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

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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.

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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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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).

$$R_{U.L.} = f(c_d; \varphi_d; \dots) \quad (1)$$

where

$$c_d = F_c c \quad (2)$$

$$\varphi_d = F_\varphi \tan \varphi \quad (3)$$

where c and φ are the characteristic soil shear strength parameters and $R_{U.L.}$ 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, $R_{U.L.}$, as shown in Eq. (4).

$$R_{U.L.} = f(c; \varphi; \dots) / F_R \quad (4)$$

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

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