

Comparison of Axial Compressive Load Capacity of Piles by Different Methods

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Abstract— Determining the correct bearing capacity of piles has important technical and economic significance for the construction using the pile foundation. However, this is a complicated problem because the bearing capacity of piles depends on many different factors such as soil conditions, geometrical dimensions of piles, method of pile construction, etc. Pile load static compression test in the field is usually performed to verify and estimate the bearing capacity. Due to time and some other practical conditions, some constructions cannot load on piles until failure. In this article, test data is analyzed to predict the ultimate load of Pre-stressed Concrete spun pile PHC. This analysis is based on the results of the four static compression test, which was carried out at Riverside Apartment construction site in Ho Chi Minh City. Four piles have a diameter of 600mm and a length of about 38m-41m. The geological survey at the site was conducted to a maximum depth of 80m. The ultimate bearing capacity of piles is determined by different methods including Vietnamese standard TCVN 10304:2014 (2014), formula of Japanese Institute of Architects (1988), graph method of Chin-Kondner (1970), Decourt (1999), Mazurkiewicz (2003). Based on the value of ultimate load capacity of four piles were calculated by five different methods, it is shown that each method can estimate different ultimate load capacity of piles. Within the scope of this study, the number of four test piles, and five methods of calculating pile load capacity selected, it shows that when using the formula Institute of Architecture of Japan - AIJ (1988) calculates the ultimate bearing capacity of piles giving more reliable results than the other four methods. Compared with the obtained value when the static compression failing test TP1, the TCVN and the Mazurkiewicz method give the results that are not much different from each other.

Keywords— Pile capacity; Pile load; Pile load test; ultimate bearing capacity

I. INTRODUCTION

Pile foundation is commonly used in high-rise building because of its load capacity. Pile foundation is used when the ground has the soft soil layer on the surface, which is not able to bear the construction load. In this case, piles transfer load to the deeper hard soil layer.

Prediction and determination pile bearing capacity have a great influence on the economic – technical factors of the construction. Using highly reliable method in calculating the bearing capacity makes the selection of pile bearing capacity, pile cross section, pile length quickly, accurately and cost-effectively.

The correlation between the pile head displacement caused by the axial compressive load which is shown in the graph of piles static compression test is one of the bases of determining the ultimate compressive load capacity for the design pile

foundation. Due to some limited conditions, in practice, it is usually to choose the maximum compressive load acting on the pile head pile, about 1,5 to 2 times the design load in the test at the site. Therefore, in some cases, the pile static compressive test has not given the ultimate bearing capacity of piles. Mazurkiewicz, Chin, Kondner and Decourt have proposed graphical methods based on the correlation between compressive load and pile displacement to predict the ultimate bearing capacity of piles.

The research content of this paper is the synthesis of static of static compression test data of 4 piles of high-rise apartment built in Ho Chi Minh City, accompanied by data of the pressure force when constructing piles into the ground such as analyzing the load-displacement curve of piles, calculating the ultimate compressive capacity of piles by a number of different methods and building the correlations between the ultimate compressive capacity of piles and piling stopping force, maximum pile test load and pile design bearing capacity. From the analysis and comparison, the conclusions of the research can be drawn.

II. LITERATURE REVIEW

There have been many studies on predicting the bearing capacity of piles from theoretical and experimental results. These are the works of Mirza (1997) [1], Dewaikar and Pallavi [2], Nabil [3], Brinch Hansen [4], Mazurkiewicz [5], Abdelrahman [6], Chin-Kondner [7], Hansen [8], Davisson [9], Fuller-Hoy [10], De Beer [11].

Mirza (1997) [1] introduced a simple method for calculating the frictional resistance of driven piles into clay. This method is based on the correlation between the characteristic indicators and strength of soils derived from marine clay. The results show that except for the short piles in the hard to very hard clay, the predictions are agreement with the measure results at the site. This correlation is presented that the skin friction component can be calculated and the importance of liquidity index in calculating static capacity is shown.

Dewaikar and Pallavi (2000) [2] analyzed the load test data at the site to predict the ultimate bearing capacity of piles. This analysis was based on 40 results of pile load test obtained from various civil and infrastructure projects constructed in the Mumbai region of India. This study showed that the collected data were analyzed by different methods such as semi-empirical and graphical methods.

Nabil [3] studied the group effect of bored piles based on the field test performed at a site in South Surra, Kuwait. The study also includes load testing on single piles in compression

and tension states. There are two groups of piles made, each group consists of five piles. The spacing of piles in the selected pile group is two and three times the pile diameter. The group coefficient value found is 1.22 and 1.93 in case the distance between the two piles is 2d and 3d respectively, where d is the bored pile diameter.

In a number of documents and different standards, the results of pile compression test have been explained and been proposed to determine the ultimate load capacity from this test.

J. Brinch Hansen [4] proposed an estimate for calculating the Ultimate bearing capacity, Q_u . Method of Brinch Hansen 80% have a the following simple relation:

$$Q_u = \frac{1}{2\sqrt{C_1 C_2}} \quad (1)$$

where, C_1 : slope of the straight line, C_2 : y-intercept of the straight line.

Mazurkiewicz proposed a method of extrapolating load and settlement curves [5] [6]. Accordingly, the proposed method is: The plot of the loading test curve toward the settlement was based on the result of load test in the observed location. Drawing lines from some selected settlement points until they cross the curve. Vertical line is being drawn until it reaches loading pivot. From the cross of the load, a line with an angle of 45° is being made until it crosses the next line. These points are connected until straight line is formed. The cross of the straight line with loading pivot is its ultimate load. This method gives the assumption that loading curve movement forms the shape of parabola. Therefore, the value of the collapsing loads, obtained by using Mazurkiewicz method, should approach 80% of the standardized criteria.

Another method that can determined the ultimate bearing capacity of piles proposed by Chin, based on the research results of Kondner [7], allows the extrapolation of the failure load in the static load tests. The method consists of dividing each respective load applied by the settlements and put it in the y-axis. In turn, the x-axis, places the settlements obtained during the static load test. The load limit is given by the inverse of the slope formed by the points plotted on the graph.

Another chart method is proposed by Decourt, which method is similar to those used in the method of Chin-Kondner [7] and Hansen [8]. To apply this method, divide each load with its corresponding settlement and plot the resulting value against the applied load. The Decourt extrapolation load limit is the value of load at the intercept and the slope of the line as given in the equation below.

$$Q_u = \frac{C_2}{C_1} \quad (2)$$

A common and relatively widespread method is the Davisson (1972) [9]. It has been suggested by Davisson as the load which is accordance by a movement which exceeds elastic pressure (which is assumed by a column which stands by itself) at the value of 0.15 inches and a factor which is relevant to the measurement of Pile Measurement divided by 120.

According to the Fuller-Hoy method, the ultimate bearing capacity of piles corresponds to where the slope of the load

- settlement curve is 1.27 mm/ton. Practically, the ultimate load is determined by finding the point at which the curve at 1.27 mm/ton slope plotted on the graph is tangent to the curve [10].

Determine the ultimate load of piles according to the method of De Beer [11], the correlation values between load and settlement of piles are plotted logarithmic chart. When the values fall on two approximately straight lines, the intersection of these defines a limit load that is considered a pile yielding load.

III. SOIL INVESTIGATION AND TEST PILE PARAMETERS

A. Soil profile

The soil investigation consists of 6 bore holes drilled to 80 m depth. The layout of the geological boreholes at the construction site is as shown in Figure 1. The soil profile at the site is reported to consist of clay and sand, and is presented in Figure 2. The water table varies from -3.3 m to -5.0 m below the ground surface.

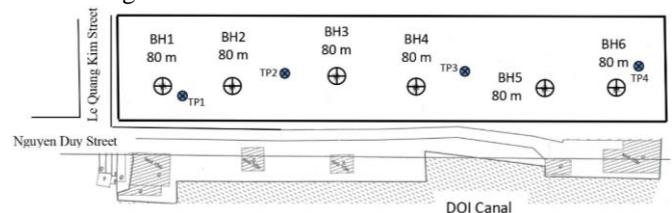


Fig. 1. General layout of the site with the locations of boreholes.

TABLE I. PARAMETERS OF SOIL LAYERS.

Symbol of Soil layers	Soil description	c (kPa)	ϕ (Degree)	SPT N
A	Fill soil, broken rock and brick	-	-	-
1	Muddy Clay with organic very soft	6.3	3.97	0÷3
2A	Hard plastic sandy Clay	26.7	13.50	10÷17
2B	Stiff plastic clay	31.4	13.23	10÷13
3	Stiff plastic clayey Sand	9.2	23.26	12÷29
4A	Hard Clay	61.3	16.45	26÷42
4B	Stiff plastic sandy Clay	28.7	14.18	16÷29
5	Plastic clayey Sand	9.1	23.50	32÷50

A variety of laboratory and field tests were performed at the site for the determination of soil conditions and pile design parameters. The subsurface soil parameters are shown in Table I and Table II.

TABLE II. PHYSICAL PROPERTIES OF SOIL LAYERS.

Symbol of Soil layers	Water content (%)	Plasticity index I _p (%)	Liquidity index I _L	Unit weight (kN/m ³)	Void ratio e _o
A	-	-	-	-	-
1	73.16	28.3	1.2	15.2	1.975
2A	21.2	14.5	0.33	19.8	0.659
2B	24.92	18.5	0.20	19.6	0.732
3	18.89	6.4	0.35	20.1	0.582
4A	20.05	22.5	< 0	20.7	0.581
4B	21.55	14.9	0.24	20	0.638
5	19.24	6.3	0.36	20.1	0.591

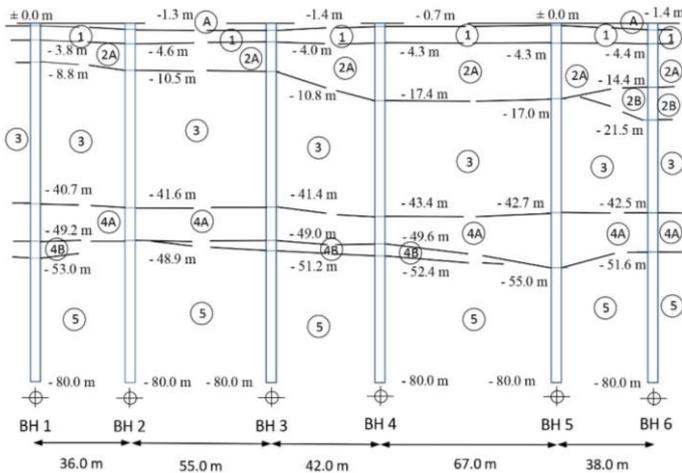


Fig. 2. Geological section at the site.

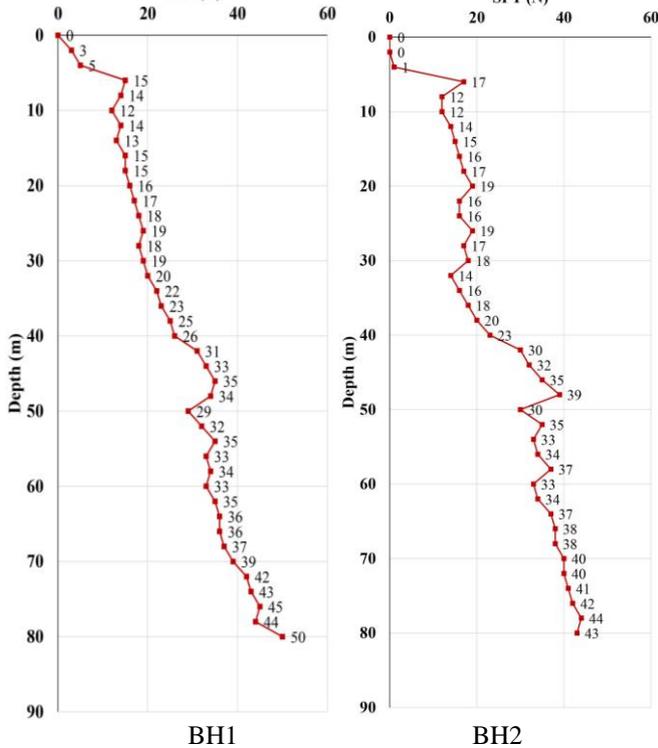


Fig. 3. Variation of SPT - N with depth for borehole BH1 and BH2.

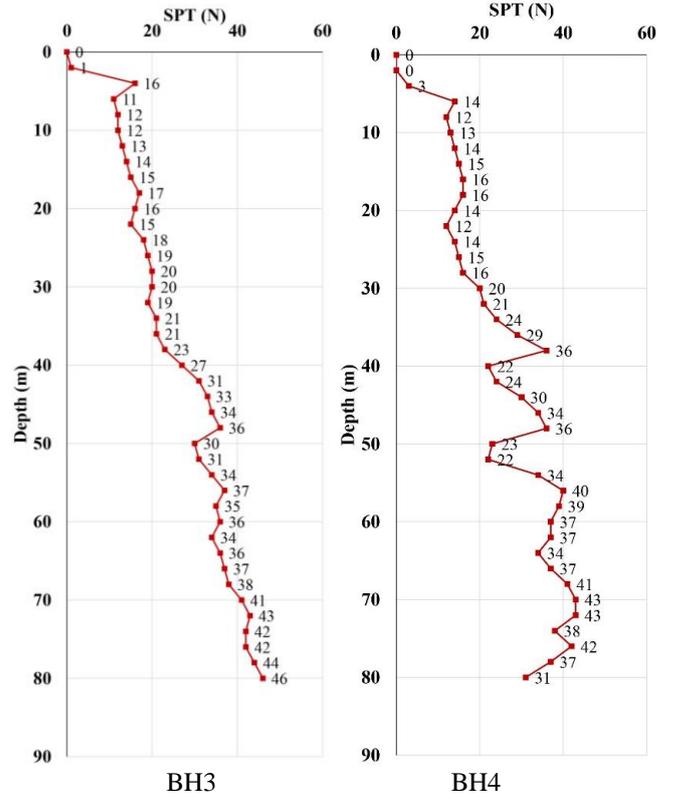


Fig. 4. Variation of SPT - N with depth for borehole BH3 and BH4. The SPT profile along with soil parameters with depth for each borehole are shown in Figure 1, 2, 3, 4.

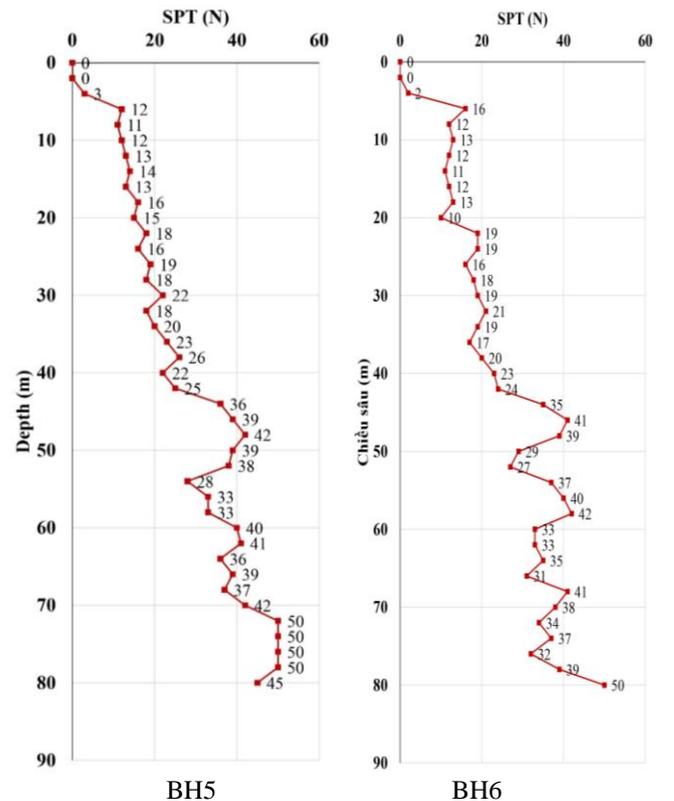


Fig. 5. Variation of SPT - N with depth for borehole BH5 and BH6.

B. Test Pile Parameters

Piles selected in this study is Pre-stressed Concrete spun pile PHC with $d = 600$ mm with the design load capacity $Q_d = 250$ ton (the working load).



Fig. 6. Pre-stressed Concrete spun pile PHC at the site.

At the site, four test piles labeled as TP1, TP2, TP3 and TP4 respectively are compressed into the ground to the design depth and ensure not to exceed the maximum pile pressure value F_{pmax} . Method of compressing the pile by using the load from the counterweight to create the force to push the pile to the ground. Correlation between Pile pressing force (F_p) and Depth of embedment z for each pile are shown in Figure 7.

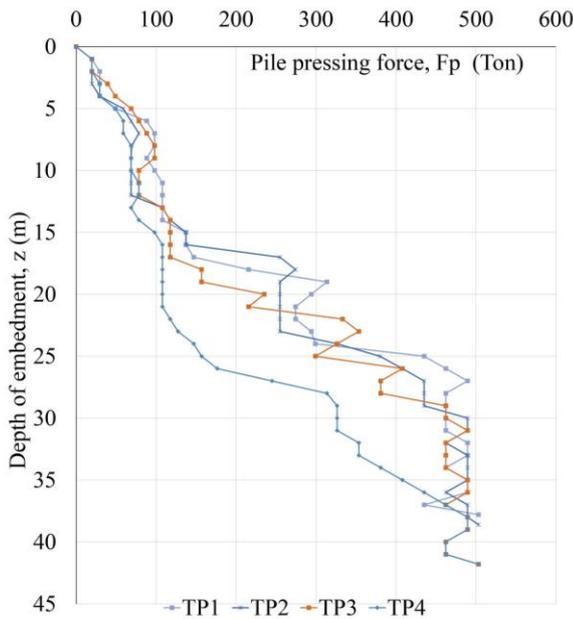


Fig. 7. Relationship between pile pressure value and pile tip depth.

With each pile we have found that pile pressing force tends to increase proportionally to the pile tip depth and reaches the maximum value of $F_{pmax} = 503.2$ tons when the pile is stopped.

IV. DETERMINE PILE CAPACITY

The objective of research was to calculate the amount of bearing capacity of single pile, based on several conventional methods. It is obtained based on soil investigation in the field; they were value of SPT, liquidity index (boring log) data for one location from some points of observation and the analysis of the bearing capacity of the single pile and its settlement, based on loading test data.

In the research scope of this paper, it is calculating the ultimate bearing capacity of the piles by using the formula based on Vietnamese standards (Pile Foundation – Design Standard: TCVN 10304: 2014) [12] and from the pile test results.

A. Prediction of Pile Load Capacity Using Vietnamese Code

First, based on the geological cross-section in Figure 2 and the location of the pile, establish the actual geological column that the experimental pile is placed in. The stratigraphic column and the thickness of each soil layer that the four piles in the survey placed in are shown on the Figures 8 and the Figures 9.

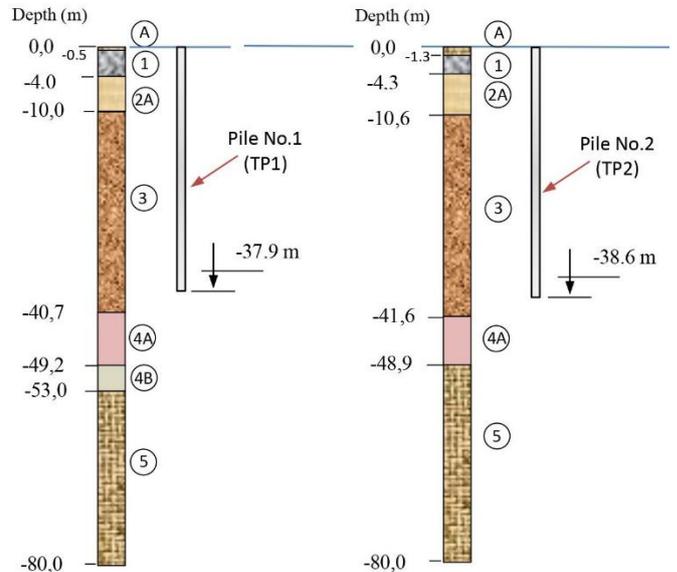


Fig. 8. Soil profile of test piles (TP1 and TP2).

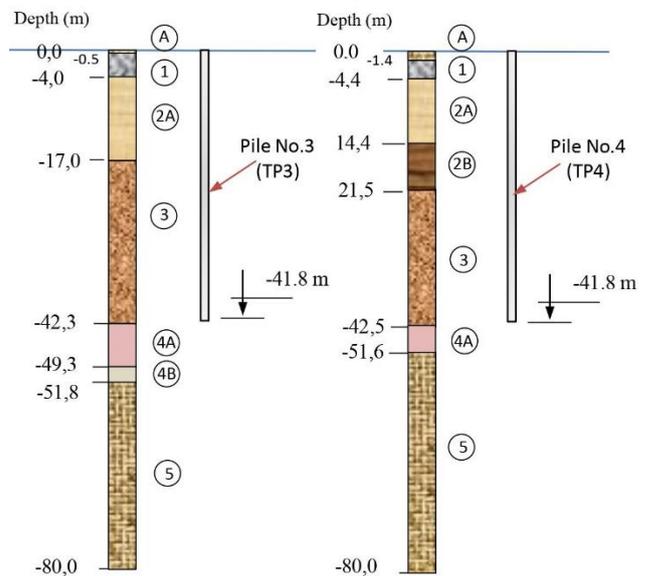


Fig. 9. Soil profile of test piles (TP3 and TP4).

The pile diameter is taken as 600 mm and the lengths of experimental piles TP1, TP2, TP3 and TP4 are 37.9 m, 38.6 m, 41.8 m and 41.8 m, respectively.

Then, the formulas for determining the ultimate bearing capacity of piles in Vietnamese standards are applied to calculate the pile bearing capacity. The ultimate bearing capacity of piles according to this standard uses the symbol $R_{c,u}$.

Case 1: The pile capacities are calculated using the provisions of the TCVN 10304: 2014 code (2014) [12].

$$R_{c,u} = \gamma_c (\gamma_{cq} q_b A_b + u \sum \gamma_{cf} f_{li}) \quad (3)$$

The parameters in this formula strictly comply with the provisions of the standard, its value depends on the geometrical characteristics of the pile, the physical and mechanical parameters of the soil obtained from laboratory experiments such as liquidity index, physical state, soil type and tip depth.

Case 2: Based on the formula Standard Institute of Architecture of Japan - AIJ (1988) - Also shown in the Appendix of Vietnamese standard TCVN 10304:2014, section G3.2:

$$R_{c,u} = q_b A_b + u \sum (f_{c,i} l_{c,i} + f_{s,i} l_{s,i}) \quad (4)$$

Different from case 1, the parameters in formula (3) are determined mainly based on soil properties obtained from field soil testing such as SPT (N) value.

Calculating the ultimate compressive strength of piles for the four survey piles, applying the formulas for the two formulas mentioned above. Summary of the Ultimate load capacity values are presented in Table III.

TABLE III. THEORETICAL PILE CAPACITIES.

Test Pile	Pile dimensions		Ultimate Pile Capacity $R_{c,u}$ (Tons)	
	Length (m)	Diameter (mm)	Case 1: TCVN 10304:2014	Case 2: AIJ (1988)
TP1	37.9	600	495	590
TP2	38.6	600	503	594
TP3	41.8	600	529	622
TP4	41.8	600	567	687

The values of the bearing capacity of the piles calculated according to the formula will be compared with the pile load capacity obtained from the static compression test of the piles themselves.

B. Estimating the ultimate compressive strength of the pile from the field pile static compression test

The four test piles TP1, TP2, TP3 and TP4 have a diameter of 600 mm and a length of 38.8 m, 39.5 m, 41.0 m and 41.0 m respectively and have a working load of 250 tons.



Fig. 10. Pile head displacement meter.

The pile static compression test at the site in 3 stages. Stage 1 with a pile head compression load value of 100% of the working load (the value is 250 tons). Stage 2 with pile head compression load value 200% working load (value is 500 tons) and stage 3 with maximum compressive load (Q_{max}) 220% working load (value is 550 tons).

The load-displacement relationship of the static compression test piles TP1, TP2, TP3 and TP4 at the stages of

compressive loading and unloading are shown in Figures 11, 12, 13 and 14 respectively. The value of pile head displacement corresponding to each level of compressive load with the maximum at each stage of the piles is summarized in Table IV.

TABLE IV. RECORDED HEAD SETTLEMENT.

Stage	Recorded maximum head settlement (mm)			
	TP1	TP2	TP3	TP4
1	9.35	7.56	8.00	5.99
2	24.15	23.33	20.03	19.53
3	51.01	29.16	24.10	24.22

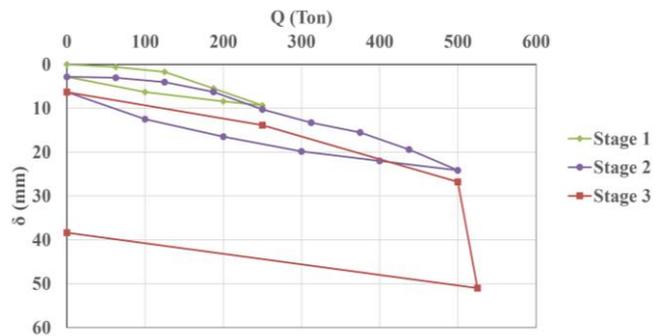


Fig. 11. Load – settlement relationship for pile TP1.

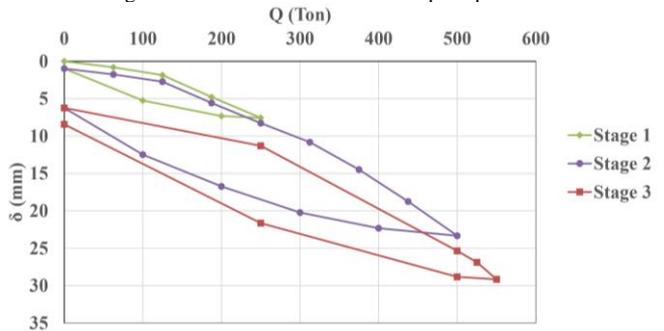


Fig. 12. Load – settlement relationship for pile TP2.

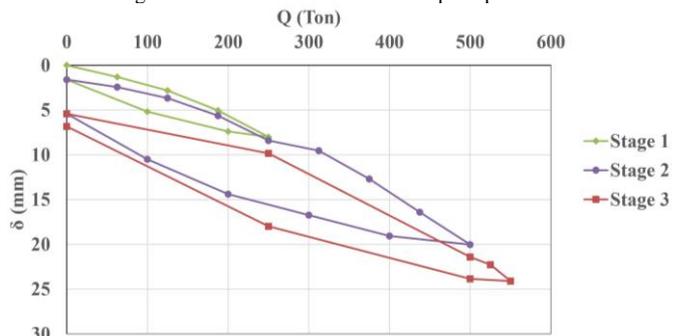


Fig. 13. Load – settlement relationship for pile TP3.

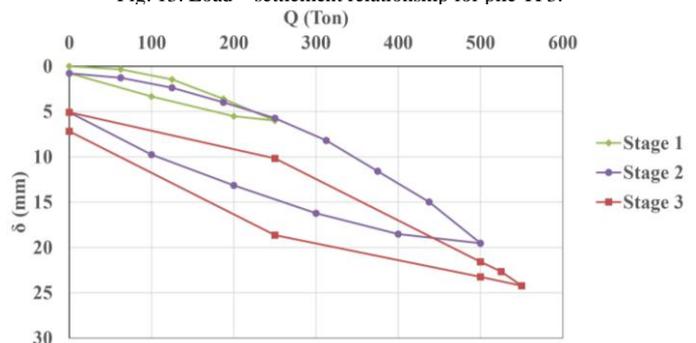


Fig. 14. Load – settlement relationship for pile TP4.

In this section, we use the method of estimating the ultimate bearing capacity of the pile by the graphical method based on the Load - displacement curve in the first stage in the pile static compression test at the site. The graphical methods of Mazurkiewicz [5], [6], Chin-Kondner [7] and Decourt [8] have chosen to apply in this study.

Details of the relationship of Load (Q) and pile head settlement (δ) of the pile static compression test curves in phase 1 of the test piles are redrawn with a larger scale shown in Figures 15, Figure 16, Figure 17 and Figure 18.

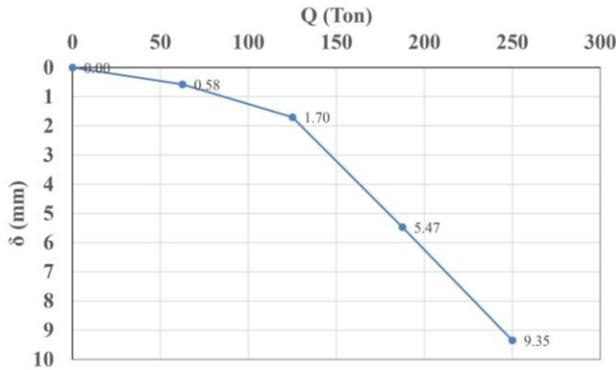


Fig. 15. Load – settlement relationship for pile TP1 (Stage 1).

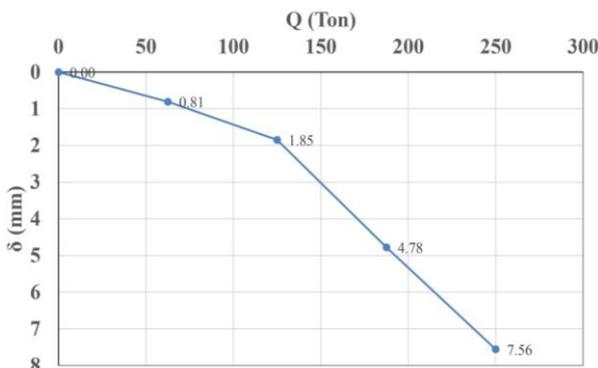


Fig. 16. Load – settlement relationship for pile TP2 (Stage 1).

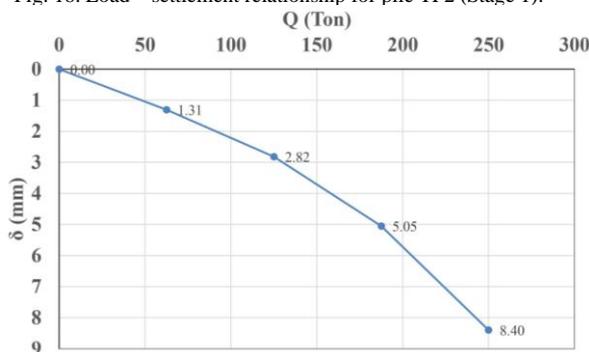


Fig. 17. Load – settlement relationship for pile TP3 (Stage 1).

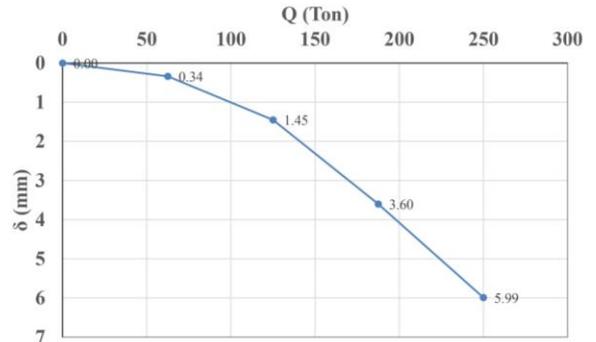


Fig. 18. Load – settlement relationship for pile TP4 (Stage 1).

C. Graphical method used to determine Ultimate Capacity of Piles

1) For TP1 pile

a) Method of Mazurkiewicz

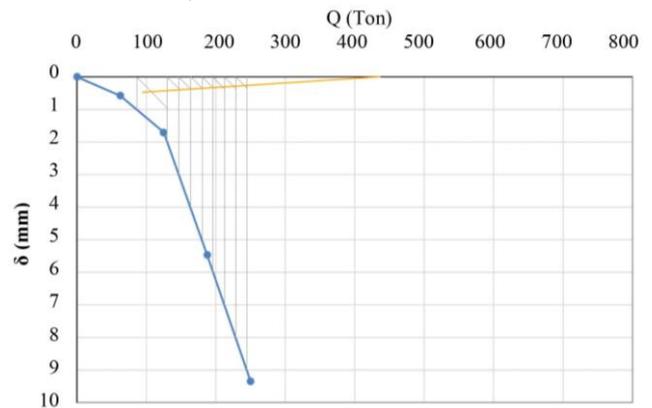


Fig. 19. The graph of determining Q_u of the pile TP1 using Mazurkiewicz method.

Estimated ultimate compressive capacity of piles by this method is $Q_u = 440$ ton.

b) Method of Chin-Kondner

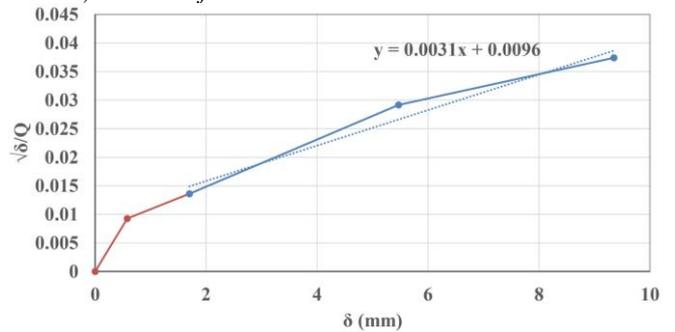


Fig. 20. The graph of determining Q_u of the pile TP1 using Chin-Kondner method.

$$Q_u = \frac{1}{C_1} = 323 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 323$ ton.

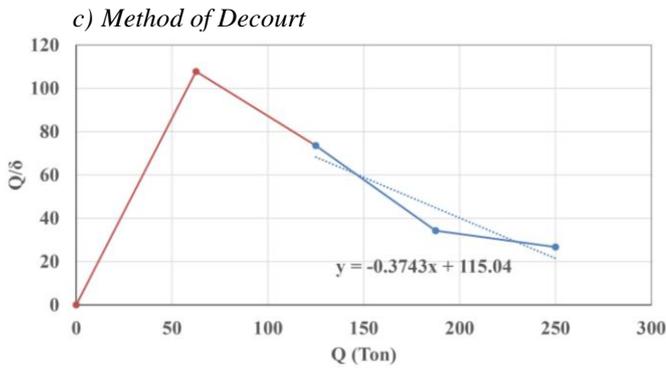


Fig. 21. The graph of determining Q_u of the pile TP1 using Decourt method.

$$Q_u = \frac{C_2}{C_1} = 308 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 308$ ton.

2) For TP2 pile

a) Method of Mazurkiewicz

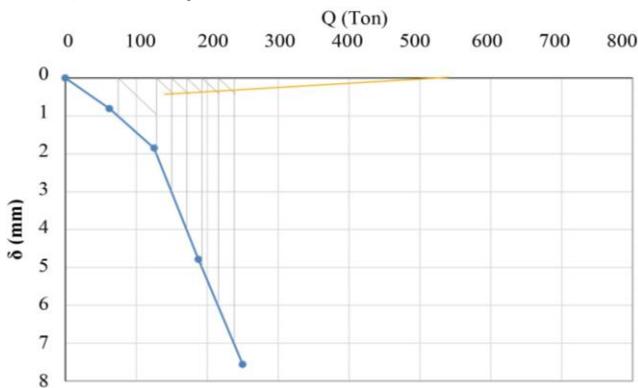


Fig. 22. The graph of determining Q_u of the pile TP2 using Mazurkiewicz method.

Estimated ultimate compressive capacity of piles by this method is $Q_u = 510$ ton.

b) Method of Chin-Kondner

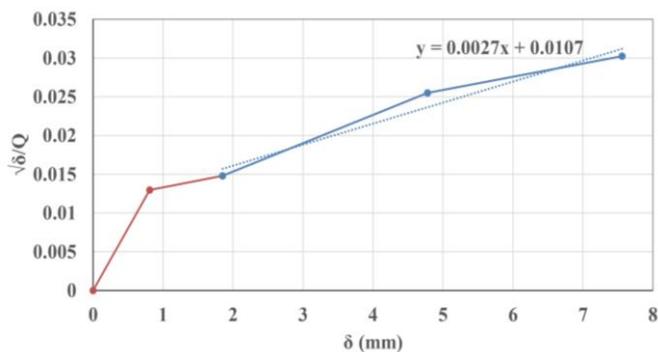


Fig. 23. The graph of determining Q_u of the pile TP2 using Chin-Kondner method.

$$Q_u = \frac{1}{C_1} = 371 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 371$ ton.

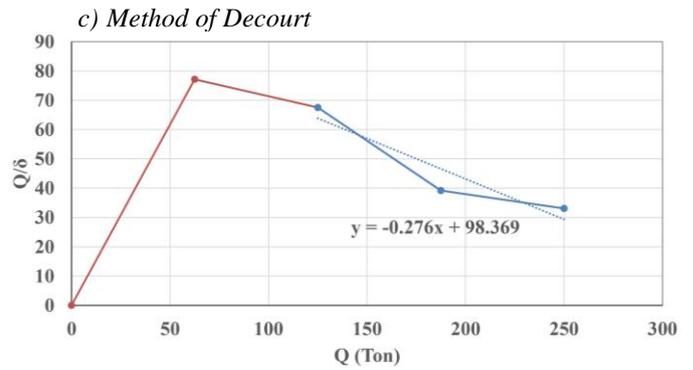


Fig. 24. The graph of determining Q_u of the pile TP2 using Decourt method.

$$Q_u = \frac{C_2}{C_1} = 357 \text{ ton}$$

3) For TP3 pile

a) Method of Mazurkiewicz

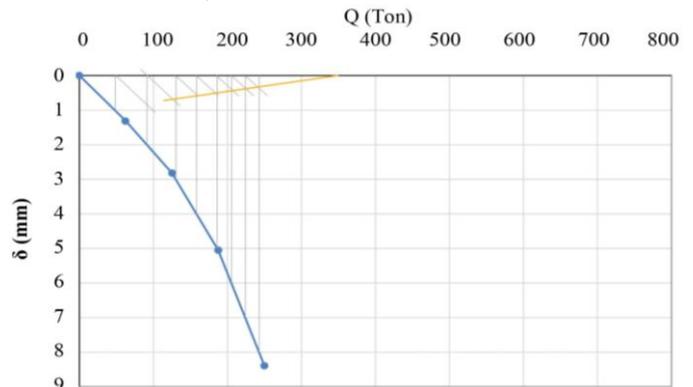


Fig. 25. The graph of determining Q_u of the pile TP3 using Mazurkiewicz method.

Estimated ultimate compressive capacity of piles by this method is $Q_u = 350$ ton.

b) Method of Chin-Kondner

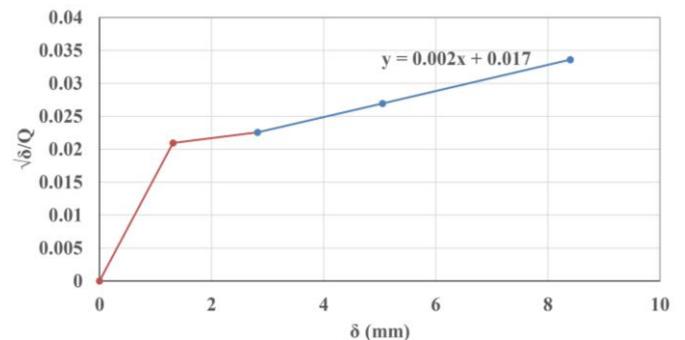


Fig. 26. The graph of determining Q_u of the pile TP3 using Chin-Kondner method.

$$Q_u = \frac{1}{C_1} = 500 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 500$ ton.

c) Method of Decourt

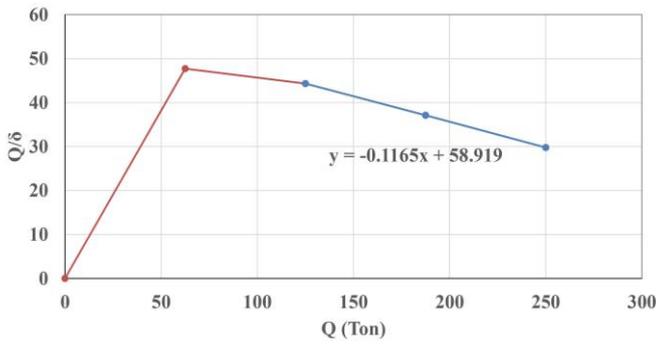


Fig. 27. The graph of determining Q_u of the pile TP3 using Decourt method.

$$Q_u = \frac{C_2}{C_1} = 506 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 506$ ton.

4) For TP4 pile

a) Method of Mazurkiewicz

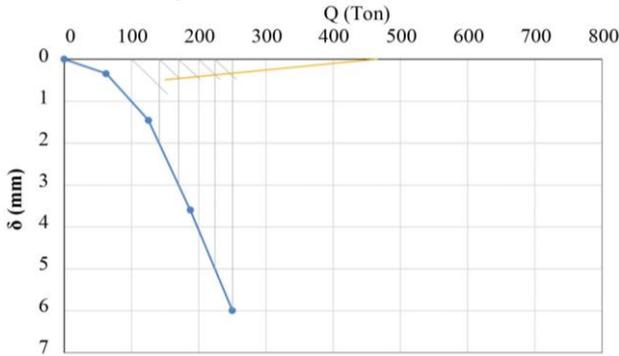


Fig. 28. The graph of determining Q_u of the pile TP4 using Mazurkiewicz method.

Estimated ultimate compressive capacity of piles by this method is $Q_u = 460$ ton.

b) Method of Chin-Kondner

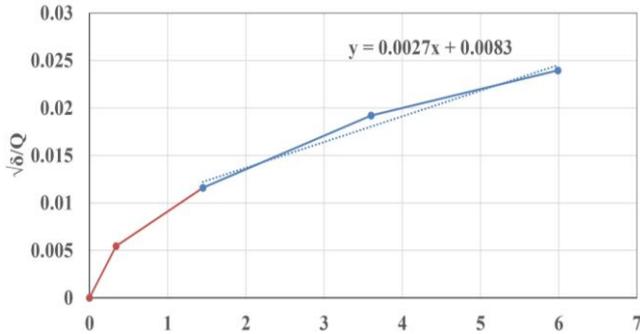


Fig. 29. The graph of determining Q_u of the pile TP4 using Chin-Kondner method.

$$Q_u = \frac{1}{C_1} = 371 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 371$ ton.

c) Method of Decourt

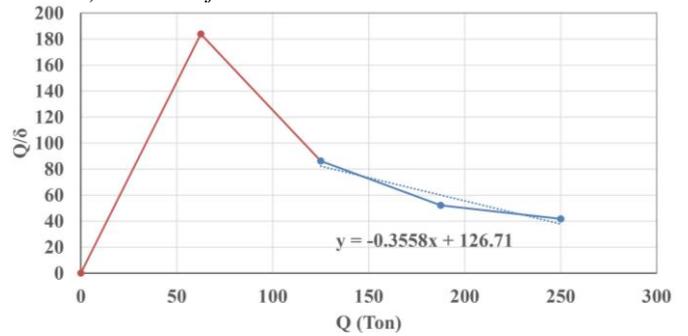


Fig. 30. The graph of determining Q_u of the pile TP4 using Decourt method.

$$Q_u = \frac{C_2}{C_1} = 356 \text{ ton}$$

Estimated ultimate compressive capacity of piles by this method is $Q_u = 356$ ton.

D. Results and Discussions

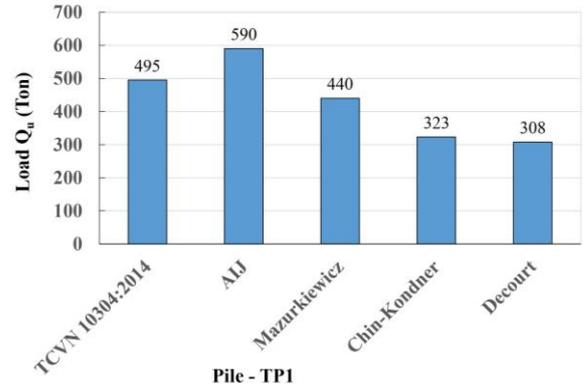


Fig. 31. Q_u of TP1 pile is calculated by 5 different methods.

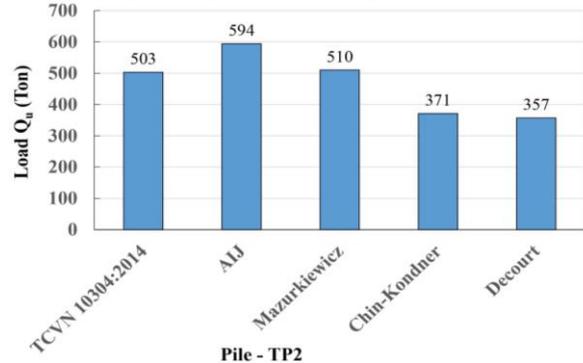


Fig. 32. Q_u of TP2 pile is calculated by 5 different methods.

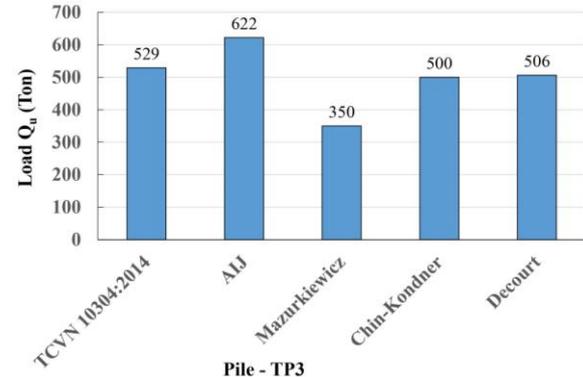


Fig. 33. Q_u of TP3 pile is calculated by 5 different methods.

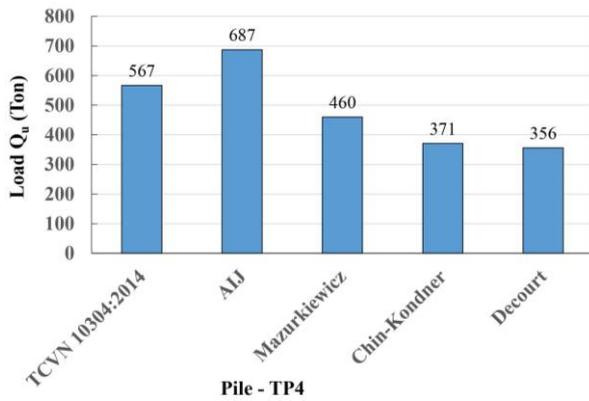


Fig. 34. Q_u of TP4 pile is calculated by 5 different methods.

The Ultimate load capacity of four piles are shown on the Figures from Figure 5 to Figure 7 when calculated by 5 different methods.

Let the symbol Q_{max} be the maximum load of the static compression test at the site and Q_u is the estimate of the ultimate load capacity of the pile by different methods. Calculate the ratio between Q_u and Q_{max} and those value are compared between test piles as well as between different calculation methods. The results are presented in Figure 35 and Figure 36.

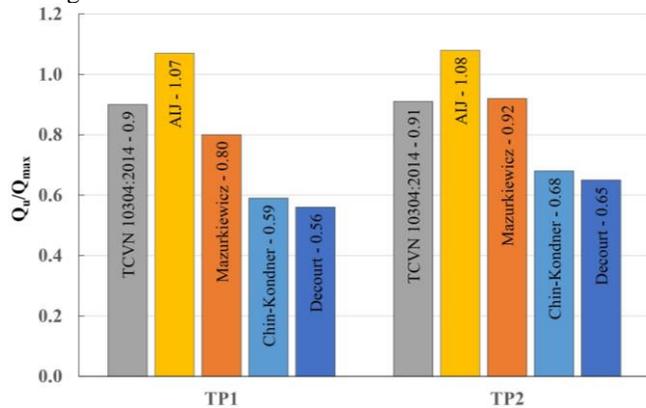


Fig. 35. Value of Q_u/Q_{max} for TP1 pile and TP2 pile.

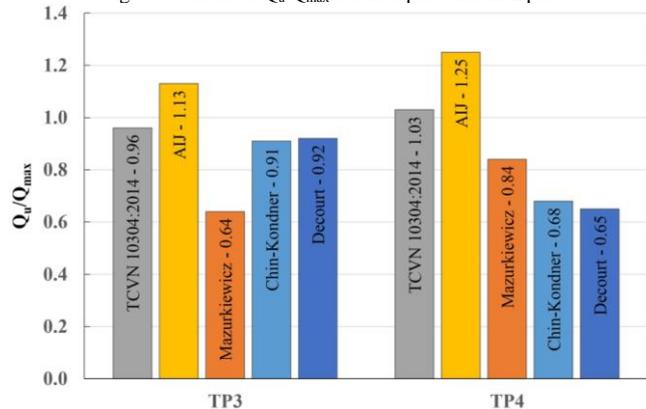


Fig. 36. Value of Q_u/Q_{max} for TP3 pile and TP4 pile.

Set the symbol Q_d to be the working load of the pile. Calculate the ratio between Q_u and Q_d and those value are compared between test piles as well as between different calculation methods. The results are presented in Figure 37 and Figure 38.

Some of the comments made are as follows:

With one pile, different calculation methods result in the ultimate bearing capacity of piles having different values. The method of calculation by the formula has greater results than the method based on the graph of the load relationship and the pile settlement in the pile static compression test. The pile load capacity calculated according to the AIJ formula gives the maximum value.

With 4 static compression test piles in the field, TP1 pile has reached the failure value, which means that the value of the ultimate load capacity of this pile has been determined as $Q_u = 500$ tons. Therefore, it can be seen that the calculation method according to TCVN and AIJ formulas as well as Mazurkiewicz's graphical method gives relatively consistent results compared to the other two methods.

For piles TP2, TP3 and TP4, the pile compression test at the site reached the value of $Q_{max} = 550$ tons, however, these piles have not reached the pile failure limit. Therefore, it can be commented that the calculation of the bearing capacity according to the formula of the Japanese Institute of Architects - AIJ (1988) is relatively more reliable than the other four methods.

It is difficult to comment on which calculation method gives more reliable results. With this pile condition, it is found that this method gives more reliable results, but this method gives unreliable results compared to other pile conditions. The results of calculating the ultimate bearing capacity of each pile are different, depending on each geological form as well as on the value of compressive load and pile displacement when testing piles statically and using different calculation methods.

If we compare the working load of the pile with the ultimate load capacity calculated by five different methods, we find that the factor of safety FS for the piles:

- Pile TP1: $FS = (1.23 \div 2.36)$; Pile TP2: $FS = (1.43 \div 2.38)$;
- Pile TP3: $FS = (1.40 \div 2.49)$; Pile TP4: $FS = (1.42 \div 2.75)$;

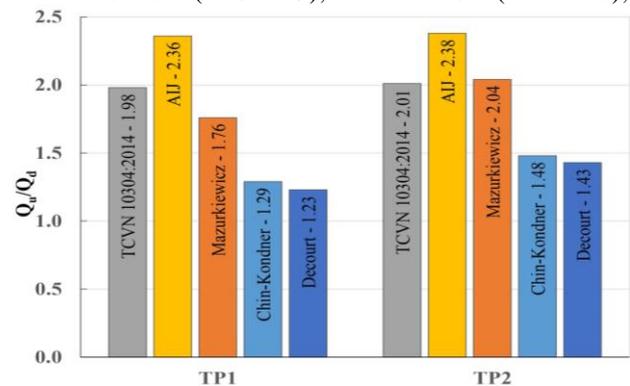


Fig. 37. Value of Q_u/Q_d for TP3 pile and TP4 pile.

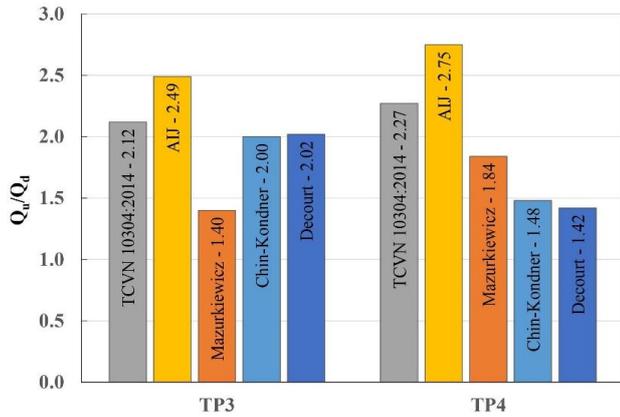


Fig. 38. Value of Q_u/Q_d for TP3 pile and TP4 pile.

V. CONCLUSIONS

The ultimate capacity Q_u for each test pile was predicted using five methods stated above including two methods using theory formula and three graphical methods based on static load test that are used in the evaluation of the pile load test. It is difficult to comment on which calculation method gives more reliable results. With this pile condition, it is found that this method gives more reliable results, but this method gives unreliable results compared to other pile conditions. The results of calculating the ultimate bearing capacity of each pile are different, depending on each geological form as well as on the value of compressive load and pile displacement when testing piles statically and using different calculation methods. Each method can estimate different ultimate load capacity of piles. Within the scope of this study, the number of 4 test piles, and 5 methods of calculating pile load capacity selected, it shows that when using the formula Institute of Architecture of Japan - AIJ (1988) calculates the ultimate bearing capacity of piles giving more reliable results than the other four methods. Compared with the obtained value when the static compression failing test TP1, the TCVN and the Mazurkiewicz method give the results that are not much different from each other.

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