HBRC Journal (2015) **xxx**, xxx–xxx

Housing and Building National Research Center

HBRC Journal

http://ees.elsevier.com/hbrcj

FULL LENGTH ARTICLE

Application of ultimate limit state design for axially loaded single piles in Egyptian geotechnical practice

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Received 5 July 2014; revised 13 January 2015; accepted 8 February 2015

KEYWORDS

Limit state design;
Egyptian Code of Practice;
Geotechnical design;
Load and resistance factor design;
Pile foundation;
Calibration

Abstract For a long time, the framework of geotechnical design in Egypt has been based mainly on Working Stress Design (WSD) philosophy with the global safety concept as presented in the current version of the Egyptian Code of Practice for Soil Mechanics and Foundations Design and Construction [1]. This design philosophy is supported by long-term experience, considering local experiences and is adopted to fulfill the required safety margin. Limit State Design (LSD) philosophy, on the other side, has already been applied for the design of reinforced concrete structures as introduced in the Egyptian Code of Practice for the Design and Construction of Reinforced Concrete Structures [2]. Applying LSD for superstructure and WSD for foundations often results in design misleading because of the incompatibility between the two design philosophies. Accordingly, implementation of LSD philosophy for geotechnical designs in Egypt has become mandatory and the transition to this new design philosophy of LSD should be as smooth and gradual as possible to allow for a better acceptance by the Egyptian geotechnical community. LSD philosophy using partial safety factors has been applied worldwide using two different approaches; factored strength approach and factored resistance approach. During this study, resistance reduction factors are calibrated on the basis of calibration-by-fitting technique, to be used with factored resistance approach for axially loaded single piles. The calibrated resistance reduction factors from this study are found to be relatively consistent with those values adopted in other geotechnical design codes worldwide.

Introduction

Design methods in both geotechnical and structural engineering may be generally associated with some degrees of uncertainties due to potential material variability and/or uncertainties of the adopted design model itself. These various uncertainties are usually accounted for through the implementation of safety factors. Working Stress Design (WSD) and Limit State Design (LSD) are the main two philosophies that

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Peer review under responsibility of Housing and Building National Research Center.

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http://dx.doi.org/10.1016/j.hbrcj.2015.02.004
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generally deem the application of the factors of safety, however, through two different concepts. Working stress design, also referred to as allowable stress design, has been used, as a basic design approach, for many years in civil engineering. It was recommended for the geotechnical applications in Egypt in 80's as adopted in the first Egyptian Code of Practice for design of foundations. In this design philosophy, a single global safety factor is employed, representing the ratio between ultimate resistance and allowable (working) loads. This concept was successfully applied in the geotechnical engineering practice for numerous decades in many parts of the world, probably because of its simplicity. Nevertheless, the WSD concept is associated with a fundamental shortcoming that it does not differentiate between variable uncertainties that are potentially incorporated in either loads or resistances. Moreover, some adopted global safety factors are based on local experience and engineering judgment.

Limit State Design (LSD), on the other hand, applies the concept of partial safety factors. In general, limit state is a characterized condition beyond which the structure or any of its elements will fail to fulfill its functions. Mortenson [3] indicated that the LSD represents a mathematical formulation of the design process. For the basic concept of partial safety factors, encountered by the LSD philosophy, the characteristic load values are increased via load factors, whereas, the nominal resistances are decreased by reduction factors. The LSD concept seems advantageous over the WSD one, since the former provides partial safety factors that can separately account for the different uncertainties in both loads and resistances. Two categories of LSD concept have been introduced in the literature: the ultimate limit state (ULS) and the serviceability limit state (SLS). ULS accounts for the adopted safety condition of structures and stands for defining the design limits that are needed to avoid structural damage or instability. SLS, on the other side, denoted the conditions that may undermine the structure's function and that may influence the structure's serviceability under working unfactored loads.

Geotechnical designs in Egyptian practices have been based mainly, for a very long time, on WSD philosophy applying the concept of global safety factors. This is dedicated in the Egyptian Code of Practice for Soil Mechanics and Foundations Design and Construction, ECP-202 [1]. On the other hand, LSD philosophy with partial safety factor concept has been applied in the Egyptian practice for the design of the structural elements, as presented in the Egyptian Code of Practice for the Design and Construction of Reinforced Concrete Structure, ECP-203 [2]. Applying the LSD for the superstructure design and WSD for foundations design often results in design misleading and inconsistency because of the incompatibility between the two design philosophies. Accordingly, the implementation of LSD in geotechnical design in Egypt has become a mandatory requirement.

In accordance, transition methodology is needed to move from WSD to LSD. Becker [4] indicated that a transition from WSD philosophy to LSD should be smooth and gradual as possible. Calibration by fitting and calibration using reliability theory are the two common techniques that have been proposed in the literature for transition from WSD to LSD. Goble [5] applied the calibration-by-fitting technique for the AASHTO- LRFD [6]. Allen [7] indicated that the calibration-by-fitting technique may be appropriate to determine values of partial safety factors for LSD when the compiled statistical data are inadequate. On the other side, Paikowsky et al. [8] applied reliability-based methods, e.g. First Order Reliability Method (FORM), to calibrate partial safety factors for deep foundations.

The objective of this paper was to examine the transition methodology from the commonly used WSD philosophy in geotechnical design in Egypt to the LSD philosophy, focusing on application to design of axially loaded single piles. The examined transition is based on the calibration-by-fitting technique, where values of partial safety factors for ULS design of piles are investigated to provide similar design estimates to that obtained from the WSD. The calibration process is applied for a number of commonly used design methods of pile foundation in the Egyptian geotechnical practice, including static formula, dynamic formula, empirical load–settlement relationship for the design of large diameter bored piles as well as the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT)-based correlations. Influences of some design aspects on the calibrated partial safety factors are investigated.

Different approaches of ultimate limit state for geotechnical design

Limit state design concept with partial safety factors has been developed for geotechnical design with two different approaches, which are the factored strength approach, i.e., material strength approach, and the factored resistance approach, i.e. Load and Resistance Factor Design (LRFD). Conceptually, the two approaches are similar with respect to the factored loads. In the two approaches, factored loads are calculated by increasing the nominal load values by using load factors, which have values greater than unity. The difference between the factored strength and the factored resistance approaches lies in the concept of reducing the material resistance.

In the factored strength approach, the individual soil strength parameters are independently reduced via reduction factors. Subsequently, a factored resistance is normally forecasted from that reduced strength parameters, as exemplified in Eq. (1).

$$R_{\text{U.L.}} = f(c_d; \varphi_d; \ldots) \tag{1}$$

where

$$c_d = F_c\, c \tag{2}$$

$$\varphi_d = F_\varphi \tan\varphi \tag{3}$$

where c and φ are the characteristic soil shear strength parameters and $R_{\text{U.L.}}$ is the ultimate limit pile resistance that is a function, among others, of the design values of soil cohesion and angle of internal friction, c_d and φ_d, respectively. The factors F_c and F_φ are the reduction factors for soil cohesion and soil angle of internal friction, respectively.

In the factored resistance approach, the factored resistance is normally forecasted from the original unfactored strength parameters. The forecasted resistance is then reduced via a partial reduction factor, F_R, to obtain the ultimate limit, i.e. factored, resistance, $R_{\text{U.L.}}$, as shown in Eq. (4).

$$R_{\text{U.L.}} = f(c; \varphi; \ldots)/F_R \tag{4}$$

Ovesen and Orr [9] clarified the concept of the factored strength approach as shown in Fig. 1. The unfactored

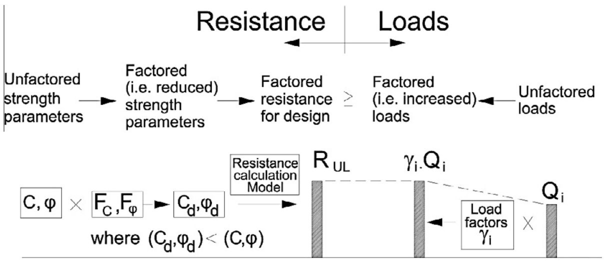

Fig. 1 Schematic diagram for the concept of factored strength approach [9].

characteristic soil strength parameters, i.e. c and φ, are firstly reduced by means of partial factors, i.e. F_c and F_φ, respectively, to give the factored strength parameters, c_d and φ_d. These factored strength parameters are used to calculate the ultimate limit resistance ($R_{U.L.}$). On the other hand, the working or unfactored loads are increased by means of load factors to give the factored loads. The main criterion of LSD can be sustained as long as the factored resistance is equal to or more than the factored loads.

Fig. 2 schematically illustrates the factored resistance approach, as described by Ovesen and Orr [9]. This figure shows that the unfactored resistance is calculated from the unfactored characteristic soil strength parameters. The unfactored resistance, e.g. pile side, base and total resistance can be also calculated from the in-situ correlations. A single resistance factor (F_R) is applied to reduce the unfactored resistance to a factored, i.e. ultimate limit resistance ($R_{U.L.}$). The factored loads are calculated in the same manner as for the factored strength approach.

One salient disadvantage of the factored strength approach is that it accounts only for certain sources of uncertainties, that are associated with soil strength parameters. Other different sources of uncertainties related to, for example, design calculation model and construction techniques, are not deemed in the factored strength approach. Furthermore, this approach cannot be applied with geotechnical design models that are based on correlations with results of in-situ test, e.g. Standard Penetration Test (SPT) and Cone Penetration Test (CPT), which are not the direct measurements of soil strength parameters.

In the factored resistance approach (i.e., LRFD), on the other hand, different sources of uncertainties that may affect the estimate of soil resistance may be considered. This is achieved through the use of a reduction factor for the estimated resistance. In this reduction factor, the impact of different sources of uncertainty may be dimensioned. Becker [10]

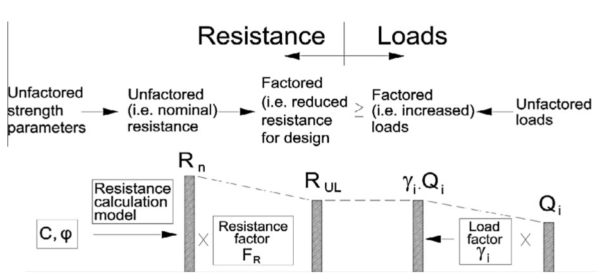

Fig. 2 Schematic diagram for the concept of factored resistance approach [9].

pointed out that the LRFD approach may be advantageous and more desired for geotechnical designs than the factored strength approach. Merits of the LRFD rely on its applicability with the design correlations that are based on in-situ test results, such as SPT and CPT, where the SPT and CPT-based estimate of resistance is reduced by the single reduction factor.

Extensive developments of the application of LSD and partial safety factors concept for geotechnical and foundations designs have been introduced in several international design codes of practice and regulations, such as Danish Code of Practice for Foundation Engineering [11], Eurocode 7 [12], National Building Code of Canada [13], Canadian Highway Bridge Design Code [14], Canadian Foundation Engineering Manual [15] and American Association of State Highway and Transportation Officials (AASHTO) [16].

Transition from WSD to ULSD for geotechnical design of pile foundations

A logical development in the adopted design concepts in the Egyptian geotechnical practices to have a transition from the commonly used WSD to LSD has become of essential need in most design codes. The transition process requires, in essence, calibrated partial safety factors to be implemented in the use of LSD. Allen [7] pointed out that, in absence of complied and adequate statistical data, calibration by fitting can be the most appropriate technique to find out reasonable values of the partial factors. In the calibration-by-fitting technique, the values of partial safety factors of the LSD are examined to give the same design estimates obtained from WSD. The major merit of this technique is that it provides a basic link between the new LSD practice and the current practice of WSD. It may be useful for further refinement of the calibrated partial safety factors through applying more advanced techniques, such as reliability theory or neural networks. The basic shortcoming of the calibration-by-fitting technique is that the calibrated partial safety factors may be associated with a level of inadequate information on uncertainties and probability of failure alike that encountered with the corresponding global safety factor of the WSD.

Calibration of LSD reduction factors for geotechnical design of axially loaded single pile in the Egyptian Code of Practice

The current version of the Egyptian Code of Practice for Soil Mechanics and Foundations Design and Construction [1] presents several methods for estimating the geotechnical capacity of single pile under axial loads. These methods involve the static formula for side and base resistances of small diameter bored and driven piles, the dynamic formula (Hiley's formula) for driven piles, the empirical load–settlement method for large diameter bored piles, in addition to generic empirical correlations with the results of in-situ tests, such as SPT, CPT and PMT. It is worth mentioning that a large diameter bored pile is defined in ECP-202 [1] as a drilled shaft having a shaft diameter of greater than 60 cm. Throughout all of the above cited design methods, the pile is designed on the base of the WSD concept to forecast the allowable pile capacity. Thus, a global safety factor is applied and that varies through the different design methods. Out of the different methods given in

ECP-202 [1] for pile geotechnical design, some methods were examined to estimate the limit state pile capacity using the Load-Resistance concept.

The fundamental challenge was to yield reasonable partial safety factors, i.e. reduction factors, for the ultimate pile resistance. As the line of this research is objecting toward gradually changing the design philosophy from WSD to LSD, the required partial safety factors for LSD of piles were decided to be determined by means of the calibration-by-fitting technique. For the investigated pile design methods from ECP-202 [1], partial safety factors for pile base and side resistances or reduction factors for total pile resistance were iterated to yield similar estimates to that acquired from the working pile design with global safety factor. This calibration methodology was applied to the static and dynamic design formulas, the design method for large diameter bored piles, the design method based on results of static pile load test as well as the SPT and CPT-based empirical correlations, as discussed in detail in the following sections.

Calibration of reduction factors for total pile resistance from static formula

In the ECP, the ultimate total pile resistance (R_u) is defined as the summation of the ultimate pile base resistance (R_b) and the ultimate pile side resistance (R_s), as given by Eq. (5). The allowable pile resistance (R_a) is subsequently estimated through dividing the total pile resistance (R_u) by a global safety factor (FS_g) or through dividing the ultimate pile base and side resistances (R_s and R_b) by partial safety factors for base and side resistances (FS_b and FS_s), respectively, as exemplified in Eqs. (6.a) and (6.b). The values of FS_g, FS_b and FS_s are greater than one. The allowable pile resistance (R_a) is considered to equal the anticipated working load (Q_w) to be carried by the single pile. The pile working load comprises in general two components, one is for the working dead load (Q_D) and the other is for the working live load (Q_L), as shown in Eq. (7). Eqs. 6.a, 6.b, 7, 8 represent the WSD concept that has been adopted for geotechnical pile design in ECP [1] for a very long time.

$$R_u = R_s + R_b \quad (5)$$

$$R_a = \frac{R_u}{FS_g} \quad (6.a)$$

$$R_a = \frac{R_b}{FS_b} + \frac{R_s}{FS_s} \quad (6.b)$$

$$Q_w = Q_D + Q_L \quad (7)$$

$$Q_w \leqslant R_a \quad (8)$$

In the Load-Resistance concept, the ultimate limit pile resistance ($R_{U.L.}$) can be determined through multiplying the ultimate total pile resistance (R_u) by a reduction factor (F_R), as depicted in Eq. (9). Value of F_R is generally less than one. The ultimate limit total pile resistance ($R_{U.L.}$) is considered equal to, or greater than, the ultimate limit load ($Q_{U.L.}$) to be carried by the single pile. The ultimate limit load is estimated by multiplying the dead and live load compounds by increasing factors γ_{DL} and γ_{LL}, respectively.

$$R_{U.L.} = F_R \cdot R_u = Q_{U.L.} = \gamma_{DL} \cdot Q_D + \gamma_{LL} \cdot Q_L \quad (9)$$

In the present study, the reduction factor (F_R) for the total pile resistance was calibrated for pile design using static formula to provide the same estimates from WSD. In this regard, definition for R_u was deduced from Eq. (6.a), i.e. $R_u = FS_g (Q_D + Q_L)$, and substituted into Eq. (9). Consequently, the following expression for the reduction factor (F_R) could be obtained:

$$F_R = \frac{\gamma_{DL} + \gamma_{LL}\left(\frac{Q_L}{Q_D}\right)}{FS_g\left(1 + \frac{Q_L}{Q_D}\right)} \quad (10)$$

For the static formula design method in the ECP-202 [1] the recommended value of FS_g varies with the considered case of load combination. For the combination of dead and live loads only, the FS_g is recommended equals 3.0. This value becomes 2.50 and 2.0, respectively, if the wind loads and seismic loads are considered. Accordingly, the FS_g-value was constantly assigned equals 3.0 in Eq. (10), considering the load combination of dead and live loads. Moreover, the ratio Q_L/Q_D shown in Eq. (10) represents the ratio of live to dead load ratio. The Q_L/Q_D ratio is generally adopted in the literature ranging between 0.1 and 0.35 [17]. The Q_L/Q_D ratio was varied in Eq. (10) throughout a range of zero to one to cover a wider range than that proposed in the literature. Load factors γ_{DL} and γ_{LL} are substituted by 1.4 and 1.6, respectively, as recommended by the ECP-201 [1] and ECP-203 [2].

Values of reduction factor F_R were calculated corresponding to the assigned different ratios of Q_L/Q_D. The results are presented by the solid curve in Fig. 3. It may be noticed in Fig. 3 that the value of F_R slightly increases with the increase in the Q_L/Q_D ratio. It can be dedicated from Fig. 3 that, for the investigated range of Q_L/Q_D, F_R ranges from 0.467 to 0.5 at FS_g value of 3.0.

Calibration of partial safety factors for driven pile resistance from Hiley's dynamic formula

For axial capacity of driven piles, dynamic formulas can be employed for estimating pile capacities. The ECP-202 [1]

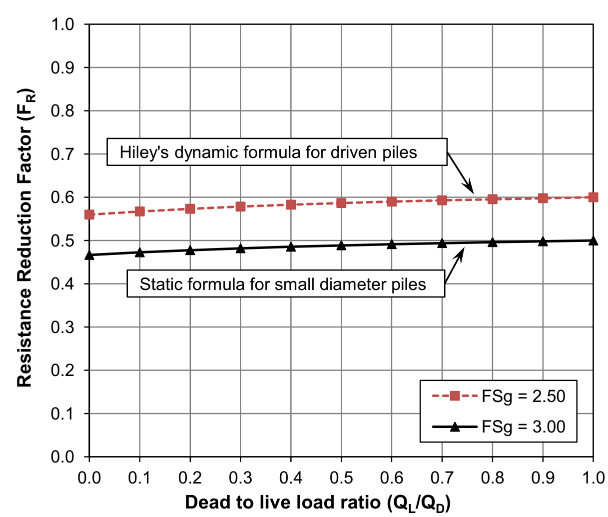

Fig. 3 Relation between calibrated F_R and Q_L/Q_D ratio for static and dynamic formula design methods adopted in the ECP-202 (2001).

Please cite this article in press as: Y.M. El-Mossallamy et al., Application of ultimate limit state design for axially loaded single piles in Egyptian geotechnical practice, HBRC Journal (2015), http://dx.doi.org/10.1016/j.hbrcj.2015.02.004

recommends use of Hiley's formula for estimating the capacity of the driven piles in cohesionless soils. The ultimate pile resistance of the pile is estimated as presented in Eq. (11).

$$R_u = \frac{Wh}{S + \frac{C}{2}}\eta \quad (11)$$

where R_u is the ultimate driving resistance of the pile, W is the weight of the ram in kN, h is effective height of fall of the ram, S is the penetration of pile per hammer blow, C is the summation of the temporary compression and η is the efficiency of the hammers. The ECP-202 [1] presents several equations and charts for temporary compression C in Eq. (11). The allowable capacity of the driven pile (R_a) is then estimated by factoring the R_u using FS_g as previously shown in Eq. (6.a) and the allowable working load on pile (Q_w) shall be less than or equal to the R_a as adopted in Eq. (8). The ECP-202 [1] recommends the FS_g-value for Hiley formula design method, to be in the range between 2.0 and 3.0. In this section, the FS_g is substituted by an average value of 2.5.

In the Load-Resistance concept of LSD, the ultimate limit resistance ($R_{U.L.}$) is calculated via reducing the R_u by reduction factor F_R and then checked to be greater than or equal to the ultimate limit loads ($Q_{U.L.}$). The reduction factor (F_R) for the driven pile resistance was calibrated by applying the calibrated-by-fitting technique. The aforementioned range and values for Q_L/Q_D ratio, γ_{DL} and γ_{LL} are considered in this section.

Values of the calibrated reduction factor F_R along with changing the Q_L/Q_D ratio, at FS_g equals 2.5 are presented by the dotted curve in Fig. 3. It can be observed from Fig. 3 that, for the investigated range of Q_L/Q_D, F_R ranges from 0.56 to 0.6 at FS_g-value of 2.5.

Calibration of partial safety factors for total resistance of large diameter bored piles

For large diameter bored piles, i.e. piles of diameter more than 60 cm, ECP-202 [1] recommended another design method for determining allowable pile resistance. According to ECP-202 [1], allowable pile capacity, based on WSD philosophy, for a large diameter bored pile is calculated throughout constructing an empirical load–settlement relationship for the pile. This empirical relationship is plotted for both pile side and base resistances against pile settlement. The load–settlement relationships of pile side and base resistances are constructed via using tables in which ultimate skin friction and ultimate end bearing of pile are given, each for both cases of cohesionless and cohesive soils. Subsequently, the load–settlement relationship for the total pile resistance can be constructed by superposition of the relationships of pile side and base resistances. Hence, ultimate pile resistance (R_u) can be estimated by summation of the ultimate pile side resistance (R_s) and the ultimate pile base resistance (R_b). ECP-202 [1] gives a more detailed explanation for this design method. Allowable pile capacity is then calculated via applying Eq. (6.a). The axial load taken by each pile is then checked to be kept equal to or less than the allowable pile capacity, as illustrated by Eq. (8).

For LSD of the large diameter bored piles, Eq. (9) represents the basic criteria of the design philosophy used for the Load-Resistance concept. In this section, the calibrated reduction factor (F_R) for the total pile resistance was calibrated for the empirical load–settlement relationship used for the design of large diameter bored piles. The calibrated-by-fitting technique is employed to find out calibrated F_R values. The methodology incorporates multiplying the estimated total ultimate pile resistance (R_u) by a reduction factor (F_R) to get the ultimate limit pile resistance ($R_{U.L.}$). Accordingly, reduction factor (F_R) could be calibrated through Eq. (10). According to ECP-202 [1], for large diameter bored piles axially loaded from dead and live loads, FS_g is substituted with 2.0 in Eq. (10). Same as it was done in the last section, Q_L/Q_D ratio, γ_{DL} and γ_{LL} are substituted by a range from zero to 1.0, 1.4 and 1.6, respectively.

Results of the calibrated reduction factor F_R along with changing the Q_L/Q_D ratio, at FS_g equals 2.0 are shown in Fig. 4. It can be observed from Fig. 4 that, for the investigated range of Q_L/Q_D, F_R ranges from 0.7 to 0.75 at FS_g-value of 2.0 and increasing the Q_L/Q_D ratio increases the value of F_R.

Calibration of partial safety factors for total resistance evaluated from static pile load testing

Based on the results of static pile load test, load–settlement relationship of the tested pile can be plotted and the ultimate pile capacity (R_u) can be estimated from such relationship. The estimated R_u is then reduced by applying a safety factor FS_g, following the WSD concept, in order to estimate R_a, as previously presented in Eq. (6.a). The ECP-202 [1] provides, for evaluating R_a from results of static pile load test, a value of 2.0 for FS_g in case of dead and live loads, a value of 1.75 in case of considering the wind loads and a value of 1.5 when considering the earthquake loading case.

In LRFD-concept, the ultimate limit resistance of the pile ($R_{U.L.}$) is calculated according to Eq. (9) by reducing the R_u using means of F_R. In this section, the reduction factor (F_R) is calibrated for evaluating the pile resistance from results of static pile load test via calibration-by-fitting technique. Substituting in Eq. (10) with the same range and values for Q_L/Q_D ratio, γ_{DL} and γ_{LL}, applied in previous sections, the relationship between F_R and Q_L/Q_D ratio for FS_g-value of 2.0 is plotted as illustrated in Fig. 4.

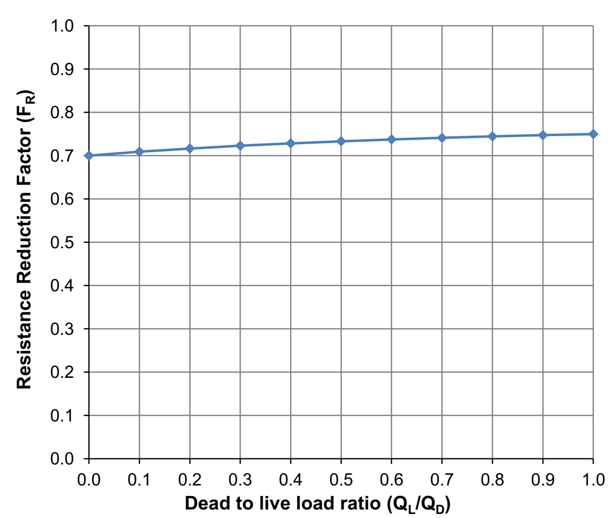

Fig. 4 Relation between F_R and Q_L/Q_D ratio for the empirical load–settlement relationship design method of axially loaded large diameter bored pile and static pile load test design method at FS_g equals 2.0.

Calibration of partial safety factors for pile side and base resistances from SPT-based empirical correlation

In the Egyptian Code of Practice for pile design [1], empirical SPT-based correlation is provided to estimate the pile capacity in cohesionless soil. This correlation can be exemplified as follows:

$$R_u = 225N_b\,A_b + 2N_L\,A_s \tag{12}$$

where R_u is the ultimate pile resistance, N_b is the average value of SPT-blow counts encountered within an arbitrary end bearing zone of 3d above and d below the pile tip, for a pile shaft diameter d, N_L is the average value of SPT-blow counts along the pile shaft length, A_b is the area of the pile base and A_s is the side area of the pile shaft. It is worth mentioning that, in the correlation given above, the term (225 N_b A_b) represents the ultimate pile end bearing capacity (R_b), whereas the term (2 N_L A_s) stands for the ultimate pile skin friction capacity (R_s). The above correlation applies for both small and large diameter bored piles, as well as for driven piles. The main divergence in the application of the above SPT-based correlation for bored and driven piles relies upon the adopted safety factors.

The ECP-202 [1] recommends the use of the two different values of factors of safety FS_b and FS_s, for the individual SPT-based estimates of R_b and R_s, respectively, in Eq. (11). This is in order to forecast the allowable pile capacity utilized in the WSD-concept as per Eq. (6.b).

In this section, the calibrated-by-fitting technique is employed to find out calibrated partial safety factors, F_{Rb}, and F_{Rs}, for pile base and side resistance, respectively, to coincide with the SPT-based empirical correlation given in the ECP-202 [1]. The methodology incorporates multiplying the SPT-based estimate of the ultimate pile base resistance (R_b) by a partial safety factor (F_{Rb}). In the same manner, the SPT-based estimate or the ultimate pile side resistance (R_s) is multiplied by a partial safety factor (F_{Rs}). The result is the ultimate limit total pile resistance ($R_{U.L.}$), which should equal the ultimate limit load on single pile ($Q_{U.L.}$), as shown in Eq. (12).

$$R_{U.L.} = F_{Rs}\cdot R_s + F_{Rb}\cdot R_b = Q_{UL} = \gamma_{DL}\cdot Q_D + \gamma_{LL}\cdot Q_L \tag{13}$$

Dead load can be expressed from Eq. (6.b) as follows:

$$Q_D = \frac{R_b}{FS_b} + \frac{R_s}{FS_s} - Q_L \tag{14}$$

By substituting the term of Q_D from Eq. (13) into Eq. (12), the following expression could be obtained for the partial safety factor for pile base resistance (F_{Rb}):

$$F_{Rb} = \left(\frac{R_s}{R_b}.FS_b + FS_S\right)\left(\frac{\gamma_{DL} + \gamma_{LL}\left(\frac{Q_L}{Q_D}\right)}{FS_s.FS_b\left(1 + \frac{Q_L}{Q_D}\right)}\right) - \left(\frac{R_s}{R_b}\right)F_{Rs} \tag{15}$$

The ratio of the ultimate pile side resistance to the ultimate pile base resistance (R_s/R_b) shown in Eq. (14) can be substituted with the ratio of pile side to total ultimate resistance (R_s/R_t), the so-called share of pile side resistance, as follows:

$$\frac{R_s}{R_b} = \frac{R_s/R_t}{1 - (R_s/R_t)} \tag{16}$$

Substituting R_s/R_b from Eq. (15) into Eq. (14) yields:

$$F_{Rb} = \left(\frac{R_s/R_t}{1-(R_s/R_t)}.FS_b + FS_S\right)\left(\frac{\gamma_{DL} + \gamma_{LL}(Q_L/Q_D)}{FS_s\cdot FS_b(1+[Q_L/Q_D])}\right) - \left(\frac{R_s/R_t}{1-(R_s/R_t)}\right)F_{Rs} \tag{17}$$

For calculating the allowable resistance of driven piles in cohesionless soils utilizing the SPT-based empirical correlation provided by the ECP-202 [1], values of 2.00 and 2.50 are recommended for the safety factors FS_s and FS_b for the pile base and side resistances, respectively. In order to find out calibrated partial safety factors (F_{Rb} and F_{Rs}) for LSD that coincides with the implemented WSD concept in the ECP-202 [1], the methodology discussed in the this subsection was followed, based on the deduced Eq. (14). The share of ultimate pile side resistance (R_s/R_t) can be estimated from the results of the SPT-based correlation in the ECP-202 [1]. The ratio R_s/R_t would vary in the value between zero (i.e. end bearing pile) and 1.0 (i.e. friction pile). The value of R_s/R_t may depend on several factors, such as subsurface soil conditions, pile type, pile length and diameter and pile construction technique. In Eq. (14), the ratio of R_s/R_t was varied between zero and 0.95. A value of 1.0 was not assigned for the ratio of R_s/R_t since Eq. (14) applies for R_s/R_t less than one. Moreover, the dead to live load ratio (Q_D/Q_L) was varied in the range of zero to 1.0. Load factors $\gamma_{DL}$and γ_{LL} were constantly taken 1.4 and 1.6, respectively.

A sample of the results is illustrated in Fig. 5, which exhibits the variation of the calibrated partial safety factors F_{Rb} with the corresponding F_{Rs}-values at different values of the R_s/R_t ratio, however at a value of the Q_L/Q_D ratio equals 0.2. It should be mentioned that the results shown in Fig. 5 are calibrated corresponding to values of the safety factors of FS_b and FS_s that equal 2.5 and 2.0, respectively; for the case of driven piles.

Every point on the obtained trends in Fig. 5 represents a couple of F_{Rb} and F_{Rs} values for the partial safety factors required to be applied with ULSD to have the same design results obtained from the conventional WSD philosophy at certain Q_L/Q_D and R_s/R_t ratios. It may be noted that all of the relation trends in Fig. 5 intersect at one certain point.

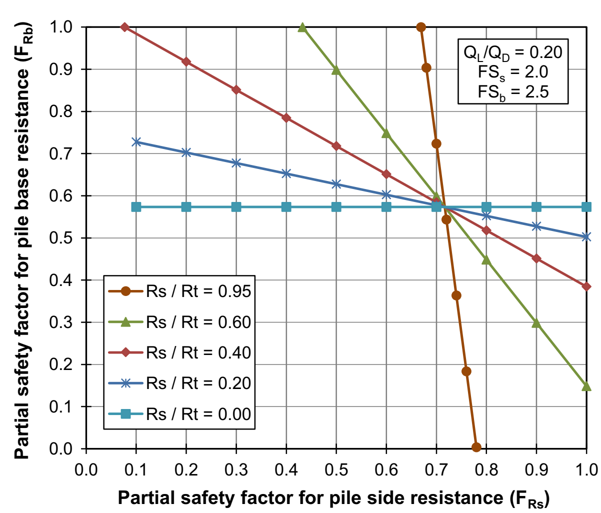

Fig. 5 Calibrated F_{Rs} and F_{Rb} with respect to the skin friction share for SPT-based driven piles.

This characteristic point satisfies the calibration condition for all values of the R_s/R_t ratio. At this characteristic point, the value of F_{Rb} and F_{Rs} are 0.573 and 0.717, respectively. These two values of F_{Rb} and F_{Rs} are consistent with the value of the previously calibrated reduction factor (F_R) for the total pile resistance at the global safety factor (FS_g) of 2.5 and 2.0, respectively, and at Q_L/Q_D ratio equals 0.2 (revoke Figs. 3 and 4).

Values of F_{Rb} and F_{Rs} for the intersection point can be calculated and plotted at different values of Q_L/Q_D ratio. Fig. 6 represents the variation of Q_L/Q_D ratio with F_{Rs} and F_{Rb} for the intersection characteristic point shown in Fig. 5. From Fig. 6, it can be noted that values of F_{Rb} and F_{Rs} vary in a relatively narrow range when changing Q_L/Q_D from zero to 1.0.

Calibration of partial safety factors for pile side and base resistances from CPT-based empirical correlation

An empirical correlation for estimating the ultimate pile capacity (R_u) from results of CPT is provided in ECP-202 [1]. This correlation is provided to estimate the pile capacity in loose to dense sand or medium to stiff clay soil and it is expressed as shown in Eq. (17).

$$R_u = \alpha q_c A_b + f_c A_s \quad (18)$$

where R_u is the ultimate pile resistance, q_c is the average penetration resistance of the static cone encountered within an arbitrary end bearing zone of 6d above and 3d below the pile tip level, for a pile shaft diameter d, α represents a factor that depends on the ratio between the pile diameter to the cone diameter and it can be assumed 0.7 as recommended in ECP-202 [1]. The term f_c represents the average frictional resistance of the static cone along the pile shaft length, A_b is the area of the pile base and A_s is the side area of the pile shaft. It is worth mentioning that, in the correlation given above, the term (α q_c A_b) represents the ultimate pile end bearing capacity (R_b), whereas the term (f_c A_s) stands for the ultimate pile side frictional capacity (R_s). The above correlation applies for both small and large diameter bored piles, as well as for driven piles. The main divergence in the application of the above CPT-based correlation for bored and driven piles relies upon the adopted safety factors.

Same as it was previously clarified in SPT-based correlation, the ECP-202 [1] recommends the use of the two different values of factors of safety FS_b and FS_s, for the individual CPT-based estimates of R_b and R_s, respectively. This is in order to forecast the allowable pile capacity utilized in the WSD-concept as per Eq. (6.b).

In this section, the calibrated-by-fitting technique is also employed to find out calibrated partial safety factors, F_{Rb}, and F_{Rs}, for pile base and side resistance, respectively, to coincide with the CPT-based empirical correlation given in the ECP-202 [1]. The methodology incorporates multiplying the CPT-based estimate of the ultimate pile base resistance (R_b) by a partial safety factor (F_{Rb}). In the same manner, the CPT-based estimate or the ultimate pile side resistance (R_s) is multiplied by a partial safety factor (F_{Rs}). The result is the ultimate limit total pile resistance ($R_{U.L.}$), which should equal

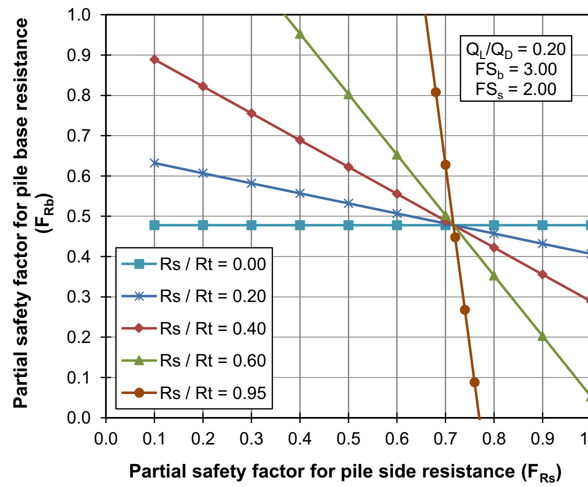

Fig. 7 Calibrated F_{Rs} and F_{Rb} with respect to the skin friction share for CPT-based driven piles.

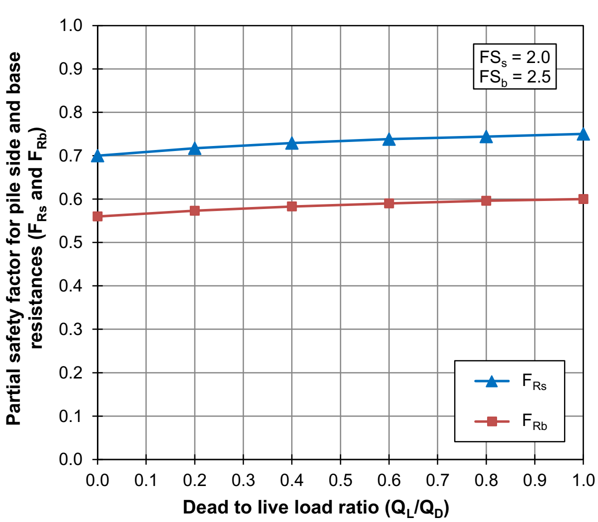

Fig. 6 Variation of Q_L/Q_D with F_{Rb} and F_{Rs} of the intersection point for SPT-based driven piles.

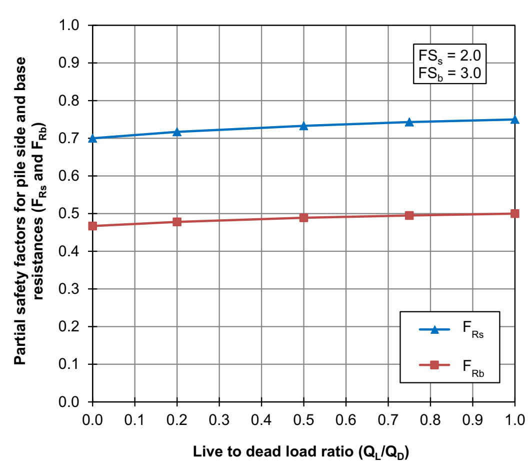

Fig. 8 Variation of Q_L/Q_D with F_{Rb} and F_{Rs} of the characteristic intersection point for CPT-based driven piles.

Please cite this article in press as: Y.M. El-Mossallamy et al., Application of ultimate limit state design for axially loaded single piles in Egyptian geotechnical practice, HBRC Journal (2015), http://dx.doi.org/10.1016/j.hbrcj.2015.02.004

Table 1 Proposed values for F_R in comparison with F_R values in some international geotechnical codes of practice.

Case/code of practice	Resistance reduction factor (F_R)										
	Proposed for ECP-202 (2001)	CFEM (2006)	AASHTO (2007)						NCHRP 507 (2004)	Eurocode 7 NA to BS EN 1997-1:2004	DIN 1054:2010-12
			α-method		β-method		λ-method				
			Clay	Sand	Clay	Sand	Clay	Sand			
Bored piles (Static analysis)	0.48	0.40	0.45	–	–	0.55	–	–	0.50	0.59	–
Driven piles (Static analysis)	0.48	0.40	0.35	–	0.25	–	0.40	–	0.50	0.67	–
Driven Piles (Dynamic analysis)	0.57	0.50	0.65						0.55	0.67	0.73
Static load tests	0.72	0.60	0.70						0.70	0.67	0.73
Large diameter bored piles	0.72	0.60	0.45	–	–	0.55	–	–	0.80	0.59	0.73
Driven piles, SPT-method, R_s	0.72	–	0.30 (Sand)						0.50	–	–
Driven piles, SPT-method, R_b	0.57										
Driven piles, CPT-method, R_s	0.72	–	0.50						0.50	–	–
Driven piles, CPT-method, R_b	0.48										

ECP-202: Egyptian Code of Practice for Soil Mechanics and Foundations Design and Construction, Part 4, Deep Foundations.
CFEM (2006): Canadian Foundation Engineering Manual.
AASHTO (2007): LRFD Bridge Design Specifications, American Association of State Highway and Transportation Officials.
NCHRP 507 (2004): National Cooperative Highway Research Program (507), Load and Resistance Factor Design (LRFD) for Deep Foundations, Transportation Research Board (TRB).
Eurocode 7- NA to BS EN 1997-1:2004: UK National Annex to Eurocode 7: Geotechnical design- Part 1: General rules.
DIN 1054:2010-12: Subsoil- Verification of the safety of earthworks and foundations- Supplementary rules to DIN EN 1997-1.

the ultimate limit load on single pile ($Q_{U.L.}$), as previously illustrated in Eq. (9).

Following the same procedures of the calibration deduced in the previous section, the expression given in Eq. (16) for the partial safety factor for pile base resistance (F_{Rb}) was also used for the calibration of F_{Rs} and F_{Rb} for CPT-based pile capacity correlation. The calibrated values of F_{Rs} and F_{Rb} can be plotted for CPT correlation along with changing the skin friction share (R_s/R_t) at Q_L/Q_D ratio equals 0.2, as presented in Fig. 7. It should be highlighted that the results presented in Fig. 7 are calibrated corresponding to FS_b and FS_s values of 3.0 and 2.0, respectively; which are applied for the empirical CPT correlation in case of driven piles.

The relation trends shown in Fig. 7 intersect at a characteristic point that defines values for F_{Rb} and F_{Rs} of 0.478 and 0.717, respectively. Going back to Figs. 3 and 4, it can be noted that the aforementioned values of F_{Rb} and F_{Rs} are also consistent with previously calibrated values of F_R for the total pile resistance at FS_g values of 3.0 and 2.0, respectively, and at Q_L/Q_D ratio equals 0.2. Fig. 8 represents the variation of Q_L/Q_D ratio with F_{Rs} and F_{Rb} for the intersection characteristic point shown in Fig. 7. From Fig. 8, it can be noted that values of F_{Rb} and F_{Rs} vary in a relatively narrow range when changing Q_L/Q_D from zero to 1.0.

Validation of the calibration technique

The calibration-by-fitting technique applied in this study aims mainly to keep the design outputs from both WSD and LSD philosophies quite close. In this section, illustrative numerical example is introduced as a validation for the calibrated reduction factors to the pile design with regard to the current Egyptian field of practice. The illustrative example is presented for the static formula design method provided in ECP-202 [1] for the design of axially loaded small diameter piles.

A bored pile of diameter 0.6 m is assumed to be loaded with dead and live loads of 1500 kN and 300 kN, respectively (Q_L/Q_D ratio of 0.2). The subsurface soil profile can also be assumed to consist of a deep deposit of silty sand layer of bulk unit weight, φ and c equals 18 kN/m^3, 33° and 15 kPa, respectively. Applying the static design formula presented in the current ECP-202 [1] for the design of the abovementioned axially loaded single pile, which follows WSD philosophy; the required embedded length of the pile equals 19.72 meters.

In the LRFD approach, factored, i.e. increased, loads shall be kept less than or equal to the factored, i.e. reduced, resistance. The factored loads shall be calculated by applying means of load factors for the dead and live loads. According to ECP-203 [2] and ECP-201 [18], load factors for dead and live loads are 1.4, and 1.6, respectively. Hence, the factored loads ($Q_{U.L.}$) shall equal 2580 kN. Applying a value of 0.48 for the reduction factor F_R in Eq. (9), which follows the LSD philosophy; the embedded pile length equals 19.65 m, which is quite close to that obtained from the classical WSD philosophy, i.e. 19.72 meters, currently adopted in the ECP-202 [1]. After all, the pile length to be executed shall be approximated to 20.0 m. Thus, there will not be any significant over-design or under-design estimates when applying the LSD side by side with the WSD during the transition period of the Egyptian geotechnical design code of practice. Validation of the calibrated reduction factors for more design methods is provided in a study conducted by Zayed [21].

Conclusions

It was generally highlighted that WSD philosophy has been used in different applications of the geotechnical design in

Egypt as presented in the current version of ECP-202 [1]. Nevertheless, LSD philosophy is applied for the structural designs in Egypt as adopted in ECP-203 [2]. Applying the two different design concepts through the superstructure elements and the foundations may lead to design misleading and inconsistency. Therefore, the implementation of LSD in geotechnical engineering applications in Egypt has become of great importance. Accordingly, smooth and gradual transition procedure between the two design concepts has become mandatory. In this paper, a methodology was examined for transition from the commonly used WSD philosophy in geotechnical designs in Egypt to the LSD philosophy, focusing on applications to design of axially loaded single piles. The transition methodology was based on the calibration-by-fitting technique. Thus, partial safety factors for LSD were calibrated to provide similar design estimates to this obtained from WSD. The calibration methodology was applied on selected methods for geotechnical pile design presented in the ECP-202 [1]. The selected methods are the static formula, dynamic formula, empirical load–settlement relationship for the design of large diameter bored piles and the empirical SPT-based correlation. Results of this study are summarized in Table 1. The F_R values calibrated in this study can be presented as the proposed F_R values for the development of the ECP-202 [1] to included partial resistance reduction factors for ULSD of axially loaded single piles. The partial safety factors recommended from this study in Table 1 are chosen at Q_L/Q_D ratio of 0.20, which has been used in the literature [17] as an average value for reinforced concrete structures. Comparisons between resistance factors recommended in this study with those recommended by other studies and some international design codes [8,15,16,19,20], are presented in Table 1. As can be noted from Table 1, there is good agreement between the resistance reduction factors adopted in this study and some international LRFD-based geotechnical codes, except for the SPT and CPT-based design methods. Values of F_{Rb} and F_{Rs} proposed from this study for SPT-based empirical correlation differ in a notable degree from those values introduced in AASHTO [6] and NCHRP [8]. This difference can be explained by the different correlations used in ECP-202 [1], AASHTO [6] and NCHRP [8]. The ECP-202 [1] uses its characteristic correlation for SPT-based design which is completely different from Meyerhof's and Schmertmann's method used in AASHTO [6] and NCHRP [8], respectively. For the same reason, difference in reduction factors for CPT-based correlation exists. Also, ECP-202 [1] uses its unique correlation for CPT-based design of piles while both AASHTO [6] and NCHRP [8] use Nottingham and Schmertmann's method. The current study can provide a rigorous basis for transition from the classical WSD to the new LSD philosophy in the Egyptian practice for the axially loaded single piles.

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