Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

# Reliability of rigid piles subjected to lateral loads

*W. Puła*, A. Różański*

*Wrocław University of Technology, Faculty of Civil Engineering, Institute of Geotechnics and Hydrotechnics, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland*

ARTICLE INFO

*Article history:*
Received 23 April 2012
Accepted 26 April 2012
Available online 4 May 2012

*Keywords:*
Reliability index
Response surface
Soil strength parameters

ABSTRACT

In this paper the complete solution to the problem of random lateral bearing capacity of rigid piles has been presented. The suggested solution is based on the limit states theory approach proposed by Brinch Hansen [2]. A revised approach utilising the response surface method is proposed and compared with the solution presented in earlier papers. Both cases of non-cohesive and cohesive soils are studied. In addition, the influence of spatial averaging is also analysed. Numerical algorithms, for both cases of cohesive and cohesionless soils, have been developed in order to evaluate probability of lateral bearing capacity exceeding. As it has been demonstrated random fluctuations of soil properties can cause significant changes in the value of ultimate lateral loading determined according to the Brinch Hansen method. Series of numerical examples under consideration give some important conclusions concerning an influence of soil properties randomness on safety evaluations.



## 1. Introduction

Methods elaborated in this paper have been inspired by many computations carried out when the modernisation of main railway tracks in Poland has been started. In almost all cases there was a need to replace existing foundations – of overhead electrical transmission lines supports – by new foundations. One of possible solutions was to apply single pre-cast concrete piles as a foundations of electrical line supports (as demonstrated in Fig. 1). In many cases, due to lengths of piles and soil conditions, piles had to be considered as rigid ones. Therefore the lateral ultimate soil resistance has been considered. The ultimate lateral resistance of the soil in the vicinity of a pile is not very often treated in the engineering practice. This is due to fact that majority of piles used in foundation engineering are not rigid [1]. Therefore the probabilistic approach, in this area, is almost forgotten in the literature. Among deterministic methods the solution proposed by Brinch Hansen [2] is considered as a one of the most precise, however simplified approaches elaborated by Broms [3,4] are more commonly used. The vital point in the Brinch Hansesn method is the position of the rotation centre $z_r$ of the pile under consideration (see Fig. 2). It is possible to prove that the ultimate horizontal loading $H_u$ is highly sensitive to the location of the centre of rotation $z_r$. The rotation centre itself is subjected to random fluctuations due to inherent uncertainty of soil properties (mostly the strength parameters) as well as uncertainty in geotechnical recognition. Therefore a probabilistic approach to this problem seems to be quite adequate. On the other hand solutions of deterministic problem could not be written in a closed mathematical form. Due to this difficulty standard probabilistic approaches could not be applied straightforward. A solution of the reliability problem associated with laterally loaded piles is the objective of this paper.

The problem of the reliability of rigid piles subjected to lateral loads in the context of piles capacity has been discussed in earlier works [5,6]. In the papers an algorithm for evaluating reliability indices (and corresponding failure probabilities), based on the SORM method [7], was introduced. The algorithm

*Corresponding author. Tel.: +48 502209006; fax: +48 713284814.
E-mail address: Wojciech.Pula@pwr.wroc.pl (W. Puła).

1644-9665/$ - see front matter © 2012 Politechnika Wrocławska. Published by Elsevier Urban & Partner Sp. z.o.o. All rights reserved.
http://dx.doi.org/10.1016/j.acme.2012.04.007

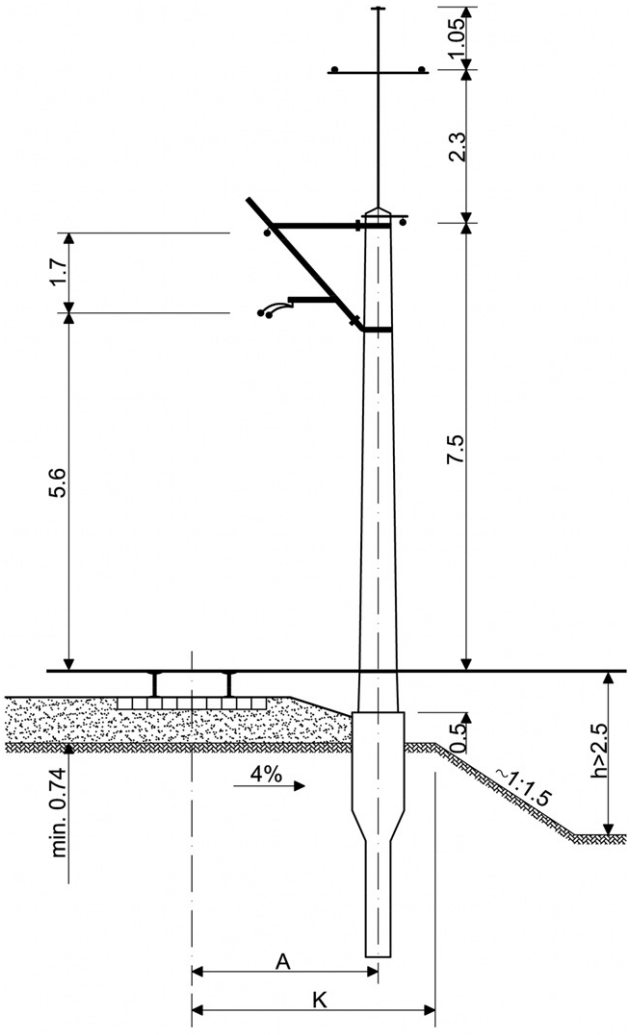


**Fig. 1 – An example of overhead electrical transmission line support founded on a single pile (railway line near Wrocław, Poland).**

was also supported by symbolic computations utilising *Mathematica* [8] software as well as some power series expansions. This solution in the next parts of the present paper will be, for simplicity, called the "*symbolic algorithm*". The application of the "symbolic algorithm" in many computational examples shows, however some important inconveniences that are described in further sections of the present paper. Moreover the "symbolic algorithm" has given a solution solely for cohesionless soils. The present paper is a comprehensive study on the reliability problem mentioned above.

The paper is organised as follows. First, for better understanding the Brinch Hansen method, it is shortly described. In next Section the probabilistic approach is formulated. Next, the static equations corresponding to the problem are solved. Then, for comparison with further results, the "symbolic algorithm" is shortly presented. Finally the new approach based on the response surface method [9,10] is demonstrated. The new approach covers both cases, namely a cohesionless and a cohesive soil and allows to overcome numerical difficulties that appeared in the "symbolic algorithm". Moreover the effect of spatial averaging of soil properties has been also discussed.

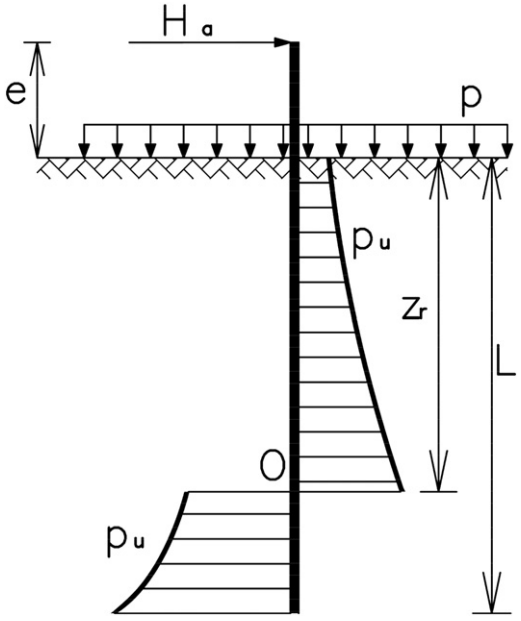


**Fig. 2 – A scheme of rigid pile embedded in a soil and subjected to lateral load.**

## 2. Formulation of the problem

### 2.1. *Deterministic approach*

Consider a rigid pile subjected to a lateral load as presented in Fig. 2. The mechanism associated with the failure assumes a rotation of the pile around centre *O* due to external load as well as reaction of surrounding soil. Assume that $H_u$ and $M_u$, denote the ultimate lateral load and ultimate value of the moment, respectively, inducing an ultimate ground resistance $p_u(z)$ on the depth z.

Treating the pile as a strip of the width *D* (or diameter *D* in the case of a pile of circular cross-section) and the length *L* the following equilibrium equations can be written:

$$H_u = \int_0^{z_r} p_u(z) D\, dz - \int_{z_r}^{L} p_u(z) D\, dz \tag{1}$$

$$M_u = H_u e = -\int_0^{z_r} p_u(z) Dz\, dz + \int_{z_r}^{L} p_u(z) Dz\, dz \tag{2}$$

where $z_r$ is the ordinate of the rotation centre as indicated in Fig. 2. The above equations have to be solved with respect to unknown ordinate $z_r$ of the rotation centre and the ultimate value of the lateral load $H_u$.

It is evident that the solution of Eqs. (1) and (2) depends on the resultant (passive minus active) ultimate lateral soil resistance $p_u(z)$ distributed along the pile's length. In the simplest case, i.e. under assumption that the resistance $p_u(z)$ does not depend on z, $p_u(z) = p_u$, the solution of Eqs. (1) and (2) takes the following form:

$$z_r = \frac{1}{2}\left(\frac{H_u}{p_u D} + L\right) \tag{3}$$

$$\frac{H_u}{p_u DL} = \sqrt{\left(1 + \frac{2e}{L}\right)^2 + 1} - \left(1 + \frac{2e}{L}\right). \tag{4}$$