



THE ANCHORED PILE WALL OPTIMIZATION USING NLP APPROACH

HELENA VRECL-KOJC

About the author

Helena Vrecl-Kojc
University of Maribor,
Faculty of Civil Engineering
Smetanova ulica 17, 2000 Maribor, Slovenia
E-mail: helena.vrecl@uni-mb.si

Abstract

The type of a retaining structure as well as the structure configuration mainly depends on geological conditions. If geological, urban and other data allow an alternative, the costs should also be considered as an important factor. In geotechnical practise, pile walls are especially used in excavations, in the erection of traffic facilities and in the sanitation of landslides. This paper is aimed at presenting economical differences between cantilever and anchoring pile walls and the impact of different parameters on costs. The optimization method, which uses mathematical programming, gives an optimal solution to geometry, self-manufacturing costs, and other characteristics of the structure in a uniform optimization process. This paper presents the optimization process using the nonlinear programming (NLP) approach for the anchored pile wall. The application presented only serves to confirm the effectiveness of the proposed optimization method. Therefore, the retaining structure is situated in homogeneous non-cohesive soil at three different soil friction angles of 35°, 30° and 25°. The generalized analytical method, the USA method, which was first introduced by Bowles [3], is used in the application. The analysis of the results shows the impact of parameters, the main controlling factors, configuration geometry and savings. The optimal results allowed from 18 up to 47 per cent savings compared to the cantilever pile wall depending on ground and structure input data and the excavation depth.

Keywords

retaining structure optimization, NLP approach, USA analytical method

1 INTRODUCTION

In the field of geotechnical design the safety factor is not the only one important to be nowadays. Designers are also challenged by reducing costs and minimizing the amount of material required. The use of optimization methods in this field is not appropriate just for minimizing costs, but also for shortening design periods and flexibility. The optimization which uses mathematical programming methods has been applied in many different scientific research areas for several years. Literature on optimization design programming of geotechnical structures is scarce. However, some works of the geotechnical structures optimization [2], [5], and also the optimization problems in other types of structures [1], [8], [10] should be mentioned. In our research works in the past years we have researched the parametric non-linear analysis of embedded retaining structures and the scope for analyzing of soil-structure interaction [11], [12], which has also been considered in the present work.

A uniform optimization process with simultaneous analyses of structural dimensions, gives an optimal solution. The objective function, that has to be minimized, is defined as an economical function and it is subjected to a set of equality and inequality constraints. The general data, excavation depth and soil properties are constant input parameters, whilst structural parameters, such as cross-section, embedment depth, anchoring force, stresses and deflections appear as variables. Equality and inequality constraints and the variables represent a rigorous system of design, loading, stress, and other functions taken from structural analysis. The variables are calculated when the objective function converges during the optimization process. The retaining structure is designed in accordance with European guidelines [6], [7] in order to satisfy the requirements of both the ultimate and serviceability limit states. Section 2 presents the USA analytical method used in the application of NLP approach, whilst Section 3 focuses on the application of the NLP approach. A detailed analysis of the results, the contribution of each parameter to optimization and the identification of the main controlling factors, are all given in Section 4. Economical



comparisons between cantilever and anchored pile walls are made depending on excavation depths for different soil properties.

2 GENERALIZED ANALYTICAL METHOD

Several different methods for geotechnical analyses of anchored and cantilever pile walls are used in geotechnical practice, i.e. the UK simplified method, the UK full method, and the USA method [3]. Individual methods considered different assumptions of soil pressure distribution and deformations of the embedded part of the retaining structure. At the anchored walls the increase of anchoring force means the decrease of embedment depth. Minimum embedment depth needed at maximum anchoring force is achieved at a pile wall with free support, when the rotation of the wall around the anchoring point is prevented (Fig. 1c). Economical optimization is performed using the USA method which was first introduced by Bowles [3] for homogeneous soil. The method is performed in a generalized form, and the results are afterwards transformed into real values. In the region between the depths d_1 and d the resulting resistances have the form of polygonal net pressure distribution (Fig. 1). The unknown embedment depth d in the soil at the toe of the pile wall is determined by using the equilibrium of horizontal forces (1), while the depth d_1 is determined by the moment equilibrium condition (2).

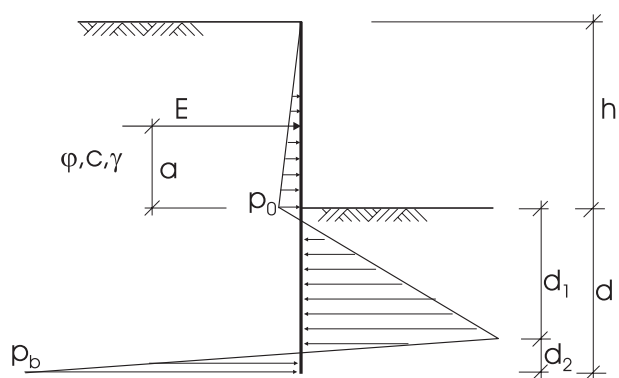
$$(E' - P'_{an}) + (\gamma' K + (K - 1)d') \cdot (d' - d'_1) - 0.5p'_0(d' + d'_1) - (K - 1)d'd'_1 = 0 \quad (1)$$

$$d'_1 \cdot ((K - 1)d'^2 - E' + P'_{an} + p'_0 d') - (E'(3a' + 2d') - P'_{an}(3h'_{an} + 2d') - 0.5p'_0 d'^2) = 0 \quad (2)$$

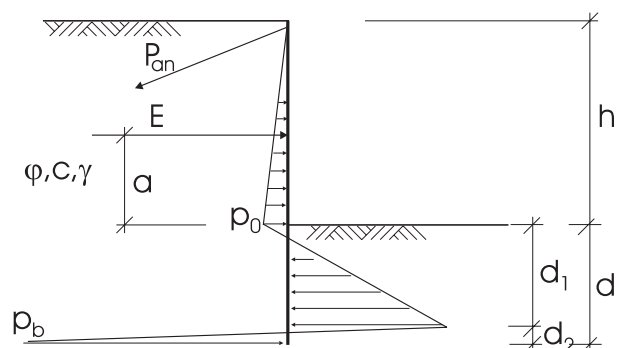
where the generalized quantities are:

$$d'_1 = (h' \cdot d_1)/h, \quad d' = (h' \cdot d)/h, \quad K = K_{p\varphi}/K_{a\varphi}, \quad E' = 2E/(h \cdot \gamma^2 \cdot K_{a\varphi}), \\ p'_0 = -2, \quad a' = a/h, h'_{an} = 0.95h' \quad (3)$$

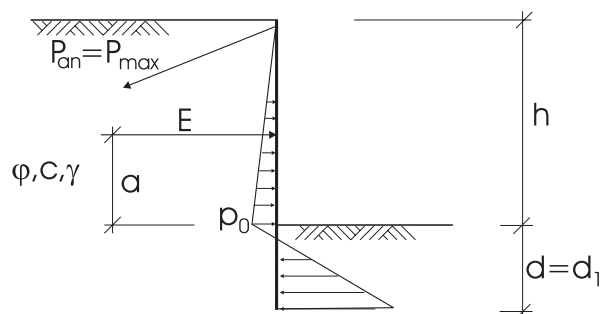
$K_{a\varphi}$, $K_{p\varphi}$ denote the coefficients of active pressures and resistances respectively for the influence of soil weight [9], E is the resulting force of active pressures above a dredge line, h is the actual excavation depth, and a is the distance of the resulting force of active pressures from the dredge line. The symbol φ denotes the soil friction angle, γ denotes the actual weight of the soil layer in which the analyzed retaining structure is embedded, $\gamma' = 1.0$ denotes the generalized soil unit weight, $h' = 1.0$ is the generalized excavation depth, d' is the generalized embedment depth.



a) Cantilever pile wall ($P_{an}=0$), $d_2=d_{2max}$



b) Anchored pile wall (P_{an}), d_2



c) Maximal anchored pile wall (P_{an-max}), $d_2=0$

Figure 1. a), b) and c). Influences and resistances according to the USA method

Fig. 1 shows three cases of anchoring forces:

- a cantilever pile wall has maximum value of d (d_2),
- an anchored pile wall where the embedment depth d (d_2) decreases, and
- a fully anchored pile wall $P_{an}=P_{an-max}$ where d_2 is zero and d is minimum.

Fig. 2 presents generalized dependence of $(d_2/d)'$ and P_{an}' with $(h/d)'$ for different soil types.

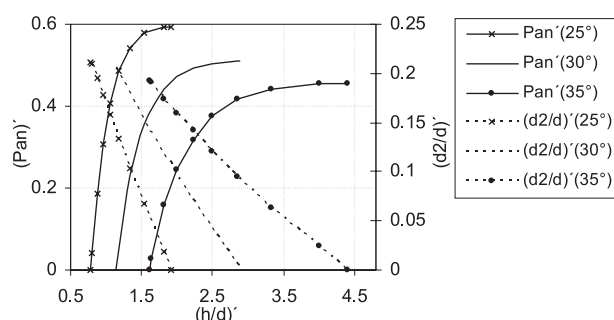


Figure 2. Generalized anchoring forces and generalized ratio $(d_2/d)'$ depending on $(h/d)'$ for soil friction angles of 35°, 30° and 25°

The actual values of the inner forces (T_m , M_m) and the anchor force (P_{an}) are calculated using Eqs. (4) to (6).

$$M_m' = \frac{2 \cdot M_m}{\gamma \cdot h^3 \cdot k_a} \quad (4)$$

$$T_m' = \frac{2 \cdot T_m}{\gamma \cdot h^2 \cdot k_a} \quad (5)$$

$$P_{an}' = \frac{2 \cdot P_{an}}{\gamma \cdot h^2 \cdot k_a} \quad (6)$$

M_m' , T_m' , P_{an}' are the generalized values of maximum moment, shear force and anchoring force, and k_a is the coefficient of active pressure [9]. The results of anchoring force and inner forces are substituted in the optimization model by a set of function constraints.

3 APPLICATION OF THE NLP APPROACH

3.1 STRUCTURE GEOMETRY

An optimization model for the anchored pile wall (Fig.3) is composed of the following construction elements: bored piles, anchors, a connection beam and upper formative segments. The piles of the diameter B with the excavation depth h , the embedment depth d , and the axial distance e_{pil} are fixed together with the connection beam. The pile wall is anchored into the soil with prestressed anchors. The axial distance of anchors is e_{an} , l_v and l_p are fixed and free lengths of an anchor, δ is anchor inclination.

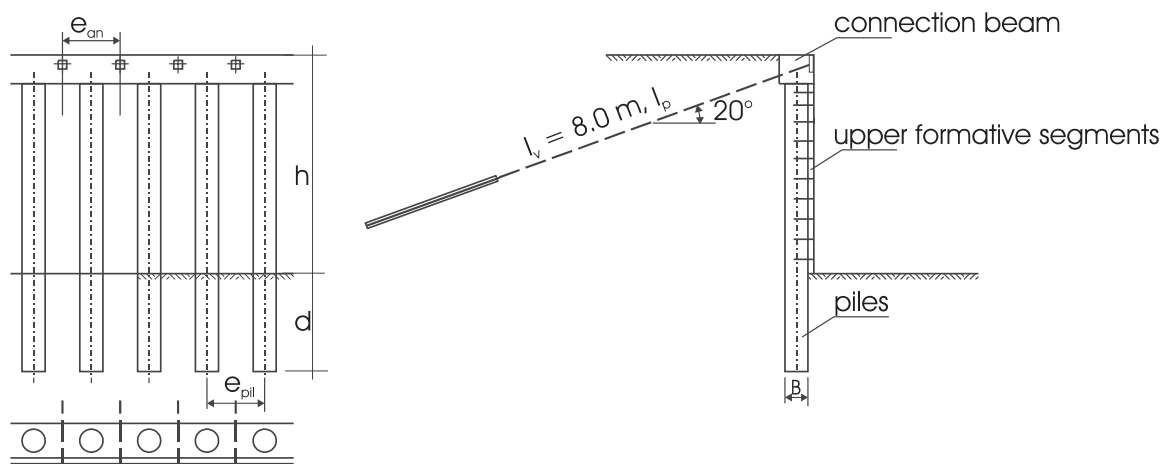


Figure 3. Longitudinal and cross sections of the structure



3.2 INPUT PARAMETERS: CONSTANTS, VARIABLES AND THE OBJECTIVE FUNCTION

Concrete and structural steel material characteristics are defined as constants (Table 1). The constant input parameters in the optimization model are soil properties and the characteristics of the pile wall (i.e. generalized and actual excavation depths). The presented application only serves to confirm the effectiveness of the proposed optimization method. Therefore the retaining structure is situated in homogeneous non-cohesive soil at three different soil friction angles of 35° , 30° and 25° , and at soil weight $\gamma = 21 \text{ kN/m}^3$.

The fixed anchor length is 8 meters, and the free anchor length has to be calculated in accordance to the standards.

Table 1. Constants in the optimization problem

Concrete strength - the concrete compressive strength (f_{cd})	25 MPa
Reinforcing steel - the design yield strength (f_{yd})	400 MPa
Prestressed steel (F_{py}/F_{pu})	1570/1770 MPa

The variables of the optimization model are the characteristics of the pile and anchors, and the pile and anchor axial interspaces (Table 2).

The upper formative segments have a height of 250 cm, and are fixed to the piles with injected anchors of necessary length.

Table 2. Variables in the optimization problem

Pile diameter	60 to 200 cm
Pile axial distance	B+20 cm to 3B
Number of anchor wires N_{an} (diameter/wire=15.4mm ²)	2 to 5
Thickness of upper formative segments	30 to 50 cm

The objective function of the optimization model is an economical function representing the construction costs. The material and other costs involved in the objective function are shown in Table 3.

Table 3. Material and other costs in the optimization problem

Concrete, concreting *	120 EUR/m ³
Boring in soft to half-hard soil *	(90•B+70) EUR/m
Reinforcing steel	0.85 EUR/kg
Panelling costs	15 EUR/m ²
Anchor 2x0.6, 3x0.6, 4x0.6	45,50,55 EUR/m

*pile wall of total length:

- a.) > 15 m: costs of boring and concreting increases for 20%
- b.) > 20 m: costs of boring and concreting increases for 40%

4 ANALYSIS OF THE RESULTS

This section presents the impact of parameters on optimization results, main controlling factors, configuration specifications, and savings.

In the optimization procedure it was established that the anchoring force function and the moment function mostly contribute to the optimization results, yet depending on the below controlling factors:

- excavation depth h ,
- dependence between e_{an} and e_{pil} ,
- number of wires per anchor N_{an} ,
- maximum axial distance of piles e_{pil} which is $3 \cdot B$,
- maximum percentage of longitudinal reinforcement,
- drilling and concreting costs of piles.

A detailed presentation of the results is seen in Fig. 4, where input parameters are $\varphi = 35^\circ$, $h = 12 \text{ m}$, $N_{an} = 3$. Fig. 4 a) shows the results when $e_{an} \neq f(e_{pil})$: the configuration of the structure is asymmetric, the analysis gave the optimal results by maximally spaced piles ($e_{pil} = 3B$), while anchors are located in the connection beam in a distance of e_{an} . Fig. 4 b) shows the results when $e_{an} = 0.50 \cdot e_{pil}$. In this case the configuration specification of the structure is symmetric; three anchors are placed between the axial distances of a pile. Increase the anchoring force has a major influence on the economical function, therefore e_{an} influences the value of e_{pil} and consequently of B . The economical function C , that must be multiplied by 10 to get a real value of costs, has a maximum value in a cantilever wall at $P_{an} = 0$, and then decreases to the optimum value at $P_{an-opt} \sim 0.70 P_{an-max}$. Increasing the anchoring force from $0.70 P_{an-max}$ to P_{an-max} means a different increase in costs, depending on the parameters e_{an} , e_{pil} and B which contribute to the economical function. Fig. 4b) shows that costs of pile wall configuration with P_{an-max} are even higher from costs of the cantilever wall.



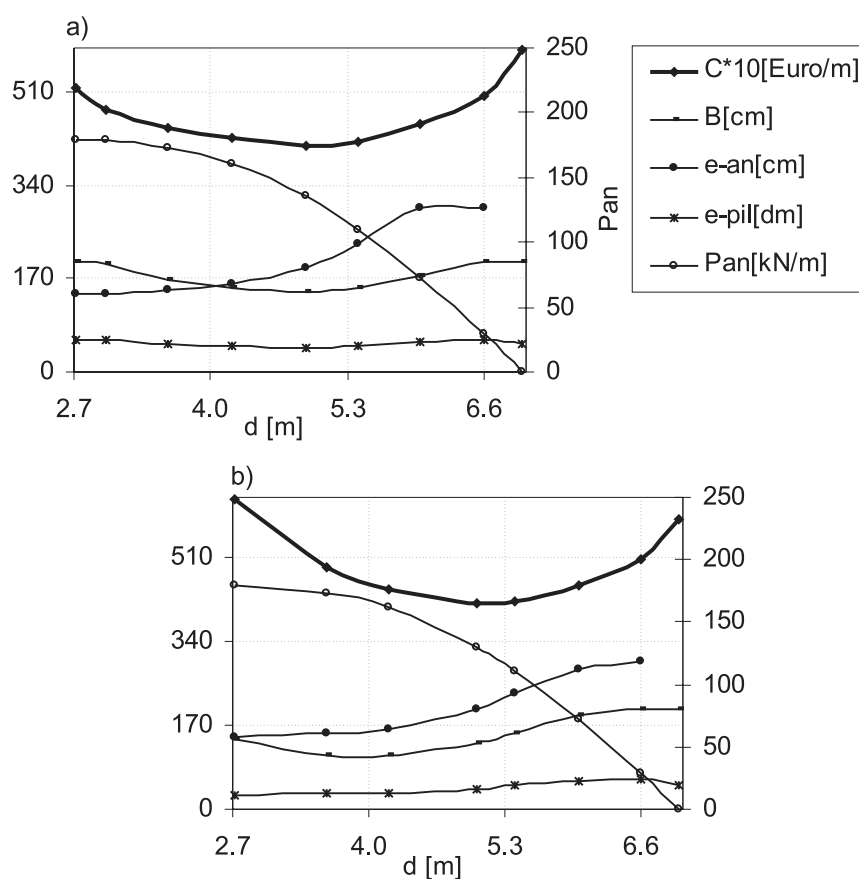


Figure 4. Cost optimization results for different wall parameters of e_{an} and e_{pil} (soil friction angle $\varphi = 35^\circ$, $h = 12$ m, $N_{an} = 3$):
 a) $e_{an} \neq f(e_{pil})$, and b) $e_{an} = 0.50 \cdot e_{pil}$ (the legend is shown in Fig. 4 a)

Fig. 5 presents the economical functions for different excavation depths h . Input parameters are $\varphi = 35^\circ$, $N_{an} = 3$, $e_{an} = 0.33 \cdot e_{pil}$. The optimal costs increase for 70 per cent, when the excavation depth increases from 8 to 12 meters.

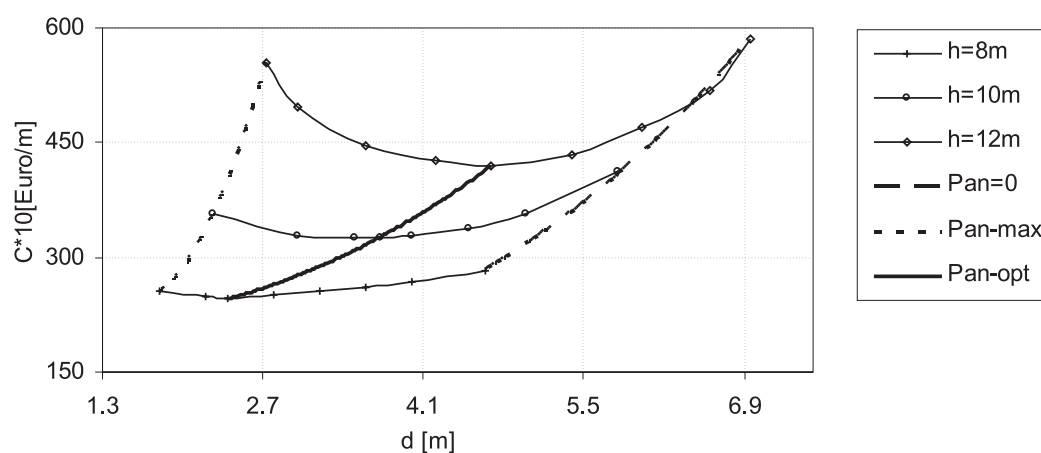


Figure 5. Cost optimization results for different wall parameters of h (soil friction angle $\varphi = 35^\circ$, $e_{an} = 0.33 \cdot e_{pil}$, $N_{an} = 3$)

The next parameter that contributes to the optimization is the number of wires per anchor N_{an} . Increasing the number of wires has a big influence (Fig.6). The costs increase for more than 20 per cent with $N_{an}=2$. The results indicate that a higher number of wires should be used in the case of good geological conditions.

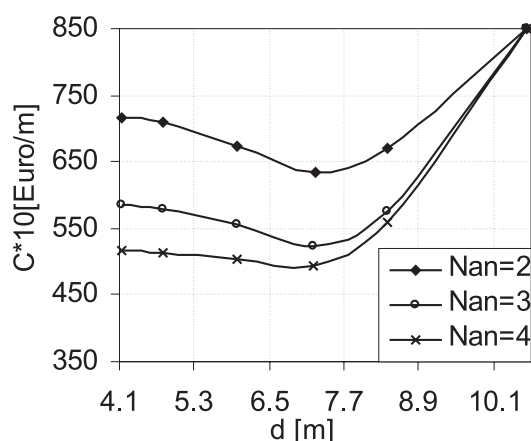


Figure 6. Cost optimization results for different wall parameters of N_{an} , soil friction angle $\varphi = 30^\circ$, $e_{an} = 0.33 \cdot e_{pil}$, $h = 12\text{m}$

The economical savings factors Δ [%] between the anchoring pile wall $P_{an} = P_{an-opt} \sim 0.70 P_{an-max}$ and the cantilever pile wall $P_{an} = 0$ (Fig. 7) show that economical savings increase with the excavation depth and with the worsening of soil properties. The application has proved the effectiveness of the optimization method, especially for higher structures located in bad ground conditions.

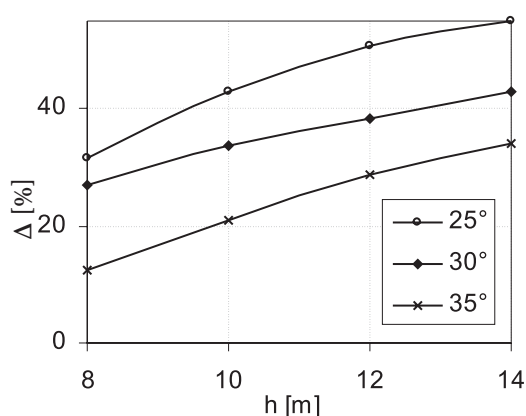


Figure 7. Diagrams of economical savings Δ [%]

5 SUMMARY

The intention of the present paper is to present economical differences between a cantilever and anchoring pile wall and the impact of different parameter on costs. The type of a retaining structure as well as the structure configuration (the optimal number and layouts of the structural elements) mainly depends on geological conditions. If geological and other factors allow an alternative, the costs should also be considered as an important factor.

Cantilever and anchored pile walls sustain overturning movements and horizontal forces, which are caused by backfill soil and other possible loadings. Contact pressures and resistances are distributed over the embedment depth due to backfill loading so that the entire retaining structure remains in equilibrium. The limit state of the retaining structure is achieved when the distribution of contact pressures and extensive regions of plastification in the ground are re-established at the embedded part of the structure, and the structure is no longer capable of taking additional backfill loading. Therefore, only those retaining structures which have a comparable level of safety and reliability for the limit states of the ground bearing capacity, as well as for the limit states of cross-sections of retaining structures, can be optimal. The USA analytical method is used in the cost optimization, preformed by a nonlinear programming (NLP) approach.

The final result of the optimization process is the most efficient structure which satisfies all the required geometrical and behavioral conditions. Similar optimization models can also be developed for other types of geotechnical structures, soil properties and ground characteristics using a corresponding geostatic method and other input parameters. The advantage of the presented optimization process is that it gives an optimal solution of geometry, design, self-manufacturing costs and other characteristics of the structure, depending on the input parameters.

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