Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Reliability of diaphragm wall in serviceability limit states

M. Wyjadłowski[a,*], W. Puła[a], J. Bauer[b]

[a] Faculty of Civil Engineering, Wrocław University of Technology, Wybrzeże St. Wyspiańskiego 27, 50-370 Wrocław, Poland

[b] Faculty of Geoengineering, Geology and Mining, Wrocław University of Technology, Na Grobli 15, 50-421 Wrocław, Poland

ARTICLE INFO

Article history:
Received 12 July 2014
Accepted 2 February 2015
Available online 26 February 2015

Keywords:
Reliability index
Diaphragm wall
Ditlevsen's bounds

ABSTRACT

The paper describes a procedure using serviceability limit state equations to calculate the reliability index for a laterally loaded diaphragm wall. The reliability indices related to the serviceability limit state have been obtained by creating two response surfaces: one based on the maximum lateral displacements of wall head and the other one using the maximum values of bending moments widening cracks in the wall concrete. The global reliability index has been obtained by using the appropriate system reliability formulae proposed by structural reliability theory.

1. Introduction

Lateral loads have at least the same importance as axial compressive loads on diaphragm wall and therefore they must be carefully taken into consideration during design.

A better understanding of the mechanisms involved in the excavation soil–structure interaction could reduce costs and help avoid potential problems. Lateral loading of a diaphragm wall may be due to active loading where external loads are applied at the wall head or due to passive loading where lateral movement of the soil induces bending stresses in the wall [1]. Modern methods and the current design practice for diaphragm walls are presented in monographs [2,3].

However, simple engineering approaches could not serve in all complex geotechnical situations. Therefore new methods are still being developed. For example Osman and Bolton [4] proposed a design method that addresses the real nature of serviceability and collapse limits in soils, which always show a nonlinear and sometimes brittle response. The method is based on an application of the theory of plasticity accompanied by the introduction of the concept of "mobilizable soil strength."

Zhang and Ng [5] indicated that geotechnical structures are more often governed by allowable displacements' requirements than by ultimate limit requirements.

One important problem that leads to premature deterioration in concrete wall is the development of cracks as a consequence of deflection of wall [6].

* Corresponding author. Tel.: +48 602538756.
E-mail addresses: marek.wyjadlowski@pwr.wroc.pl (M. Wyjadłowski), wojciech.pula@pwr.wroc.pl (W. Puła), jerzy.bauer@pwr.wroc.pl (J. Bauer).

http://dx.doi.org/10.1016/j.acme.2015.02.001

Previous research dedicated to developments of cracks was mostly based on results in fracture mechanics in reinforced composites [7], while the recent approaches use numerical models usually in conjunction with finite element approaches (e.g. [8]). One of the latest issues is the paper of Pietruszczak and Haghighat [9]. The authors [9] address the problem of modeling of mixed mode cracking in concrete structures within the context of a constitutive law with embedded discontinuity. This approach, which was originally developed for describing the propagation of localized deformation, is enhanced to model a discrete nature of crack propagation.

While these models are a great step forward, they are generally deterministic and do not consider inherent variability in material properties, construction processes, and environmental conditions. As a result, these models do not accurately capture the true risk of cracking in concrete elements. In a research paper [10] Radlinska uses Monte Carlo method and Load and Resistance Factor Design (LRFD) approach to incorporate different sources of variability in investigating the probability of cracking in restrained concrete members.

Contemporary methods of risk assessment and reliability analysis of geotechnical problems usually require development of limit state function. In many cases if the limit state function is not given in an explicit form the response surface method is utlilised. This method has been successfully applied in some areas related to the present study approaches dedicated to reliability analyses of laterally loaded piles. One of the important contributions to addressing this problem is presented in the paper by Tandjiria et al. [11]. The paper provides a probabilistic analysis concerning the risk of pile head displacements as well as the maximum bending moments, which did not exceed allowable values. In a paper by Imançli et al. [12] on developing limit state functions via response surface method, maximum bending moment data under service load condition computed using 3D finite element analysis, which better represents the three-dimensional nature of the soil–structure interaction, were used by considering the pile rigidity. In the paper by Haldar and Babu [13], the properties of soil surrounding the pile have been characterized by non-Gaussian random fields. This approach allows incorporating the spatial variability of soil parameters into reliability computations.

In the present study the SORM (second order reliability analysis) has been applied to incorporate different sources of uncertainty [14] in investigating the probability of exceeding allowable values of lateral displacement of wall head and the widening of cracks. For large variation coefficients of material constants or other parameters, ultimate and serviceability limit state calculations could be combined with reliability analysis [15].

Two types of serviceability limit state were selected for the analysis: a lateral displacement of wall head and the widening of cracks perpendicular to the wall axis. According to serviceability limit state principles, the displacement cannot exceed the predefined allowable value u_{all}, and crack widening – the allowable value w_{lim}. Exceeding the values u_{all} or w_{lim} is regarded as a structural failure.

As a result of random fluctuations in soil parameters, these conditions make two events that, with adequately high probabilities, should satisfy the following inequalities:

$$\{u \le u_{all}\}, \quad \{w_k \le w_{lim}\} \tag{1}$$

where u stands for a lateral displacement of wall head and w_k stands for crack widening. Failure-free operation requires that conditions (1) are satisfied simultaneously. From the point of view of reliability theory, it is a two-component serial system.

In a general case, the resulting failure probability

$$p_F = 1 - P[(u \le u_{all}) \cap (w_k \le w_{lim})] \\ = P\{(u > u_{all}) \cup (w_k > w_{lim})\}, \tag{2}$$

is higher than probabilities of failures obtained in the case of not meeting both limit state conditions.

In order to simplify the calculations, it is worth replacing the crack widening condition in inequality (1) with an equivalent condition comprising the maximum bending moments in wall:

$$\{M_g \le M_{Sd}\} \tag{3}$$

where M_g denotes the value of the maximum bending moment causing crack widening by w_k, and M_{Sd} is a bending moment causing crack widening by w_{lim}. Additionally, this form of crack widening limit condition enables taking into account the ultimate limit condition:

$$\{M_g \le M_{ult}\} \tag{4}$$

If inequality $M_{ult} \le M_{Sd}$ is satisfied, inequality (4) will replace inequality (3) in the calculations.

The adopted state of ultimate bearing capacities comprises the maximum bending moment M_g, which can occur over the whole wall length, from its head to the foot. The maximum bending moment cannot exceed the limit value M_{ult}, resulting from the adopted reinforcement ratio. Exceeding the limit value M_{ult} is considered to be a conventional structural failure, as satisfying inequality (4) still leaves a considerable margin of safety, which is not ensured by serviceability limit state conditions.

2. Description of the analyzed engineering problem

Figs. 1–3 show a vertical section of a diaphragm wall. The structure with the mean thickness of 0.5 m is made up of 9.0 m long wall embedded in layered soil. The top layer with the mean thickness of 4.0 m has a randomly varying elasticity modulus E and its depth is also a random variable. Behind the wall, there is a hollow with a free water table occurring periodically. The top two soil layers are saturated with acidic water, whose pH could cause rebar corrosion.

Standard [16] recommends that the correctness of the designed structure should be verified by analysing the ultimate limit state and serviceability limit states. The ultimate limit state condition (4) requires defining the maximum value of the boundary moment per one meter of wall length, which could be generated by a lateral force loading the wall head. At the stage of designing the wall, it was