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INTERAKCIJSKI PRISTOP H GEOMEHANSKIM ANALIZAM VPETIH NESIDRANIH PODPORNIH KONSTRUKCIJ

INTERACTION APPROACH OF GEOMECHANICAL ANALYSIS OF CANTILEVERED RETAINING STRUCTURES

Biografija

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Stanislav Škrabl je rojen 5. oktobra 1956 v Rogaški Slatini, Slovenija. Leta 1975 je maturiral na Srednji gradbeni šoli v Celju. Diplomiral je leta 1980 na Univerzi v Mariboru, kjer je tudi magistriral leta 1988 in doktoriral leta 1991.

Od leta 1980 je zaposlen na Univerzi v Mariboru, Fakulteti za gradbeništvo. Je izredni profesor za področji geotehnika in gradbena mehanika, direktor Inštituta za gradbeništvo in promet na FG in predstojnik Centra za geotehnične analize. Njegovo raziskovalno področje obsega plitvo in globoko temeljenje, prometne gradnje, sanacije plazišč ter velike deformacije plošč in poligonalnih lupin.

Je avtor ali soavtor 20 izvirnih znanstvenih člankov, 42 znanstvenih prispevkov in 14 strokovnih prispevkov na domačih in mednarodnih konferencah ter številnih strokovnih poročil, študij in revizij projektov. Njegovi raziskovalni dosežki so predstavljeni v 32 raziskovalnih nalogah, je pa tudi mentor in komentor številnim diplomantom in magistrantom.

Biography

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Stanislav Škrabl was born on 5 October 1956 in Rogaška Slatina, Slovenia. He graduated from a Secondary school in Celje in 1975. On University of Maribor, he graduated in 1980, was awarded a Master's degree in 1988 and he obtained his PhD in 1991.

Since 1980 he has been a member of staff at University of Maribor, Faculty of Civil Engineering. He is a professor for fields of geotechnics and civil engineering mechanics, director of Institute of Civil Engineering and Traffic, and manager of Center for Geotechnical Analysis. His research field include shallow and deep foundations, road construction, slope stability and large deformation of plates and polygonal shells.

He is author or co-author of 20 original scientific articles, 42 scientific and 14 technical contributions on national and international conferences and numerous geotechnical reports, studies and project reviews. His research highlights are presented in 32 research projects. He is also mentor of numerous graduate and postgraduate students.

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POVZETEK

Pri dokazovanju stabilnosti nesidranih vpetih podpornih konstrukcij se pojavljajo velika odstopanja med rezultati eksperimentalnih raziskav in interakcijskih analiz ter projektnimi podatki dobljenimi z analizami po metodah ravnotežja med aktivnimi vplivi in pasivnimi odpori, ki se največkrat uporabljajo v geotehnični praksi. Največje razlike se pojavljajo zlasti pri geomehanskih analizah kadar upoštevamo večje deleže trenja med podpornimi konstrukcijami in tlemi ter se odražajo tako v potrebnih globinah vpetosti kakor tudi v nerealnih vrednostih strižnih obremenitev podpornih konstrukcijah, ki povzročajo velike težave pri geotehničnem projektiranju pilotnih sten.

V članku je prikazana nova analitična metoda za geotehnično projektiranje vpetih podpornih konstrukcij, kjer so v analizi upoštevani le tisti odpori, ki se pri obravnavanem mejnem stanju lahko aktivirajo. Metoda temelji na nelinearnem poteku aktiviranih odporov, ki je bolj skladen z rezultati interakcijskih analiz. Predstavljeni postopek je uporaben tudi za projektiranje vpetih podpornih konstrukcij v nehomogenih pobočjih vendar le, če je konstrukcija vpeta v materiale enakih geomehanskih lastnosti. Bistvo predložene metode je v ločenem obravnavanju vplivov strižne trdnosti zemljin in trenja med konstrukcijami in tlemi na stabilnost geotehničnih konstrukcij.

Rezultati geomehanskih analiz po predloženi metodi so za tipične primere skladni z rezultati interakcijskih analiz izdelanih po MKE ter omogočajo izvrednotenje realnejših projektnih parametrov za projektiranje podpornih konstrukcije ter zato predlagamo, da se predložena metoda uporablja pri projektiranju vpetih nesidranih podpornih konstrukcij v geotehnični praksi.

INTERACTION APPROACH OF GEOMECHANICAL ANALYSIS OF CANTILEVERED RETAINING STRUCTURES

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ABSTRACT: When proving the stability of the embedded cantilevered retaining structures the great deviations arise between results of experimental researches with interaction analyses and design data obtained by analyses according the equilibrium methods between active influences and passive resistances (mostly used in geotechnical practice). The largest deviations arise particularly at geotechnical analyses when higher portions of friction between retaining structure and ground are taken into consideration. These deviations reflect on required embedment depth as well as on unreal values of shear inner forces of retaining structures. The later leads to the great problems in geotechnical design of pile wall.
The article presents a new analytical method of geotechnical design of embedded retaining structures, where are taken into consideration only those resistances that can be activated in considered limit state. The method bases on nonlinear course of the activated resistances that is in accordance with interaction analyses. The presented procedure is applicable also for design of embedded retaining structures in non-homogeneous slopes only when structure is fixed into material of the same geomechanical properties. The essential element of the given method is in the separated consideration of influences of soil shear strength and friction between structures and ground on the stability of geotechnical structures.
The results of geotechnical analyses of the typical cases according to the given method are in the accordance with the results of interaction analyses using FEM. They enable us to calculate more realistic design parameters in retaining structures design. We suggest the usage of the proposed method when designing pile walls in geotechnical practice.

INTRODUCTION

Embedded unanchored retaining structures are often used in geotechnical practice. When excavations are carried out they are used as temporary structures composed of steel profiles or sheet pile walls. When traffic objects are erected or slope is permanently retained they are used as permanent structure elements composed of concrete piles and horizontal beams or concrete sheet pile walls.
Those sort of retaining structures are, when executing excavations, at the backfill subject with earth pressures, and within the region of embedment with soil resistances that ensure its stability. The distribution of actions and resistances along embedded retaining structures is shown in Figure 1.

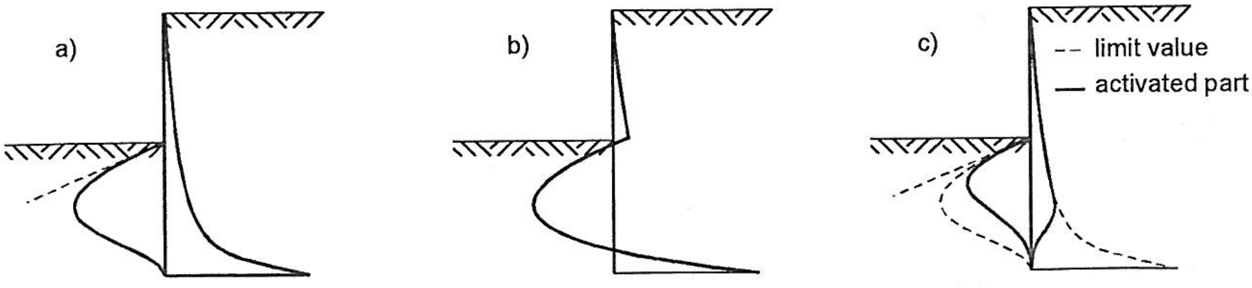

Figure 1: Actions and resistances on embedded retaining structures: a) total loading, b) their resultants, and c) stage of activated friction between retaining structure and ground

The distribution of actions and resistances depends on complex interaction interdependences between retaining structure and ground. In the literature are given many different methods of geotechnical analyses of embedded retaining structures. Several of them base on the theory of limit actions and resistances, and on some assumptions that were experimentally verified. King(1995) suggested analytical procedure of retaining structures in non-cohesive materials according to polygonal method of distribution of actions and resistances. He proposed introduction of assumption about the depth of the rotation of embedded retaining structures. Presented simplification was proofed by results of centrifugal tests. His procedure was improved by Day (1999) with introduction of function interdependence between coefficients of limit actions and resistances, and the depth of rotation of rigid retaining structure based on the results of numerical analyses using FEM. Both described methods of King (1995) and Day (1999) base on polygonal distribution of actions and resistances, so they are applicable only for analyses of retaining structures in homogenous soil. The present paper proposes a new method where non-linear distribution of actions and resistances is considered, so the results of analyses are completely comparable with those of interaction analyses. The method is given in general form and so applicable also for analyses of embedded retaining structures in non-homogeneous slopes.

STANDARD METHODS OF GEOTECHNICAL ANALYSES

The objective of geotechnical analyses that base on the method of limit equilibrium is to determine the required embedment depth and inner statical forces so that retained slope will be stabile after excavation in front of it.
In analysis is allowed to consider only that part of limit resistances that can be activated in the considered problem activated. The actual distribution of activated actions and resistances is shown in Figure 1. In analysis shall be considered such assumptions that considered resistances could actually activate at limit state during retaining structure rotation.
In Europe is mostly used UK method, where limit values of resistances are assumed to activate entirely (see Figure 2). The limit state of the bearing capacity is determined with a situation just before rotation of the retaining structure around point T (see Figure 2a)

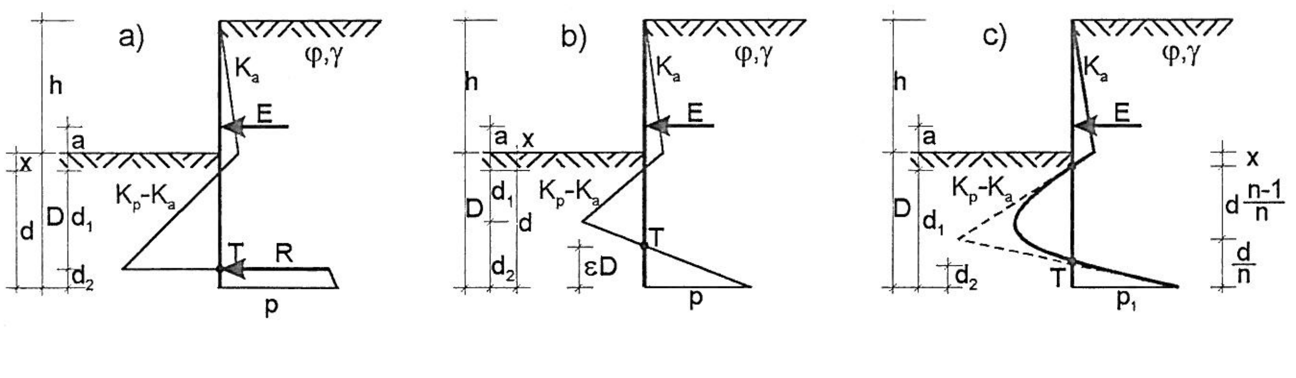

Figure 2: Distribution of actions and resistances; a) UK method, b) USA and Day method, and c) proposed method

UK simplified method

In UK simplified method a required embedment depth is determined fulfilling condition of moment equilibrium around point T (see Figure 2b) for actions and resistances above it using relation:

$$(K-1)d_1'^2 - 3E(d_1' - a') = 0 \tag{1}$$

$$K = K_p^\delta / K_a^\delta, \quad d_1' = d_1/h, \quad a' = a/h, \quad E' = 2E/(\gamma h^2 K_a^\delta) \tag{2}$$

Where R is non-equilibrate force that is equilibrated with resistances in depth of $d_2 = 0.2 \cdot d_0$.

UK improved method
In UK improved method the required depth of embedment is determined fulfilling equilibriums of horizontal forces and moments of entire retaining structure. This is achieved solving the system of Eqs. (3) and (4).

$$d' = 2d_2' + \sqrt{4d_2'^2 + (2x' + K/(K-1))d_2' + E'/(K-1)} \tag{3}$$

$$E'(3a' + 3d' - 2d_2') + (K + (K-1)(x' + d'))d_2'^2 - (K-1)(d' - d_2')^2 d' = 0 \tag{4}$$

$$d' = d/h, x' = x/h, d_2' = d_2/h, p = \gamma(K_p^\delta h + (K_p^\delta - K_a^\delta)(x' + d')) \tag{5}$$

USA method
The distribution of the resulting values of actions and resistances is shown in Figure 2b. The limit state of the bearing capacity in this method is achieved when values of resistances in depths d_1 and d under point of equalizing pressures attain limit values. Fulfilling equilibrium of horizontal forces and moments Eqs. (6) and (7) are derived.

$$d_1' = E'(3a' + 2d')/((K-1)d'^2 - E') \tag{6}$$

$$E' + (d' - d_1')(K + (K-1)(d' + x')) - (K-1)d_1'd' = 0 \tag{7}$$

DAY's method
This method presents only one of the variations of USA method. The limit state of the bearing capacity is restored when is in depth d_1 activated value of limit passive resistance. The interaction interdependences between retaining structure and ground is in skeleton considered only when zero contact pressures are arise in the height of εD above the bottom of retaining structure, where D denote embedment depth of the structure. The embedment depth is determined using Eqs. (6), (8) and (9).

$$\begin{aligned} &E'(d' - d_1' - \varepsilon(d' + x')) + (K-1)d_1'\varepsilon(d' + x')(d' - d_1') - \\ &(K-1)d_1'd'(d' - d_1' - \varepsilon(d' + x')) = 0 \end{aligned} \tag{8}$$

$$\varepsilon = 0.047\ln(K) + 0.1 \tag{9}$$

PROPOSED METHOD

The results of the performed interaction analyses using FEM show that during limit state of the retaining structure rotation the limit values of actions and resistances cannot activate throughout. In all analyzed problems were activated limit values of actions above the bottom of excavation and part of resistances just under the depth of excavation.
In the region of retaining structure embedment can be activated only part of resistances. This is due to activation of relative movements between retaining structure and ground that are not sufficient to activate limit values. At the bottom in the backfill of retaining structures is activated only one part of limit resistances in the direction of unit vector of retaining structure

plane, while the shear stress between retaining structure and ground in considered limit state cannot be activated (see Figure 1c). Also otherwise, the direction of activated shear strength between retaining structures is unfavorable and cannot contribute to the increase of resistances in this region. Generally, the value of resistances can be higher or lower than limit values of passive pressure, its actual activated value depends above all of horizontal movement of the bottom of the retaining structure towards the backfill.
The distribution of the resulting values of resistances in the region of retaining structure embedment is assumed to be in form of exponent function:

$$p_{(z)} = C_1((\frac{z}{d}) - C_2(\frac{z}{d})^n) \tag{10}$$

where $p_{(z)}$ denote the resulting values of actions and resistances in the region of retaining structure embedment, C_1 and C_2 denote constants, and n is exponent that reflect the ability of interaction system of retaining structure-ground, so that available resistances in front of the pile wall can be actually activated.
Constants C_1 and C_2 are determined satisfying the following boundary conditions:

$$\frac{\partial p_{(z)}}{\partial z}\Big|_{z=0} = \gamma(K_p^\delta - K_a^\delta), \quad p_{(z=d)} = p_1 \tag{11}$$

The value p_1 is determined in dependence of horizontal movement of retaining structure at the toe of retaining structure, and is proportional to the depth d_2 (see Figure 2c).

$$p_1 = \lambda K_p^0 \gamma d_2 = \gamma(d/n)(\lambda K_p^0 - (K_p^\delta - K_a^\delta)(n-1)) \tag{12}$$

$$C_1 = \gamma(K_p^\delta - K_a^\delta)d, \quad C_2 = 1 + (\frac{1}{n})(\frac{\lambda K_p^0}{K_p^\delta - K_a^\delta} - (n-1)) \tag{13}$$

The distribution of resistances in the region of retaining structure embedment is given with:

$$p_{(z)} = \gamma(K_p^\delta - K_a^\delta)d((\frac{z}{d}) - (\frac{z}{d})^n) - \gamma(\frac{d}{n})(\lambda K_p^0 - (K_p^\delta - K_a^\delta)(n-1))(\frac{z}{d})^n \tag{14}$$

The equilibrium condition of actions and resistances in horizontal direction is given by:

$$E = \int_{z=0}^{d} p_{(z)}dz = \gamma(K_p^\delta - K_a^\delta)d(\frac{d}{2} - \frac{d}{n+1}) - \gamma(\frac{d}{n})(\lambda K_p^0 - (K_p^\delta - K_a^\delta)(n-1))(\frac{d}{n+1}) \tag{15}$$

The condition of moment equilibrium of retaining structure is:

$$Ea = -\int_{z=0}^{d} p_{(z)}zdz = \gamma(K_p^\delta - K_a^\delta)d(\frac{d^2}{3} - \frac{d^2}{n+2}) - \gamma(\frac{d}{n})(\lambda K_p^0 - (K_p^\delta - K_a^\delta)(n-1))(\frac{d^2}{n+2}) \tag{16}$$

Expressions in Eqs. (15) and (16) can be given in following generalized form:

$$d' = \sqrt{\frac{E'n(n+1)}{(K-1)(n+2)(n-1) - 2\lambda K^0}} \tag{17}$$

$$E'a'n(n+2) + 2(K-1)d'^3(n^2 + 2n - 3) - 2\lambda K^0 d'^3 = 0 \tag{18}$$

where K^0 and λ denote the ration of coefficient of passive resistances $K^o = K^o_p / K^\delta_a$ and constant of proportionality, which value can be taken in all analyses equal $\lambda = 6\pi$.
Solving the system of non-linear equations (17) and (18), we can determine for all problems the required embedment depth of retaining structure and exponent n, which determine the level of admissible mobilization of resistances in the region of retaining structure embedment.

COMPARISON OF THE RESULTS

The results of analyses for all methods given in the form of mobilized resistances are compared with the results of FEM analyses (Day, 1999). The limit states of rigid embedded retaining structure of height equal 10 m in homogeneous non-cohesive ground for angles of friction equal $\varphi = 20$, 35 and 50° are analyzed. The coefficients of limit actions and resistances are determined according to the publication of Caquot (1948). Calculation data are presented in Table 1.

Table 1: Calculation data and limit depth of excavation for proposed method

Case	Soil and construction	K^δ_a	K^δ_p	K^o_p	Depth of excavation
1	φ=20°,c=0, δ=φ	0.4134	2.913	2.039	h=4.413m
2	φ=35°,c=0, δ=φ	0.2131	8.601	3.691	h=6.591m
3	φ=50°,c=0, δ=φ	0.1021	48.061	7.347	h=8.196m

Results of analyses in form of activated resistances and limit depths of excavation for individual methods are shown in Figure 3.

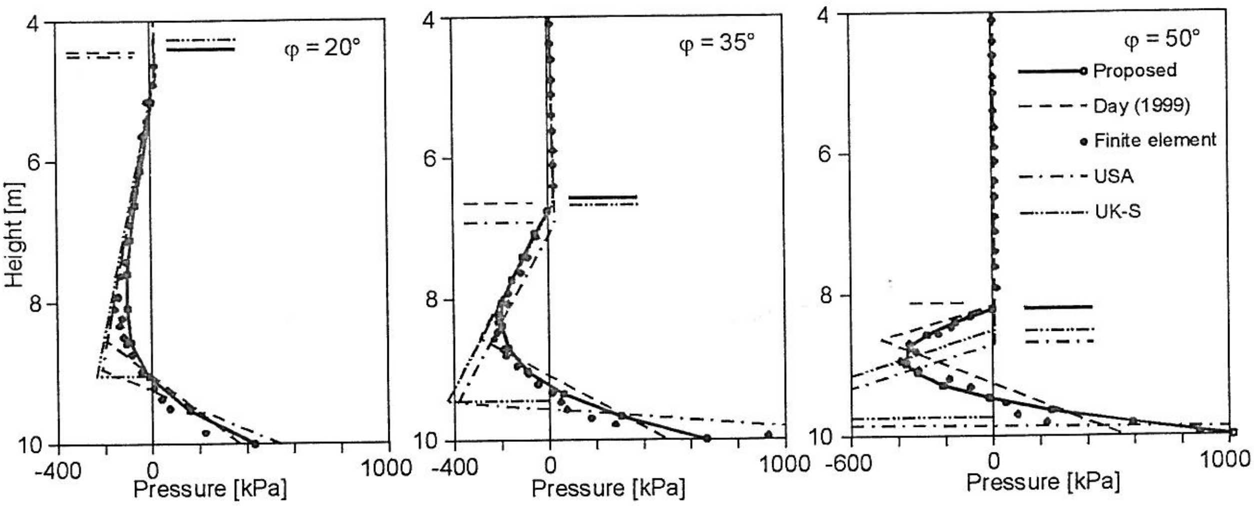

Figure 3: Limit depths of excavation and distribution of activated resistances for three considered cases

PRACTICAL EXAMPLE

We consider embedded pile wall of height h = 7.0 m that will permanently protect excavation along traffic construction. Geometrical and other geotechnical data of retaining structure are shown in Figure 4.

When analyzing complex problems in non-homogeneous slopes and when backfill of the retaining structure is subjected with surface loading the resultant value of actions and resistances above the depth where embedment starts has to be determined. The example is analyzed in accordance with geotechnical standard EN 1997-1. The design approach 1 with set of partial factors S1(B) is used. According to this standard additional safety is achieved by lowering the bottom of excavation by 0.5 m. The sum of design actions above the embeamment depth is:

$$E_d = E_g\gamma_g + E_q\gamma_q = 316.04\ \mathrm{kN/m},\quad a_d = 3.128\ \mathrm{m}$$

where E_g and E_q, respectively γ_g and γ_q denote characteristic values of permanent and variable unfavorable actions on retaining structure, respectively partial factors on actions.
Required parameters of resistances are determined considering limit values according to Caquot (1948). They are given in Table 2.

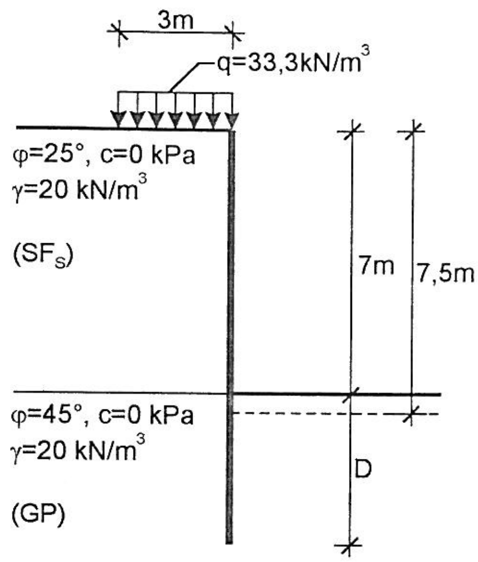

Figure 4: Geometrical and geotechnical data of retaining structure

Table 2: Characteristic data of soils

Soil	γ [kN/m³]	φ [°]	c [kPa]	δ [°]	K_a^δ	K_p^δ	K_p^o	K	K^o
1 (SF_S)	20	25	0.0	25	0.367				
2 (GP)	20	45	0.0	45	0.185	35.00	5.828	189.19	31.502

Generalized values of actions are determined using relation in Eq. (19).

$$E' = \frac{E_d}{\gamma h^2 K_a^\delta} = 3.037,\quad a' = \frac{a_d}{h} \tag{19}$$

Considering values of resistances K and K^o from Table 2, and design values of generalized actions (19) the systems of non-linear equations for individual methods of geotechnical design are solved. Design values of embedment depths D and bending moments M as well as transversal forces Q for cross-sections design of retaining structures are determined. Design values for all considered method are presented in Table 3.

Table 3: Embedment depth, maximal bending moments and transversal forces

Method	UK-S	UK-I	USA	Day (1999)	Proposed
D (m)	3.569	3.218	3.233	4.068	4.241
Q (kN/m)	1825.28	1512.85	1397.34	718.26	718.38
M (kNm/m)	1190.46	1190.46	1190.46	1190.46	1200.58

The results of analyses show that maximal bending moments are in good agreement for all methods. As expected the differences reflect in required embedment depth, while the discrepancies in transversal forces are so big that results of individual methods are not comparable to each other anymore.

CONCLUSION

Recent two methods of analysis of embedded retaining structures give satisfactory results especially in case of pile walls design, because they have small shear bearing capacity and because classical methods often require uneconomical design.

All three classical methods are not applicable in geotechnical practice, because they give to small geotechnical safety of the construction, due to the fact that all design resistances in the region of embedment depth of retaining structure cannot be activated.

The proposed method is applicable also in all kind of non-homogeneous ground with the only limitation that the slope should be homogeneous in the region of embedment of retaining structure.

Since the results of the analyses according to proposed method are the most close to the results of interaction analyses, we propose the usage of that method in geotechnical practice.

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