Assessment of load capacity of piles and conclusion of a new criterion using static load tests

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Abstract. In this study, a comprehensive evaluation of 27 field tests carried out on different piles driven in various parts of Iraq. This evaluation is made in terms of the pile bearing capacity of each pile, using nine methods. These methods are (Davison offset limit, Chin kondeer, Brinch Hansen 80%, Brinch Hansen 90%, De court, De Beer, Vander Veen, Fuller&Hoy and Butler&Hoy). The evaluation has shown that De Beer, Chin kondeer, and Vanderveen methods are the best methods because the maximum bearing capacity obtained by these methods is associated with a low pile settlement, although Vander Veen method is time-consuming. Fuller&Hoy and Davison methods are very close and give good results, the maximum bearing capacity obtained by these two methods give high pile settlement, leading to structure failure, especially for structures subjected to loading and unloading. Brinch Hansen 90% and Butler&Hoy methods are suitable methods because they give a good and acceptable bearing capacity with very small pile settlement. As for Brinch Hansen 80% and De Beer methods, they provide high bearing capacity than the failure load. They can be used by multiplying the resulting values by 0.85 to get the maximum bearing capacity of the pile. The study shows that the ratio of 10% after comparing it with results is a bit exaggerating, and 4% of pile diameter can be used as a criterion to find the ultimate load.

1. Introduction
The Pile foundation is the part of the structure used to carry and transfer the loads of the buildings structure to the bearing ground located at some depth below the ground surface [1]. The main components of the foundation are the pile cap and piles. The main types of materials used for piles are wood, steel and concrete. Piles made of these materials are driven, drilled or jacked into the ground and connected to pile caps. Depending upon the type of soil, pile material and load transmitting characteristic, piles are classified accordingly [2]. When a pile passes through poor material, and its tip penetrates a small distance into a stratum of good bearing capacity, it is called a bearing pile. When piles are installed in a deep stratum of limited supporting ability, and these piles develop their carrying capacity by friction along the surface area of the pile, they are called friction piles. Normally the load-carrying capacity of piles results from a combination of points resistance (Qb) and skin friction (Qs). The load taken by a single pile can be determined by static and dynamic load tests. The allowable load is obtained by applying a factor of safety to the failure load [2].
2. Load test on piles at the site

Pile load tests are executed in order to obtain information about both the bearing capacity and the settlement behaviour of a pile. There are two different types of pile load test commercially available. They are static and dynamic load tests, each with its own analysis methods to derive both the capacity and load settlement behaviour.

2.1. Static load test

The test pile capacity is verified by conducting actual loading tests of designated piles in the structure in accordance with ASTM D 1143 [3], slow maintained loading test method, with loads applied by hydraulic jack during a certain period of time. The safe allowable load is determined from the load-settlement curve generated by the incremental loading.

2.2. Relation between settlement and load

A relationship between settlement and load for an individual pile may be obtained by applying a load to the pile in increments ([4] and [5]) (Figure 1). A pause of sufficient duration is made after the addition of each increment to allow settlement to take place until the settlement rate decreases to a value that is acceptably small. When the settlement is measured, the load is kept constant during the pause, the resulting graph of load versus settlement represents an approximation to equilibrium conditions, and from it, the approximate settlement of a pile at a chosen working load, or multiples thereof, may be determined.

![Figure 1. Maintained Loading Pile Test (from Weltman 1980 and ICE 1978).](image-url)
2.3. Determination of ultimate load capacity

The loading of a test pile may be increased progressively by increments in the manner in order to reach the ultimate load capacity. As the maximum load capacity is approached, it may be necessary to decrease the size of the increments. The point at which the soil fails to support the pile may not be clearly shown by the results, and for this reason, the constant rate of the penetration test is more suitable [6].

2.4. Interpretation of failure load

Since a pile is stronger than the soil, the failure load is reached when rapid movement occurs under sustained or slightly increased load (the pile plunges). However, this definition is inadequate because plunging requires large movements. To be useful, a definition of failure load must be based on some mathematical rule. Furthermore, to consider the shape of the load-movement curve or, if not, it must consider the length of the pile (which the shape of the curve indirectly does). Fellenius [1975, 1980] [7] and [8] compiled several methods used for interpreting failure or limit loads from a load-movement curve of a static loading test. The most well-known method is the offset limit method proposed by Davisson [1972] [9]. This limit load is defined as the load corresponding to the movement that exceeds the elastic compression of the pile by an offset of 4 mm plus the diameter of the pile divided by 120. It must be realized, however, that the offset limit load is a deformation limit that is determined, taking into account the stiffness and length of the pile. It is not necessarily equal to the failure load of the pile.

The failure load may be defined as the load that causes a settlement equal to (10%) of the pile diameter [10]. Civil engineering code of practice No.4, 1954 suggests that the ultimate bearing capacity is that load at which the settlement rate continues at a constant rate. De Beer (1967) [11] described a method for slow tests and interpreted failure load as the loading at the intersection of two straight lines, which are plotted on the load-displacement relationship in a double logarithmic scale. Chin (1970) [12] proposed a criterion to find failure load using extrapolation for tests not carried out to failure. This method assumed that the curve of load-settlement is hyperbolic when the ultimate load is approached. Each load value is divided by settlement value, and the resulting value is plotted against the settlement; the plotted value fall on a straight line, so the inverse of the slope of this line is the Chin konder failure load.

The method of intersection is defining the failure as the load at the intersection of the initial straight portion of the curve and final straight portion of the curve, and this method is preferable if the test was continued to failure due to its simplicity in determining the interpreted failure load.

3. Results and discussion

Twenty-seven axially-loaded pile tests are selected from different locations in Iraq. The data are chosen in this paper from different resources and for different types of piles in order to analyze and to predict pile carrying load capacity using different criteria. The piles are divided into two categories: Driven and Bored piles. It is difficult to make a rational choice of the better criterion to use because the one preferred is heavily dependent on one's past experience; one of the main reasons for having a strict criterion is, after all, to enable a set of compatible reference case to be established, that's why methods are chosen for start to predict ultimate pile capacity from the load – settlement curve as shown in figure 2.
3.1. Analysis of static pile load tests

3.1.1. Davisson method
By examining the maximum loading values obtained by this method and shown in Figure (3), the following points can be concluded:

- When the pile reaches the failure state, and the deflection curve continues falling, the load settlement intersects offset limit is regarded as the load failure point. This drawback can be overcome by selecting a factor of safety of more than 2.5 so that a reasonable load-bearing capacity is obtained.
- If the pile is tested to double the working load, no intersection occurs between the load-settlement curve and offset limit, indicating the maximum load capacity. Hence, the test load can be considered as the maximum load, and a factor of safety of 2 or even 1.5 can be adopted.

Figure 2. Load settlement curve (case 1).
3.1.2. Chin Konder method

This method may be much more acceptable because acceptable, and a reasonable maximum load is obtained by this method due to the resulting fall is small compared with that of the Davisson method, as shown in Figure (4).

- If the load is three times the actual load, when the pile fails, it is noticed the resulting maximum load is not the load failure and give a low settlement. Therefore, this is a good method of analysis.
- If the pile is tested to double working loaded and it does not fail, it is found that the resulting load exceeds the test load. Therefore, this method is considered a suitable one since it reflects the actual situation and detects the maximum load when the pile succeeds or fails.

3.1.3. Decourt Method [13].

From analyzing the test results obtained from piles tested to failure, it is noticed the maximum load of this method is more than the failure load. As shown in Figure (5). Thus:

- When the pile reaches the failure stages, and we are sure it will fail, we find the maximum load of this method exceeds failure to load a little this drawback can be overcome by multiplying the maximum load from Decourt's method by 85 % to get a reasonable and acceptable load.
- If the tested pile is loaded to double the actual load and passes the test, the failure obtained can be multiplied by 85% to get an acceptable failure load.

Figure 3. Ultimate failure, according to Davisson offset limit method.
3.1.4. Brinch Hansen 80% Method [14]
Its results are similar to the results of Decourt's method to a large extent. As shown in Figure (6) and Table (1), the maximum load suggested from this method is more than load by 10%-15%. Consequently, an acceptable maximum load can be obtained by multiplying the resulting load by 85%.

3.1.5. Brinch Hansen 90%
From the sample tests carried out in this research, it is found that Brinch Hansen 90% method is extremely suitable as it gives acceptable and reasonable maximum load the original curve of load-settlement intersects with load-sett. at 0.9 Q. as shown in Figure (7). The maximum load can be found in destructive testing when loaded to actual double load no intersection occurs; therefore, this method can be used with confidence in working tests. From the drawing, it is noted that:
- If B.H. 90% curve moves in parallel to load-sett. curve, the maximum load is much more than the applied loads.
- If the last point in B.H, 90% lies directly where the last point of load-sett. curve, the maximum load is very close to the load test.
3.1.6. De Beer method
The method is based on log load – log sett, as shown in Fig (8). Piles were analyzed using this method; it is concluded chart.
- This method is applied to piles that reach the failure stage or while were tested with a load three times in magnitude the actual load.
- The fracture point can be predicted through the sharp fracture in the curve.
- This method is time-dependent. The fracturing load – settlement. Curve occurs when the pile is a test – loaded for 24 hrs.
- If the pile is loaded with a load that is double in the magnitude of the valued load and the load is kept for a long time, a fracture in load – sett. curve occurs. This load can be considered a suitable maximum load. But a factor of safety ranging between 1.5 and 1.7 should be selected.

3.1.7. Vander Veen method [15]
This is considered the most helpful method is pile testing because it gives the engineer or the designer the chance to select a variety of suggested loads while he can expect the maximum load shown in figure (9). From table (1) it is seen that it can be used with both destructive and working tests.

\begin{align*}
  y & = 4000.00x + 4410.00 \\
  R^2 & = 0.9229.00
\end{align*}

- **Figure 6.** Ultimate failure, according to Brinch Hansen 80% method.
- **Figure 7.** Ultimate failure, according to Brinch Hansen, 90%.
3.1.8. Fuller, & Hoy and Butler & Hoy Method [16] and [17]
Butler and Hoy method in fig. (10). similar to De Beer method to a great extent because it can be used Gin tests that reach the failure stage, but it is useful with tests under double working load, it can be used reliably if the factor of safety is less than 1.75 Fuller and Hoy method is similar to Davisson method except that it gives great settlement.

3.1.9. Terzaghi method
It depends on analyzing methods for finding the maximum load capacity of piles and finding maximum fall for a maximum load that is less than 10% pile diameter.

4. New criterion for determining the ultimate capacity of piles
From table (1), it is seen most failure loads is against the settlement of 4% of pile diameter. In field test, it was seen that when the pile settlement exceeds 4% of pile dimension, the dial gauge beings to fall; when the dial gauge of the load is adjusted, the pile continues falling, repeating the recon leads to final pile failure. In consequence, a 4% ratio of pile dimension is a very convenient criterion to calculate the maximum loading capacity in terms of pile dimensions.

Figure 8. Ultimate failure, according to De Beer method.

Figure 9. Ultimate failure, according to Vander Veen method.
Figure 10. Ultimate failure, according to Fuller & Hoy and Butler & Hoy method.
Based on the objective results throughout this paper, the following conclusion can be made:

5. Conclusions

Table 1. Predicted ultimate pile load by different methods.

| Pile Type | Pile Dimension | Predicted Ultimate Pile Load (Tons) |
|-----------|----------------|-------------------------------------|
|           | Length m | Dia. cm | Davison | Chin | Brinch Hansen 80% | Decourt | Brinch Hansen 90% | De Beer | Vander veen | Fuller &Hoy | Butler &Hoy | 4% of pile dia. |
| Bored     | 22.5     | 70      | 194     | 174   | 208 | 212 | 191 | 170 | 190 | 197 | 187 | 186 |
| Bored     | 22.5     | 70      | 194     | 174   | 211 | 209 | 186 | 170 | 180 | 196 | 186 | 186 |
| Bored     | 24.0     | 70      | 197     | 177   | 216 | 225 | 194 | 190 | 140 | 198 | 188 | 190 |
| Bored     | 24.5     | 70      | 193     | 174   | 208 | 221 | 194 | 190 | 140 | 198 | 186 | 183 |
| Bored     | 24.5     | 70      | 196     | 177   | 216 | 224 | 195 | 190 | 140 | 198 | 186 | 188 |
| Bored     | 24.5     | 70      | 193     | 170   | 198 | 207 | 180 | 140 | 160 | 198 | 186 | 180 |
| Bored     | 24.5     | 70      | 193     | 177   | 208 | 212 | 181 | 160 | 166 | 196 | 180 | 182 |
| Precast   | 11.0     | 28.5x28.5 | 144  | 132   | 153 | 153 | 95  | 126 | 144 | 146 | 142 | 137 |
| Bored     | 15.0     | 60      | 138     | 121   | 130 | 148 | 128 | 120 | 120 | 138 | 130 | 127 |
| Bored     | 20.0     | 60      | 200     | 177   | 218 | 211 | 198 | 190 | 200 | 200 | 195 | 190 |
| Bored     | 20.0     | 80      | 318     | 287   | 342 | 375 | 305 | 300 | 270 | 315 | 295 | 310 |
| Precast   | 12.0     | 28.5x28.5 | 91   | 79    | 100 | 95  | 82  | 80  | 85  | 92  | 90  | 86  |
| Bored     | 22.5     | 70      | 195     | 176   | 191 | 219 | 198 | 190 | 140 | 196 | 180 | 175 |
| Bored     | 23.0     | 70      | 114     | 126   | 165 | 132 | 117 | 100 | 120 | 120 | 109 | 112 |
| Precast   | 12.0     | 28.5x28.5 | 96   | 86    | 99  | 108 | 95  | 95  | 144 | 96  | 94  | 84  |
| Precast   | 12.0     | 28.5x28.5 | 78   | 69    | 99  | 83  | 75  | 63  | 75  | 78  | 75  | 75  |
| Precast   | 12.0     | 28.5x28.5 | 111  | 100   | 111 | 126 | 102 | 88  | 105 | 110 | 98  | 105 |
| Precast   | 12.0     | 28.5x28.5 | 93   | 86    | 96  | 118 | 88  | 88  | 75  | 94  | 86  | 90  |
| Precast   | 14.0     | 28.5x28.5 | 118  | 113   | 134 | 152 | 115 | 100 | 85  | 116 | 108 | 105 |
| Precast   | 12.0     | 28.5x28.5 | 94   | 86    | 106 | 112 | 89  | 88  | 95  | 94  | 87  | 90  |
| Precast   | 11.5     | 28.5x28.5 | 94   | 84    | 104 | 109 | 88  | 88  | 90  | 92  | 86  | 88  |
| Precast   | 14.0     | 28.5x28.5 | 97   | 86    | 107 | 119 | 88  | 88  | 90  | 96  | 87  | 90  |
| Bored     | 24.5     | 70      | 196     | 176   | 208 | 190 | 173 | 150 | 160 | 192 | 173 | 185 |
| Bored     | 24.5     | 70      | 130     | 119   | 144 | 139 | 125 | 100 | 110 | 136 | 114 | 118 |
| Bored     | 24.5     | 70      | 156     | 134   | 164 | 144 | 144 | 100 | 125 | 154 | 136 | 135 |
| Bored     | 24.5     | 70      | 188     | 163   | 197 | 193 | 169 | 160 | 170 | 188 | 173 | 180 |
| Bored     | 24.5     | 70      | 179     | 154   | 193 | 189 | 160 | 170 | 172 | 179 | 168 | 180 |

5. Conclusions

Based on the objective results throughout this paper, the following conclusion can be made:

- All methods can be used to evaluate piles tested three times their working capacity. In case when piles are tested, only double working loads because enough dead loads are available; therefore, Chin Konder, B.H. 90% and Davisson methods are to be used.
- For structure subjected to loading and unloading or when dynamic movements take place: it is recommended to use methods such as chin konder and Buttler methods which give less settlement.
- Brinch.Hansen. 90%, Vander Veen, De Beer and Chin knoder methods are the best methods since they give acceptable maximum load capacity against a low settlement.
- Fuller and Davisson methods should not be used because they give load capacity against great settlement resulting in early failure.
- Brinch.Hansen 80% and Decourt methods can be adopted at multiplying the maximum load obtained by 0.85.
- Butler method is similar to De Beer method, but they are to be used only in test to failure.
- The ratio 4% of pile diameter can be used as a criterion in maximum bearing capacity.
6. References

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