35	18.5	40	30	150	25	1.2
-72							

Both piles were instrumented with vibrating wire strain gauges (VWSG). Eight layers of VWSG were installed, i.e. at 0.7, 8.0, 15.3, 23.1, 30.0, 37.2, 44.8 and 52.0 m depths; with 3 numbers of VWSG at each layer. The static loading tests were carried out following ASTM 1143.

With a safety factor of around 2.5, a preliminary estimate gave an allowable axial pile capacity of 6400 kN. To optimize the design, it was decided to carry out preliminary load tests on two piles placed at a presumably weaker area as revealed by the boreholes. The two piles were tested to 300% of their design load.

Before the loading test is carried out the integrity of the piles were tested by sonic logging. Figure 16 shows the test pile no. 1 has good integrity. Test pile no. 2 also has good integrity.

Figures 17 and 18 show the load distribution along the pile shaft. The graphs show that with 300% design load, i.e. up to 19,200 kN, the shaft resistance more or less already fully mobilized, except the segment below 45m depth where the shaft resistance and the end bearing has been not fully mobilized. Figure 19 shows the pile settlement curve along with the 'ultimate' capacity derived by various methods. The load settlement curves show type 1 behavior as defined in Figure 2, which means the pile bearing capacity increases with its settlement.

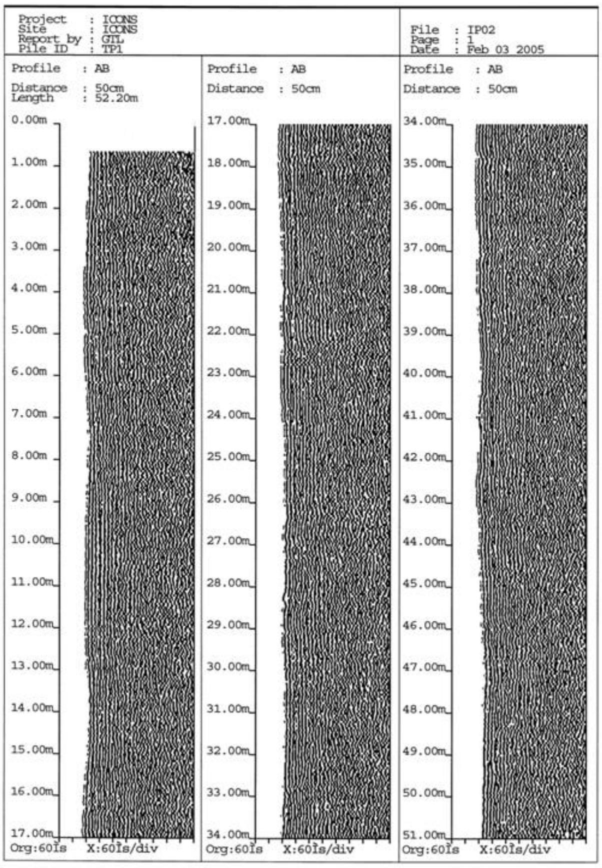

Figure 16 Sonic logging test result show good pile integrity

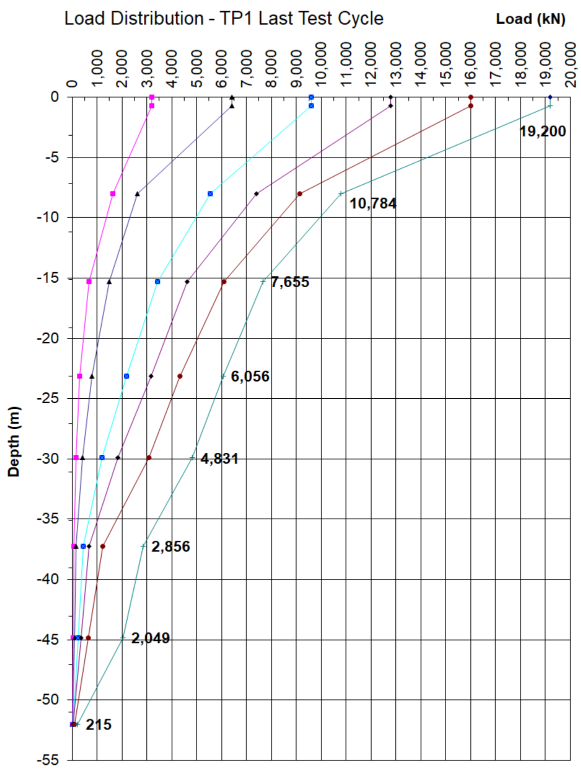

Figure 17 Load distribution curve of test pile no. 1

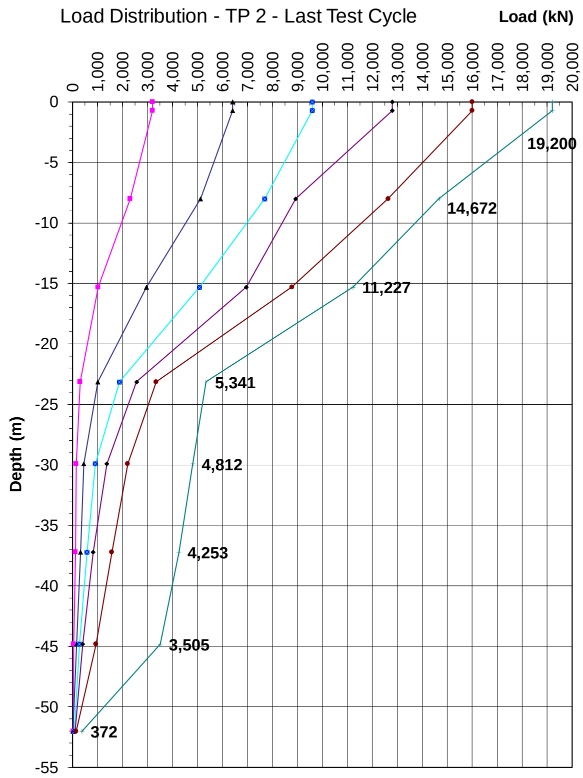

Figure 18 Load distribution curve of test pile no. 2

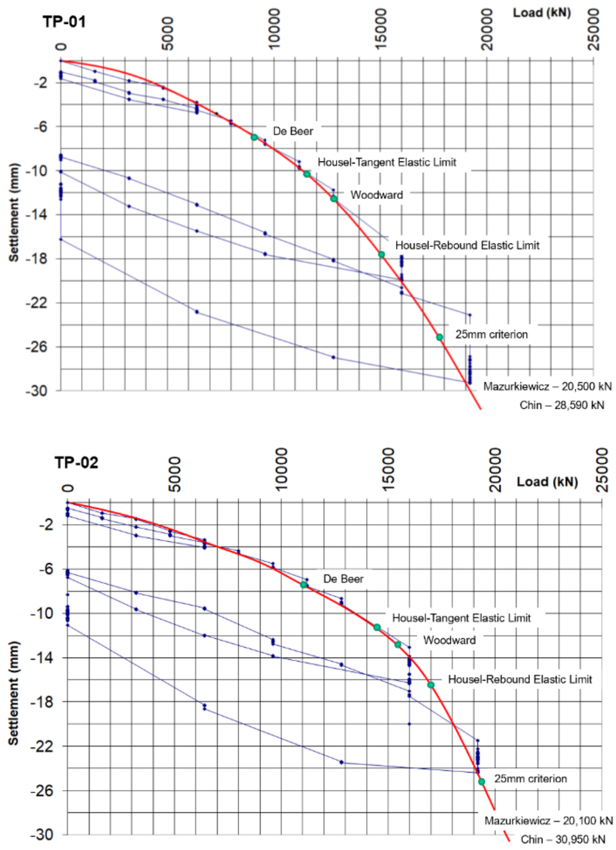

Figure 19 Load settlement curve of TP-01 and TP-02

The ultimate capacity derived by using various definitions is tabulated in Table 2. The average 'ultimate' capacity of the two test piles is around 18,000 kN. Taking the minimum safety factor of 2.5 as defined by the Indonesian National Standard (SNI 8640:2017), the allowable capacity of the pile is 7200 kN. At the 7200 kN allowable load, the settlement of the test piles are still less than 6 mm, which is also one of the criteria set in the Indonesian standard where at design load under non-seismic condition, i.e. the pile head settlement should be less than 6 mm. With these results, the initial design load of 6400 kN was increased to 7200 kN, and these two test piles were also used as working piles without any problem to the building constructed.

Table 2 Pile 'Ultimate' Capacity

'Ultimate' Capacity defined by:	TP1	TP2
	Q_{ult} (kN)	Q_{ult} (kN)
DeBeer	9,000	11,000
Housel-Tangent Elastic Limit	11,200	14,500
Woodward (12.5mm Settl.)	12,800	15,350
Housel-Rebound Elastic Limit	15,000	17,000
25mm settlement limit	19,000	19,350
Mazurkiewicz	20,500	20,100
Chin	28,590	30,950
$S_f = S_e + D/120 + 4mm$ *	25,000	25,000
Average	17,636	18,321
Average of two test piles	18,000	

* *by extrapolating the load settlement curve; S_f = settlement at failure, Se = elastic settlement of pile, D = pile diameter in*

6. DISCUSSION

The pile geotechnical 'failure', capacity, or ultimate resistance is basically a definition determined in the design stage, specifically by its magnitude of settlement (movement) at a certain load.

6.1 Using Pile Loaded to Failure as Working Pile

As discussed in section 2, in most cases, piles will not reach 'geotechnical' failure during pile load tests. In most soils, a pile's toe resistance continues to increase the further a pile is loaded. What is meant by pile loaded to 'failure' is when the tested pile is loaded beyond a certain failure criterion, e.g. pile head settle more than 4% pile diameter or other definition.

Therefore, as long as the tested pile is not structurally damage, a pile loaded to 'failure' does not mean it become unusable. In other words, a pile loaded to reach a failure criterion can still be used as a working pile as long as there is no structural damage. Furthermore, when a pile experience unloading, the next time it is loaded, it will show a stiffer response, until the previous maximum load is exceeded (see Figure 20). This behavior is very much like loading an overconsolidated soil.

However, one must pay attention when punching failure with a reduction of pile capacity occurs (type 3 failure in Figure 2). When reusing such a pile, the ultimate pile capacity has to be used instead of peak pile capacity. However, for other piles which weren't loaded, the peak pile capacity can be used as long as sufficient factor of safety is given to ensure that the pile will not be loaded beyond its peak capacity during its design life.

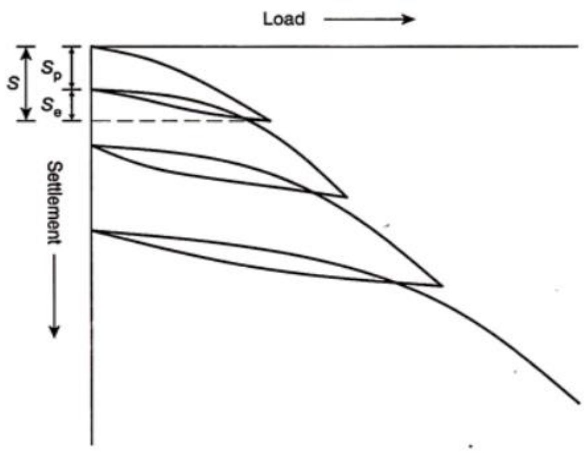

Figure 20 Load-settlement curve in cyclic pile load test (Trishna, 2018)

6.2 Using Pile Tested by Bidirectional Test as Working Pile

Similar to that discussed in Section 6.1, a pile tested by a bidirectional test can be reused as a working pile. Although there is a fracture zone in the pile, the upper and lower reinforcement cages are connected by the BD-cell's bearing plates. Besides, the fracture zone is always grouted, making the pile acts as one body.

It is also very costly to not use a pile tested by a bidirectional test. Bidirectional tests are common for large piles and offshore piles. This is because building a kentledge system or reaction piles would be time-consuming and costly. Therefore, due to economical reason, most piles tested by bidirectional tests are reused as working piles. Of course, this is also because conducting a bidirectional test does not significantly diminish the tested pile performance.

6.3 Similarity of Results from Static Load Test and BD-Test

The main objective of conducting pile load tests, regardless of the methods is to obtain the 'ultimate' capacity of the tested pile. Despite the difference in the measurement system, provided the same definition is used to determine the 'ultimate' capacity, theoretically, the static loading test and BD-test should produce more or less the same ultimate pile bearing capacity. This is because the bidirectional test is essentially a static load test as well. Bidirectional tests can provide information on both the shaft and toe resistance, while conventional static load test can only produce the total pile capacity. Fellenius (2017) considers the bidirectional tests to be superior as compared to conventional static load tests.

7. CONCLUSION

The 'ultimate' or 'failure' capacity is a definition which has to be defined and agreed upon in its design stage. A pile tested to its 'ultimate' or 'failure' load, either by a kentledge static loading test or by a bidirectional test, can still be used as working piles as long as the tested pile is not structurally damaged. Geotechnically speaking there is no difference between static loading test and bidirectional loading test.

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