PREDICTABILITY OF THE INTERNATIONAL GEOTECHNICAL CODE FOR THE ESTIMATING ULTIMATE BEARING CAPACITY OF LARGE-DIAMETER BORED PILES

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This technical report presents a comparative study of the predictability of estimating the ultimate pile capacity between widely accepted international design codes of pile foundations, including the: Japan Road Association code (JPA, 2002), DIN 4014 (1990), Egyptian geotechnical design code-Part 4 (2001), and AASHTO (2007). The ultimate pile capacities inferred from the results of load-settlement test using the Chin extrapolation method (1970) were compared with the predicted values obtained from international codes of design. The study covers a wide range of Egyptian soil formations by utilizing 58 case studies of bored piles (loading tests) constructed and tested in numerous regions inside Egypt. The average error percentage obtained from each code of design has been calculated, and the predictability of these design codes has been evaluated based on four independent statistical criteria. JRA code (2002) and DIN 4014 (1990) have revealed well predictability and accuracy of estimating ultimate pile capacity against the other international codes of design.

Key Words : *bored piles, end-bearing resistance, skin friction resistance, single pile, settlement*

1. INTRODUCTION

The current Egyptian geotechnical code, Part 4 (2001), introduces design values and empirical equations for the design of bored piles, which are related to neither physical nor mechanical properties of the Egyptian soils. Therefore, the committee for development and update of the Egyptian geotechnical code of practice has a newly initiated thinking towards enhancement of the predictability of the design code for bored piles adopted in the current version. Furthermore, some efforts have been done recently to investigate the predictability and accuracy of the design values given in the Egyptian geotechnical code for design of the bored pile foundations[1), 2), 3)].

In Egypt during the last two decades, the use of large-diameter bored piles (piles of diameter greater than 60cm) has become a constant practice in medium- to large-size projects as alternative to a group of small-diameter piles[1)]. They are constructed up to 3m in diameter, and lengths exceeding 40m, often with an under-reamed or belled base[4)].

Estimation of the allowable bearing capacity of bored piles is based mainly on consideration of stability against shear failure, and it can be estimated by dividing the ultimate bearing capacity of pile by an appropriate safety factor[5)]. The ultimate value of skin friction resistance is mobilized after settlement in the range of 5mm to 10mm, while the ultimate value of end-bearing resistance is mobilized at a toe settlement of 5% to 10% of the pile diameter. Consequently, skin friction resistance of piles, in most cases, will be fully mobilized long before the maximum base resistance is reached[6)]. However, the acceptance criteria for single bored piles after load testing is based mainly on the permissible settlement criteria in most specifications and codes. Since a large-diameter bored pile subjects a considerable volume of soil beneath its base to vertical stress,

corresponding settlement will be of higher significance in assessing its allowable bearing capacity. The governing criterion for estimating the allowable load capacity of large-diameter piles is rather a settlement criterion than a criterion for stability against shear failure.

Several methods and techniques are found in the literature for the design of bored pile foundations. Most of the international geotechnical design codes distinguish between the design methodologies of bored piles of diameter smaller than 60cm and those of diameter greater than 60cm. The design methodologies are based on recommended parameters to estimate skin friction with a limited end-bearing value that is bound with the level of acceptable settlement for a single pile. Hence, this technical report introduces an analytical and a comparative study between some of the widely used international geotechnical codes for pile foundations design. The implemented codes of design in this work are: Egyptian geotechnical design code[7] Part 4 (2001), German bored piling code[8] (DIN 4014, 1990), Japan Road Assoc. code[9] (JRA, 2002), and the AASHTO[10] (2007). Consequently, assessment of the predictability of these design codes to the ultimate capacities of large-diameter bored piles is discussed through this comparison.

Fifty-eight pile load-settlement tests, collected from many locations in Egypt were used in the study. The ultimate bearing capacities of the piles were predicted from the pile load tests results using the Chin extrapolation method[11].

2. PILE CAPACITY COMPONENTS

Pile foundations are originally designed to resist both skin friction and end-bearing loads. Thus, the design involves the use of equations of bearing capacity, such as those of Terzaghi (1943). **Fig. 1** shows a single pile of uniform cross-section, diameter D, length L, installed in a homogeneous mass of soil of known geotechnical properties. A static vertical load is applied on the pile top. If the ultimate load applied on the top is Q_u, part of the load is transmitted to the soil along the length of the pile, called the ultimate skin friction load (Q_{su}), and the balance is transmitted to the pile base, called the ultimate end-bearing load (Q_{bu})[12].

The total ultimate load Q_u is expressed as the sum of those two loads, i.e.,:

$$Q_u = Q_{su} + Q_{bu} - W_p \qquad (1a)$$

$$Q_u = \sum q_{(su)i} A_{si} + q_{bu} A_p \qquad (1b)$$

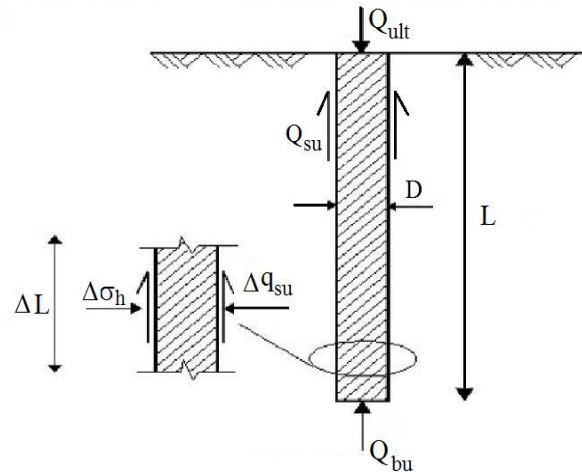where: q_{bu} = ultimate end-bearing resistance, A_p =

Fig.1 Pile resistance components generated due to external applied vertical load.

bearing area of pile base, A_{si} = nominal surface area of pile shaft in layer no. (i), $(q_{su})_i$ = ultimate skin friction resistance per unit area of the pile shaft in layer no. (i), and W_p = weight of pile (neglected).

The maximum value of skin friction resistance is mobilized after 5 to 10mm of local settlement (equivalent to 0.5% to 1% of the pile diameter in general), while the maximum value of end-bearing resistance is mobilized at a toe settlement of 5% to 10% of the pile diameter at toe[13]. After full mobilization of skin friction resistance, any increase in axial capacity is transferred fully to the pile base[14].

3. EVALUATION OF ULTIMATE PILE LOAD USING THE CHIN METHOD (1970)

To estimate the ultimate load of a pile from a loading test that was not carried out to failure, many methods have been proposed in the literature to extrapolate the load-settlement curve. In this study, the method by Chin (1970) was implemented to extrapolate the results for estimating the ultimate pile capacity. This method, termed the Chin-Kondner, is based on the assumption that the relationship between the applied load (Q) and pile head settlement (S) is a hyperbolic relationship, and that a plot of (S/Q) versus (S) is linear. Consequently, a straight line can be obtained by plotting the measured pile head displacements divided by the corresponding loads on the y-axis and the pile head settlement on the x-axis, as shown in **Fig. 2**. In a typical pile loading test, the values will fall along a straight line after some initial variation. Eq. (2a) represents a standard form of straight line equation for that line. The inverse of the slope of that equation, gives the ultimate failure load (Eq. (2b)).
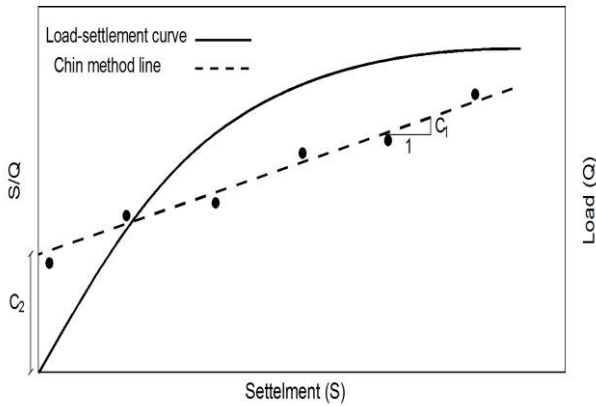
Fig.2 Determination of ultimate failure load according to the Chin-Kondner criterion (After Chin 1970).

Fig.3 Dimensions of the piles and number of databases used in the study.

$$S/Q = C_1 S + C_2 \qquad (2a)$$

$$(Q_u)_m = \frac{1}{C_1} \qquad (2b)$$

where: C_1 = slope of the straight line, C_2 = intercept of the S/Q axis.

The reason for using the Chin method (1970) is that it is applicable for both quick and slow tests, provided constant time increments are used. Also, the number of monitored values are too few in a standard test; the interesting development could well appear between the seventh and eighth load increments and be lost[15].

4. INTERNATIONAL CODES OF PREDICTING ULTIMATE VERTICAL PILE CAPACITY

Design steps (procedures) and a brief presentation for each code of practice used in this study are given in the Appendix of this technical report.

Upon reviewing the set of international design codes, implemented in this study, it has become obvious that:

- there are some design codes that clearly differentiate between the design of large-diameter bored piles and the small-diameter ones, while other codes consider the behavior of both types of piles as similar;
- there are different concepts and approaches for the design of bored piles.

On one hand, AASHTO (2007) introduced design concepts that were based on the traditional theorem of bearing capacity for estimating unit end-bearing and skin friction resistances, but it has imposed limiting design values for end-bearing and skin friction stresses that must be considered by designers during the prediction of ultimate pile capacity.
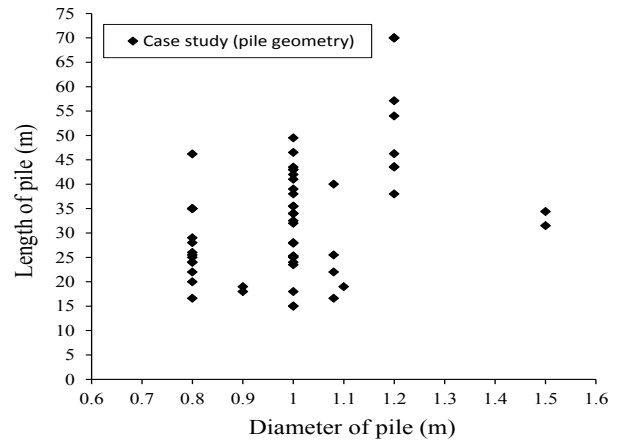
On the other hand, different methodologies for the design of bored piles have been given by the Egyptian geotechnical code (2001), the German bored piling code (DIN 4014, 1990), and Japan Road Association (JRA, 2002) in which design tables including design parameters have been presented. DIN 4014 provides a method for designing bored piles to be adopted where no experience is available and no loading tests have been carried out. The load-settlement curve of a single pile may be determined using the values given in these tables (based on CPT cone resistances) and in cohesive soils (based on C_u-values). The values given in these tables are empirical and obtained from a number of loading tests carried out on piles.

5. CASE STUDIES AND SOIL CHARACTERIZATION

(1) Database

In this study, 58 case histories of field pile-loading tests were carried out up to twice the working load according to the procedures recommended in ASTM D1143–81[16]. They were assembled from projects in several locations inside Egypt. **Fig. 3** depicts the dimensions of the piles (L and D), and the number of databases (pile-loading tests) used in the current study. The pile diameters range from 80cm to 150cm and the pile lengths extend from 15 to 70m below the ground surface. **Table 1** represents a sample of the collected data and soil profile.

(2) Soil characterization

An extensive geotechnical investigation program was carried out in the field and in the laboratory, including over 200 boreholes with depths of 25m to 80m from the ground level.

Table 1 A sample of the collected databases (pile load tests) used in the study.

Pile no.	Length (m)	Dia. (cm)	Location	Soil stratum	Depth (m)	N_{SPT}	C_u (kN/m²)	γ (kN/m³)
1	34	100	Kafr El-Skeihk	- V. soft clay	0 – 13.5	-----	15	17.2
				- Medium sand	13.5 – 15.5	18	------	17.8
				- Hard clay	15.5 – 17.8	-----	200	20
				- Dense sand	17.8 – 20	31	------	19.2
				- Hard clay	20 – 31.5	-----	200	20
				- V. dense sand	31.5 - 34	> 50	------	21
10	29	80	Al-Giza	- Medium clay	0 – 2.0	-----	50	18
				- Medium sand	2.0 – 9.0	20	-----	16
				- V. dense sand	9.0 – 15	57	-----	18.5
25	28	80	El-bihara	- Fill material	0 – 1.0	-----	-----	15
				- V. loose sand	1.0 – 4.0	7	-----	16.5
				- Medium dense sand	4.0 – 17	20	-----	18.5
				- V. dense sand	17 - 35	> 50	-----	20
35	35	80	Port Said	- Fill material	0 – 1.75	-----	-----	15
				- Soft clay	1.75 -14.8	-----	25	18.5
				- V. stiff clay	14.8 – 24.0	-----	140	17
				- Med. dense sand	24.0 – 27.0	22	-----	17.9
				- Hard clay	27.0 – 42.0	-----	200	20
				- V. dense sand	42.0 – 50.0	> 50	-----	21
47	19	110	Al-Giza	- Fill material	0 – 1.2	-----	-----	16
				- Med. stiff clay	1.2 – 4.7	-----	100	17.5
				- V. loose sand	4.7 – 10.0	8	-----	17
				- Med. dense sand	10.0 – 16.6	29	-----	18
				- Dense sand	16.6 - 25	40	-----	19
51	19	90	Damietta	- Med. stiff clay	0 – 4.7	-----	85	18.5
				- Soft clay	4.7 -6.5	-----	30	15
				- Loose sand	6.5– 11.5	12	-----	17
				- Med. dense sand (1)	11.5 – 14.8	26	-----	17.5
				- Med. dense sand (2)	14.8 – 20.0	30	-----	18.5
				- Dense sand	20.0 –25.0	40	-----	19.5

Additionally, Standard Penetration Test (SPT) and unconfined compression tests have been conducted continuously for sandy and clayey soil layers, respectively, during the boring of each borehole. Consequently, soil strength parameters (φ and C_u), which are used for pile design were estimated based on these results. **Table 1** illustrates the geotechnical soil properties for a sample of the database.

a) Cohesionless soil stratum

The SPT blow counts/30cm (N_{SPT}) along the embedded length of the pile were used as a measure of soil strength for the purpose of this study. To account more accurately for the variability of soil properties along the shaft of the pile, the embedded length of the pile shaft was divided into segments of equal thickness, and the average value of N_{SPT} over each segment was calculated. The average N_{SPT} count, N_{avej}, for each subdivision, j, was calculated as follows[17]:

$$\left(N_{SPT}\right)_{avrg} = \frac{\sum N_i Z_i}{\sum Z_i} \tag{3}$$

where: Z_i is the soil layer thickness in that segment with N_i over that layer.

In addition, as suggested by Liao and Whitman (1986), for sand, the value of N_{SPT} for each subdivision is corrected for overburden pressure, as given below[18]:

$$N_{corrt} = C_N \left(N_{SPT}\right)_{avrg} \tag{4a}$$

$$C_N = \sqrt{\frac{95.76}{\sigma_v'}} \tag{4b}$$

where: C_N is the adjustment factor for effective overburden pressure, and σ_v' is the effective overburden pressure (kPa).

b) Cohesive soil stratum

Similarly, cohesive soil layers were investigated, and the average values of undrained shear strength (C_u) were separately evaluated for each layer. The

following formula was used to estimate the average values of C_u.

$$(C_u)_{avrg} = \frac{\sum C_{ui} Z_i}{\sum Z_i} \qquad (5)$$

6. SOIL FORMATIONS IN EGYPT

According to the Egyptian geotechnical code (2001), the soil formations in Egypt can be classified into two main deposits: alluvial and desert soil deposits.

Alluvial soil formations cover most of the urban regions of Egypt. Normally, the top layer is a fill material that extends from 1.5m to 4m deep. Then, clay and silt soil appears with thickness of 0 to 8m in some areas. The following layer is silty clayey sand with thickness ranging from 3.5m to 8.5m. The ending layer is yellow to brown, medium to fine sand. **Fig. 4 (a)** illustrates a typical alluvial soil deposits profile found along the Nile valley, in the north and east of Delta, and some parts of the north coastal regions of Egypt. Regarding the ground water table, it can be detected at depth from 1m to 2m from the ground surface.

On the other hand, desert soil formations encompass the western and eastern regions of Egypt, and the majority of these areas are uninhabited. **Fig. 4 (b)** shows a typical soil profile in desert soil deposits. Typically, the first upper layer is transported soil consisting of very fine loose sand, and it extends to a depth of 2m from the ground surface. Then, the following layer is hard swelling clay with thickness of 7m. Next, the third stratum is medium to fine sand. The base stratum is sandstone and in some areas can be limestone. The ground water table is found at a deep layer of more than 40m.

7. ANALYSIS OF RESULTS

Two types of numerical analysis were performed: (1) percentage of average error, and (2) statistical analysis. Ultimate loads were calculated quantitatively on the average for all databases, even if they were occasionally overestimated and/or underestimated.

(1) Percentage of average error

This analysis indicates whether the code of design is conservative or unconservative. The results of the calculated pile capacities using the adopted international codes of design are given in **Table 2**. The working loads and the associated settlements are also presented. Moreover, percentage of average error

obtained from each code of design is given in **Table 3**. The error percentage can be calculated using Eq. (6). Moreover, it is worth mentioning that the negative sign of average error indicates that this code of design under-predictes the values of ultimate pile capacity, which means that it is a conservative design method. However, the positive sign indicates that this code is an over-predicting design method for bored pile foundations.

$$\text{Error}(\%) = \frac{\left[(Q_u)_p - (Q_u)_m \right]}{(Q_u)_m} * 100 \qquad (6)$$

where: $(Q_u)_p$ = ultimate predicted pile capacity, and $(Q_u)_m$ = ultimate measured pile capacity.

It can be seen that the JRA (2002) yields the lowest average error percentage of 11.8% compared to those values resulting from other codes of design. It is an over-predicting design method; this can be attributed to the slightly high design values adopted by the JRA (2002) for calculating both skin friction and end-bearing resistance of pile.
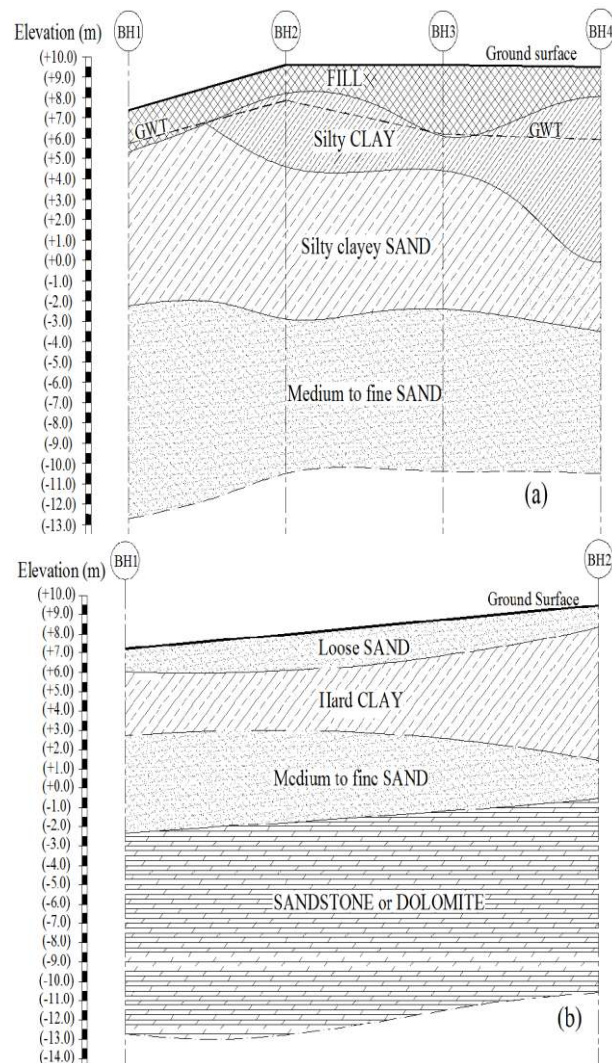

Fig. 4 Typical longitudinal cross-section of the predominant soil deposits in Egypt: (a) alluvial, and (b) desert.

Table 2 Sample of the results of predicted and measured pile capacities and settlements at working loads.

Pile no.	Length (m)	Dia. (cm)	Working load (kN)	Settlement at working load (mm)	Predicted ultimate load in kN $(Q_u)_P$				Measured ultimate pile capacity in kN $(Q_u)_m$
					Egyptian code (2001)	Japan Road Assoc. (2002)	DIN 4014 (1990)	AASHTO (2007)	
2	29	80	1500	1	4009	7931	6133	5583	7007
7	39	100	2700	1.72	9069	16183	12410	8259	10900
16	32.5	100	2200	1.87	6383	11702	8913	6260	8175
31	34.5	150	6000	8.82	14635	24498	21383	24498	24525
39	70	120	6000	8.75	12447	19187	21660	15360	19620
45	22	108	3600	1.77	6702	13281	9104	8495.50	8175

Table 3 Results of average errors obtained from thecodes of design.

Code of design	Average error percentage for 58 case studies
Egyptian code (2001)	-41%
DIN 4014 (1990)	-13.1%
Japan Road Assoc. (2002)	11.8%
AASHTO (2007)	-31.3%

Although JRA (2002) produces over-estimated values of ultimate pile capacity, it has to yield sound allowable pile capacities when factor of safety is involved in the analysis design of piles.

On the other hand, the highest average percentage of error was -41% calculated from the Egyptian geotechnical code (2001), which basically recommends low design parameters for resistance between pile shaft and soil medium during pile movement, and it also neglects the effect of soil strength around the pile tip during calculation of the end-bearing resistance. The remaining two codes of design, DIN 4014 (1990) and AASHTO (2007) gave average errors of -13.1% and -31.3%, respectively; likewise, those codes were under-predicting.

(2) Statistical analysis

In fact, assessment of accuracy and predictability of the international codes used to estimate ultimate pile capacity is based mainly on statistical analysis. The ratio between predicted and measured ultimate pile capacity, $[(Q_u)_p/(Q_u)_m]$, is a key variable in this analysis. An evaluation scheme using four criteria was considered in ranking those codes of design, as follows:

· The equation of best fit line of predicted versus measured pile capacity, $(Q_u)_p/(Q_u)_m$, with corresponding coefficient of correlation, r, referred to as (R_1).
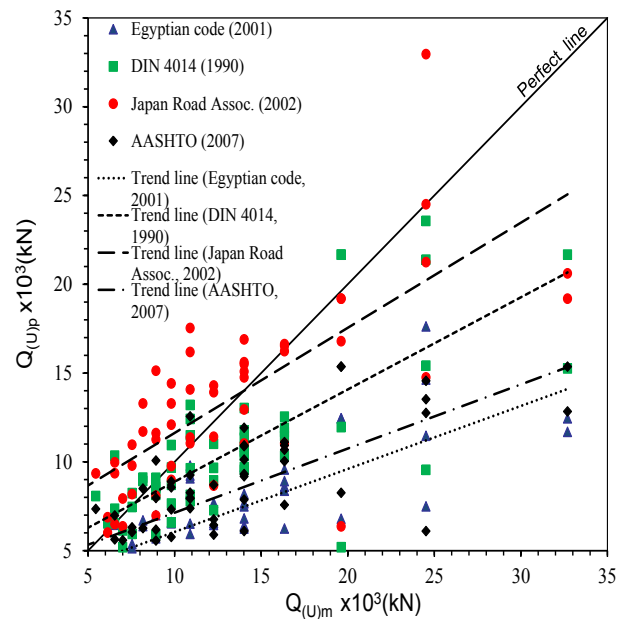

Fig. 5 Correlation between measured and predicted ultimate load for each code.

· Determination of $(Q_u)_p/(Q_u)_m$ at 50% and 90% cumulative probability, referred to as (R_2).
· The 20% accuracy obtained from log-normal distribution of $(Q_u)_p/(Q_u)_m$, referred to as (R_3).
· The arithmetic mean and coefficient of variation for $(Q_u)_p/(Q_u)_m$, referred to as (R_4).

An overall rank index (RI) is defined as the sum of ranking values obtained from the four criteria $(RI=R_1+R_2+R_3+R_4)$. The lower the ranking index, the better the performance of the design method, i.e., in accuracy and predictability[19].

a) Best fit line criterion (R_1)

Linear best fit using regression analysis was performed for each design code and the corresponding coefficient of correlation (r) was obtained. This parameter (r) is a test of the strength of the best fit equation. Practically, the code that yields the best fit equation and (r) value that are close to (1) is considered the most accurate and predictable code.

Table 4 Best fit calculations for assessment of ultimate pile capacity.

Code of design	Best fit equation	r	Ranking (R_1)
Egyptian code (2001)	$(Q_u)_p = 2.51 \times 10^3 + 0.35(Q_u)_m$	0.65	4
Japan Road Assoc. (2002)	$(Q_u)_p = 5.71 \times 10^3 + 0.59(Q_u)_m$	0.73	1
DIN 4014 (1990)	$(Q_u)_p = 3.69 \times 10^3 + 0.52(Q_u)_m$	0.76	2
AASHTO (2007)	$(Q_u)_p = 3.52 \times 10^3 + 0.36(Q_u)_m$	0.75	3

Fig.5 shows the best fit line analysis for the measured versus the predicted ultimate loads (trend line of data), and **Table 4** gives the best fit equation together with the associated coefficient of correlation r for each code. It is obvious that JRA (2002) and DIN 4014 (1990) gave trend lines that were almost close to the perfect line (inclined by 45°) with $r = 0.54$ and 0.66, respectively. It can be seen that the best fit line of JRA (2002) over-predicts the values of ultimate loads to a certain value of $(Q_u)_p$, which is equal to 14×10^3 kN. Beyond this certain value, JRA (2002) is under-predicting the ultimate loads. However, JRA (2002) globally tends to over-predict the ultimate loads of pile capacities.

On the other hand, AASHTO (2007) and Egyptian code (2001) gave low best fit equations, which were not asymptotic to (1) and their trend lines also were far from the perfect line. This denotes that these design codes were highly under-predicting the values of ultimate pile capacity than those obtained from field tests, especially the Egyptian code, which produced the best fit equation of $(Q_u)_p = 0.51(Q_u)_m$ with value of $r = 0.65$, as shown in **Table 4**.

b) Cumulative probability criterion (R_2)

The cumulative probability concept was utilized to help quantify the accuracy of the investigated codes of design in predicting the ultimate capacity of bored piles. The code that gives P_{50} value nearest to (1) together with a lower (P_{90}-P_{50}) range is considered the best design method compared to the others[19].

The first step for this criterion is to sort the ratio of $(Q_u)_p/(Q_u)_m$ for each code in an ascending order. The smallest value is given $i = 1$ and the largest one is given number $i = n$, where n is the number of the case studies (database) considered in the analysis. The cumulative probability value, CP_i, for each value of $(Q_u)_p/(Q_u)_m$ is given as follows:

$$CP_i = \frac{i}{n+1} \qquad (7)$$

Then, the relation between cumulative probability, CP_i and the values of $[(Q_u)_p/(Q_u)_m]$ is plotted; subsequently, the values of $[(Q_u)_p/(Q_u)_m]$ at 50% and 90% cumulative probability are obtained (P_{50} and P_{90}).

Figs. 6 to **9** illustrate the cumulative probability curves for all codes with the corresponding values of P_{50} and P_{90}. **Table 5** summarizes the results and
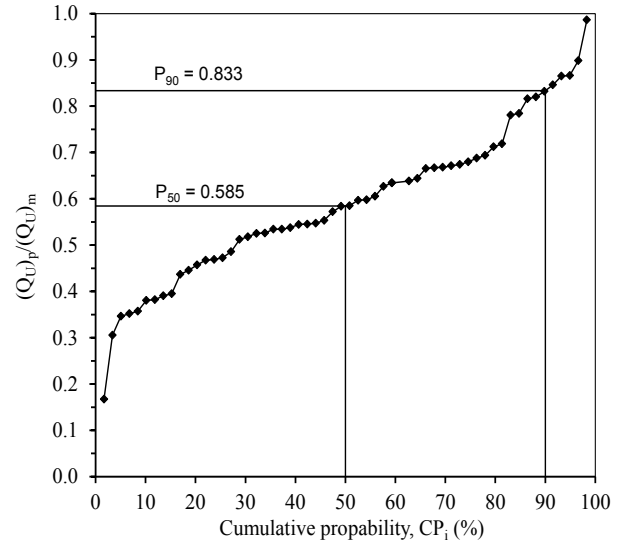

Fig. 6 Cumulative probability analysis for the Egyptian code (2001).
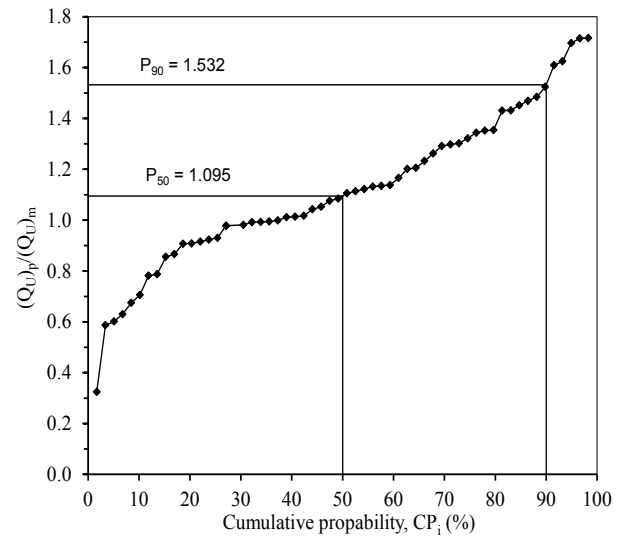

Fig. 7 Cumulative probability analysis for JRA code (2002).

ranking for each code. It is clear that JRA code (2002) is ranked as number 1, because it gives P_{50} value that approaches 1 and at the same time gives a low value of (P_{90}-P_{50}). Other codes of design are ranked as follows: DIN 4014 (1990) is in the second position; AASHTO (2007) is in the third order; and Egyptian code (2001) is in the fourth (last) position with the lowest P_{50} value. Even though the value of "P_{90}-P_{50}" shown in **Table 5** for the JRA code is higher than the others, it is ranked as 1, because it has the highest values of P_{50}, which has the first priority in ranking over the value of "P_{90}-P_{50}".

Table 5 Cumulative probability analysis results.

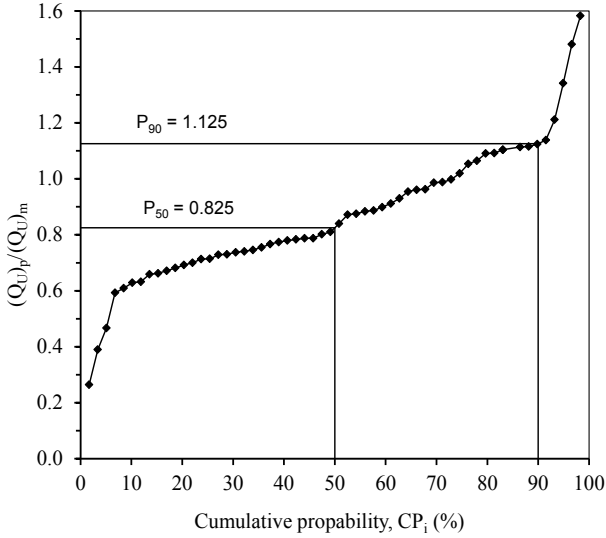| Code of design	P_{50}	P_{90}	$P_{90} - P_{50}$	Ranking (R_2)
Egyptian code (2001)	0.585	0.833	0.248	4
Japan Road Assoc. (2002)	1.095	1.532	0.437	1
DIN 4014 (1990)	0.825	1.125	0.300	2
AASHTO (2007)	0.678	0.919	0.241	3

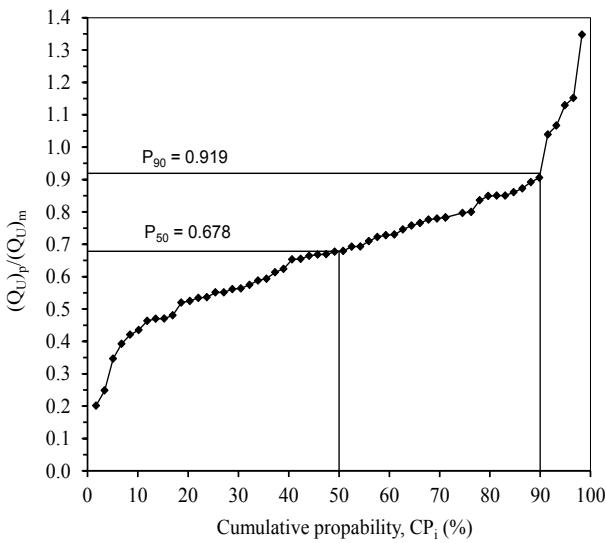**Fig. 8** Cumulative probability analysis for DIN 4014 (1990).

Fig.9 Cumulative probability analysis for AASHTO (2007).

c) 20% Accuracy level criterion (R_3)

Validating the precision of predictability of any design method is often carried out by establishing a criterion for relative standard deviation. This criterion is generally established within 10% to 20% depending on the method and the requirements of the results, where it should not deviate by more than ±20%. The accuracy level criterion denotes that the predicted pile capacities $(Q_u)_p$ lie within the range between 0.8 and 1.2 of the measured ones $(Q_u)_m$.

The log-normal distribution is acceptable for representing the ratio of $(Q_u)_p/(Q_u)_m$; however, it is not systematic around the mean, which means that

Table 6 Results of 20% accuracy range of prediction ultimate bearing capacity.

Code of design	Probability at 20% accuracy range (%)	Ranking (R_3)
Egyptian code (2001)	13.79	4
Japan Road Assoc. (2002)	48.28	1
DIN 4014 (1990)	46.55	2
AASHTO (2007)	31.03	3

the log-normal distribution does not give an equal weight of under-prediction or over-prediction. In using log-normal distribution, the mean, μ_{ln}, standard deviation, s_{ln}, and log-normal distribution density function, $f(x)$, are calculated for the natural logarithm of $[(Q_u)_p/(Q_u)_m]$, as given by Eqs. (8) to (10):

$$\mu_{ln} = \frac{1}{n}\sum_{i=1}^{n} \ln \frac{(Q_u)_p}{(Q_u)_m} \tag{8}$$

$$s_{ln} = \sqrt{\frac{\sum_{i=1}^{n}\left(\ln \frac{(Q_u)_p}{(Q_u)_m} - \mu_{ln}\right)^2}{n-1}} \tag{9}$$

$$f(x) = \frac{1}{x s_{ln} \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(x) - \mu_{ln}}{s_{ln}}\right)^2\right] \tag{10}$$

where: $x = (Q_u)_p/(Q_u)_m$, μ_{ln} = the mean of $\ln(Q_u)_p/(Q_u)_m$, and s_{ln} = standard deviation of $\ln(Q_u)_p/(Q_u)_m$.

Using the log-normal probability function, the probability of predictability of the pile capacity at any accuracy level can be determined. At a specified accuracy level (i.e., 20% of accuracy), the higher the probability, the better the accuracy of this code.

Table 6 gives the results of analysis and the ranking of the codes. **Fig. 10** shows a log-normal distributions for all code of design within the range of 20% accuracy level (hatched zone), and the 20% accuracy curves are plotted in **Fig. 11**.

Obviously, at 20% accuracy, the JRA code (2002) and DIN 4014 (1990) have the highest probability of accuracy equal to 48.28% and 46.55%, respectively. However, AASHTO (2007) comes in the third order with probability of accuracy of 31.03% (R_3=3). Finally, the Egyptian code (2001) comes in the last order with the lowest accuracy level of 13.76% (R_3=4).
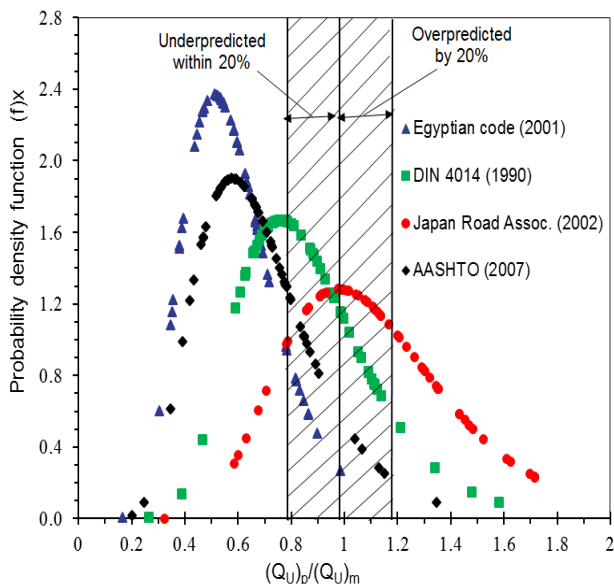
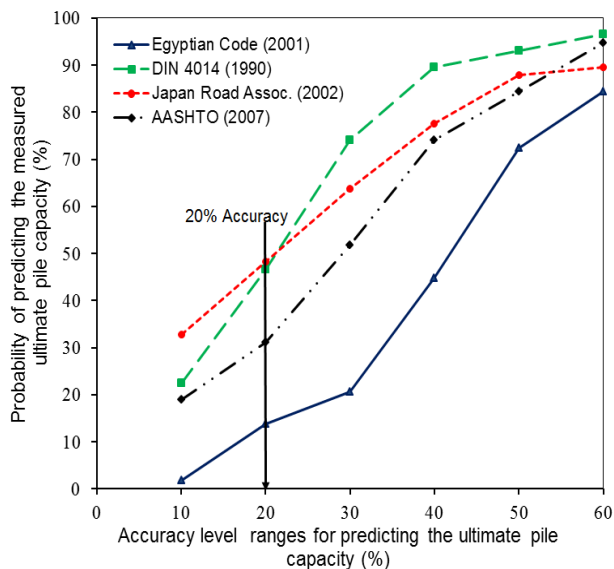**Fig. 10** Log-normal distribution of the ratio $(Q_u)_p/(Q_u)_m$ for the codes of design used in the study.

Fig. 11 Relationships between accuracy level and probability of occurrence for the codes of design used in the study.

d) Statistical parameters criterion (R_4)

The precision of each code of design can be evaluated by measuring the scatter of results around the mean value (μ) for the ratio $[(Q_u)_p/(Q_u)_m]$, and by calculating a parameter defined as (COV), which is equal to standard deviation, s, divided by μ. The most accurate method gives $\mu = 1$ and $COV = 0$. This case is ideal; however, in reality the method is better when μ is nearly equal to (1), and COV is asymptotic to zero.

Table 7 summarizes the results of the statistical parameters (μ, s, and COV) for each code used in this comparison study. It can be seen that the most accurate code is JRA (2002). Although all the codes gave high values of COV (not asymptotic zero), JRA

(2002) is still highly more reliable than the others, since its mean value ($\mu=1.12$) is the most asymptotic to (1).

e) Overall ranking index (*RI*)

Table 8 represents the final ranking records for each code of design. JRA code (2002) for estimating the ultimate pile capacity came in the first position with the lowest ranking index (*RI*=4). DIN 4014 (1990) had the second position with ranking index (*RI*=8). On the other hand, AASHTO (2007) and Egyptian code (2001) came in the third and fourth order with ranking indexes of (*RI*=13) and (*RI*=15), respectively.

8. SUMMARY AND CONCLUSION

This technical report has introduced an analysis and comparative study for 58 case histories of field pile load-settlement tests conducted on Egyptian soils. These real field databases were classified, designed, and analyzed according to the recommendations adopted widely by four international codes of practice.

Additionally, a wide comparative statistical study was performed between those codes of design, to evaluate their predictability limits. The following conclusions can be drawn:

1. The average error percentage obtained from JRA code (2002) is the lowest value (11.8%) compared to the other design codes used in this study.

2. JRA code (2002) and DIN 4014 (1990) have revealed well predictability and accuracy for estimating ultimate pile capacity, $(Q_u)_p$, compared to the other international codes of design. As a result, they were ranked in the first and second order, respectively.

3. The ultimate bearing capacities calculated by the Egyptian geotechnical code (2001) revealed that those values were extremely lower than the ultimate loads measured from in-situ pile load tests.

4. For economic purposes, re-evaluating the design factors and parameters adopted by the Egyptian code of (2001) is recommended to improve its predictability and reliability. For example, this code does not consider the effect of soil strength parameters around the pile tip for estimating q_{bu}. Introducing reasonable design values is one of the possible solutions.

Table 7 Statistical parameters for assessment of ultimate pile load.

Code of design	μ	s	COV	Ranking (R_4)
Egyptian code (2001)	0.59	0.17	0.288	3
Japan Road Assoc. (2002)	1.12	0.30	0.268	1
DIN 4014 (1990)	0.87	0.24	0.276	2
AASHTO (2007)	0.69	0.21	0.304	4

Table 8 Final ranking indexes of the codes of design for predicting ultimate pile capacity.

Code of design	R_1	R_2	R_3	R_4	$RI = (R_1+R_2+R_3+R_4)$	Ranking of the code
Egyptian code (2001)	4	4	4	3	15	4
Japan Road Asso. (2002)	1	1	1	1	4	1
DIN 4014 (1990)	2	2	2	2	8	2
AASHTO (2007)	3	3	3	4	13	3

APPENDIX

Steps for predicting ultimate pile capacity $(Q_u)_p$ using international codes of practice.

I. Representative average values for N_{SPT} and C_u are estimated for cohesionless and cohesive soil, respectively, for each soil layer using Eqs. (3) and (5), respectively.

II. N_{SPT} values must be corrected due to the effect of overburden pressure, σ_v', using Eq. (4).

III. Ultimate end-bearing force (Q_{bu}) is calculated using the following equation:

$$Q_{bu} = q_{bu} * A_p \qquad (A1)$$

where: q_{bu} = ultimate end-bearing resistance, and
A_p = pile tip area.

Table A1 gives the design formulas and the tables of design that are adopted by each code of practice for estimating q_{bu} at settlement of 10% of pile diameter for cohesionless and cohesive soils, respectively.

IV. Ultimate skin friction force, $(Q_{su})_i$, is calculated for each layer by multiplying skin friction resistance, $(q_{su})_i$, by the pile shaft surface area, A_{si}.

$$Q_{su} = \pi D \sum (q_{su})_i L_i \qquad (A2)$$

where: $(q_{su})_i$ = ultimate skin friction resistance in layer no. (i), and
L_i = the depth of soil layers in question.

Table A2 gives the design formulas and the tables of design that are adopted by each code of practice for estimating q_{su} for cohesionless and cohesive soils, respectively.

V. Total ultimate bearing capacity of a pile equals the sum of Eqs. (A1) and (A2), at a settlement value equal to 10% of a pile base diameter.

$$(Q_u)_p = Q_{su} + Q_{bu} \qquad (A3)$$

VI. The previous value, $(Q_u)_p$, is compared against $(Q_u)_m$, estimated using the Chin method (1970).

Table A1 Summary of design formulas and tables for estimating ultimate end-bearing stresses.

Code of design	Ultimate end-bearing stresses (q_{bu})	
	Cohesive	Cohesionless
Egyptian code (2001)[7]	Table 9-4 p. 65	Table 8-4 p. 64
DIN 4014 (1990)[8]	Table 2 p. 7	Table 1 p. 7
Japan Road Assoc. (2002)[9]	Table C-12-4-1 p. 300	
AASHTO (2007)[10]	$N_c C_u \leq 4$ MPa N_c is dimensionless bearing capacity factor = $6[1+0.2(Z/D)]$ Z= depth from ground surface; D= pile tip diameter.	$0.057N_{SPT}$ (for $N_{SPT} \leq 75$) 4.3MPa (for $N_{SPT} > 75$)

Table A2 Summary of design formulas and tables for estimating ultimate skin friction stresses.

Code of design	Ultimate skin friction stresses (q_{su})	
	Cohesive	Cohesionless
Egyptian code (2001)[7]	Table 11-4 p.67	Table 10-4 p.66
DIN 4014 (1990)[8]	Table 5 p. 7	Table 5 p. 7
Japan Road Assoc. (2002)[9]	Table C-12-4-5 p. 305	
AASHTO (2007)[10]	$C_u \alpha$ α= adhesion factor which can be obtained from Table 10-3-3-1-1 p. 10-86	$\beta \sigma_v' \leq 0.19$MPa β is dimensionless factor = $1.5-7.7 \times 10^{-3}(Z)^{0.5}$

REFERENCES

1) Abdel-Rahman, A. H., Rabie, M. and Awad-Allah, M. F. : Comparison between Egyptian code, DIN 4014, and AASHTO methods of predicting ultimate bearing capacity of large diameter bored piles, EL-Azher University Engineering Journal, Vol. 9, No. 3, pp. 537-547, 2006.

2) Radwan, A. M., Abdel-Rahman, A. H., Rabie, M. and Awad-Allah, M. F.: New suggested approach for design of large diameter bored piles based on finite element analysis, 12th Int. Colloquium on Structural and Geotechnical Engineering, Egypt, 2007.

3) Awad-Allah, M. F. : Prediction of bearing capacity of large diameter bored piles in some Egyptian soil – A comparison study for the actual versus the predicted values, Msc Thesis, Helwan University, Egypt, 2008.

4) Van Impe, W. F. : Pile foundation design, XVI Conference of Geotechnics in Torino, 1997.

5) Terzaghi, K. : *Theoretical Soil Mechanics*, John Wiley & Sons, NewYork, 1943.

6) Franke, E.: Design of bored piles including negative skin friction and horizontal loading, *Proc. of 2nd int. Geotech. Seminar on Deep Found. on Bored & Auger piles*, Balkema, Rotterdam, The Netherland, pp. 43-57, 1993.

7) Egyptian code of practice for soil mechanics and foundation design and construction, Part 4, 2001.

8) Deutsches Institut fur Normung (DIN 4014): German Association for Earthworks and Foundation Engineering, 1990.

9) Japan Road Association, Specifications for highway, Part IV superstructures, Ch. 12, Design of pile foundations, 2002.

10) AASHTO, LRFD Bridge Design Specification, SI units, Second Edition, 2007.

11) Chin, F. K.: Estimation of the ultimate load of piles from tests not carried to failure, *Proc., 2nd South-East Asian Conf. on Soil Eng.*, Singapore, pp.81-90, 1970.

12) Jamiolkowski, M.: Statistical analysis on shaft friction of vertical loaded bored piles, *Proc. Symposium on Deep Foundation on Bored and Auger Piles*, pp. 83-100, 2003.

13) O'Neil, M. W. : Side resistance in piles and drilled shafts, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 34th Terzaghi Lecture No. 1, pp. 1-6, 2001.

14) Lee, J. H. and Salgado, R.: Determination of pile base resistance in sands, *ASCE Journal*, Vol. 125, No. 8, pp. 673-683, 1999.

15) Fellenius, B. H.: What capacity value to choose from the results of static loading test, Fulcrum, Deep Foundations Institute, New Jersey, p. 4, 2001.

16) ASTM, Designation: 1143-81: Standard test method for piles under static axial compressive load.

17) Bowles, J. E.: *Foundation Analysis and Design*, 4th. Ed., McGraw-Hill, 1996.

18) Liao, S. S. and Whitman, R. V. : Overburden correction factors for SPT in sand, *J. of Geotech. Eng., ASCE*, Vol. 112, No. 3, pp. 373-377, 1986.

19) Titi, H. and Abu-Frasakh, M. Y. :Assessment of direct cone penetration test methods for predicting the ultimate capacity of friction driven piles, *ASCE Journal*, Vol. 130, No. 9, pp. 935-944, 2004.