Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1467

Mobilization of the earth resistance of a normally consolidated cohesive soils

Mobilisation de la résistance de la terre dans les sols cohérents normal consolidés

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ABSTRACT
Much experimental work has not been so far done to study the effect of the wall movement on earth pressure in cohesive soils in general let alone in soft cohesive soils. On the other hand, a lot of experimental works have been conducted on sand. The attempt on all the model tests on sand was to develope a mobilization function of the passive resistance dependent on the wall displacement. The paper presents an attempt to develop a soil stiffness dependent mobilization function of the earth resistance of normally consolidated soft soils numerically using the FEM. Three types of the wall movement had been investigated. These are: parallel translation, rotation of the wall about the head and the toe.

RÉSUMÉ
Jusqu'à présent on n'a pas réalisé beaucoup d'ouvrages expérimentaux pour étudier l'effet du mouvement du mur de soutènement sur la poussée du sol cohérent en général et encore moins dans les sols cohérents mous. D'autre part, beaucoup d'essais ont été effectués sur le sable. Le but de toutes expérimentations sur le sable était de développer une fonction de mobilisation de la résistance passive concernant le déplacement du mur. Le papier présente une solution numérique avec le FEM pour développer une fonction de mobilisation de la poussée passive des sols mous normal consolidés compte tenu de la rigidité du sol. Trois types du mouvement du mur ont été étudiés. Ceux-ci sont: déplacement parallèle (glissement), rotation autour de la base et de sommet du mur (basculement).

1 INTRODUCTION

In order to mobilize the earth pressure fully, active or passive, a certain wall movement is required. The amount of the movement required depends on the type of the wall movement pattern and the soil type. There are four recognized types of wall movements patterns. These are: rotation of the wall about toe, rotation of the wall about the top, deflection of the wall and lateral translation of the wall. Most often, a combination of the above movement pattern may also takes place. Much experimental work has not been done so far to study the effect of the wall movement on earth pressure in cohesive soils in general let alone in soft cohesive soils. On the other hand, a lot of experimental works have been conducted on sand. Besler (1998) summerized in his dissertation work the model tests so far conducted on sand and the recommended mobilization functions for sand. The attempt on all the model tests on sand was to developed a mobilization function of the passive resistance dependent on the wall displacement.

The paper presents an attempt to develop a soil stiffness dependent mobilization function of the earth resistance of normally consolidated soft soils numerically using the FEM. Three types of the wall movement have been investigated. These are: parallel translation of the wall, rotation of the wall about the top and rotation of the wall about the toe (Fig. 1).

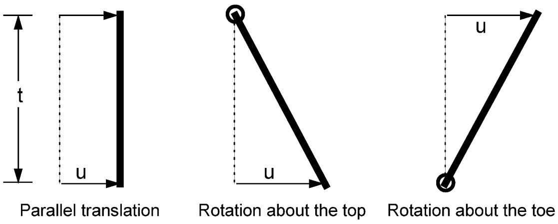


Figure 1. Types of the wall movement

2 CONSTITUTIVE SOIL MODEL

A homogeneous soft soil is assumed, whose behavior can be simulated using the advanced constitutive soil model known as the Hardening Soil Model (HSM). The HSM is developed based on the so called the Duncan Chang hyperbolic model. It, however, supersedes the hyperbolic model, because it uses the plasticity theory than the elasticity theory, it includes the dilatancy soil behavior and it introduces the yield cap. The HSM also considers the stress dependent stiffness of the soil according to the power law. For the primary deviatoric loading, the power low is given by

$$E_{50} = E_{50}^{ref}\left(\frac{c' \cdot cos\,\varphi - \sigma_3' \cdot sin\,\varphi}{c' \cdot cos\,\varphi + p^{ref} \cdot sin\,\varphi}\right)^m \tag{1}$$

where E_{50}^{ref} is the secant modulus at 50% of the failure stress and at effective reference pressure of p^{ref} and m is the exponent and it is dependent on the type of the soil.

Similarly, for the un/relaoding

$$E_{ur} = E_{ur}^{ref}\left(\frac{c' \cdot cos\,\varphi - \sigma_3' \cdot sin\,\varphi}{c' \cdot cos\,\varphi + p^{ref} \cdot sin\,\varphi}\right)^m \tag{2}$$

where E_{ur}^{ref} is the un/reloading stiffness at a reference pressure of p^{ref}. For detail Information on the constitutive model and the program refer to Gebreselassie (2003) and Brinkgreve (2002).

The soil parameters required for the HSM are given in Table 1. The contact between the soil and the wall is simulated by interface elements using the Mohr-Coulomb-Model (MCM) and its properties are given in Table 2. The wall is assumed rigid, elastic and weightless with a stiffness of $EA = 7.5 \times 10^6\ kN/m$ and $EI = 1.0 \times 10^6\ kNm^2/m$.

Table 1: HSM parameters for the soft soil layer

γ_{sat}	φ'	c'	$E_{50}^{ref} = E_{oed}^{ref}$	E_{ur}^{ref}	p^{ref}	m	R_f	K_0^{nc}	ν_{ur}
[kN/m³]	[°]	[kN/m²]	[MN/m²]	[MN/m²]	[kN/m²]	[-]	[-]	[-]	[-]
19.5	25.0	1.0	0.75 - 10	$5 \cdot E_{50}^{ref}$	100	0.90	0.90	0.58	0.20

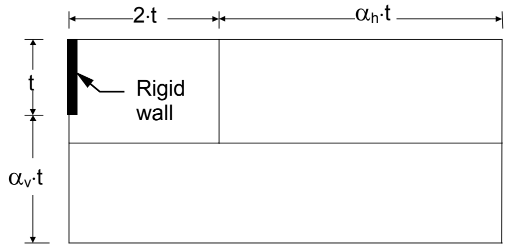
Table 2: MCM parameters for the interface elements

γ_{sat}	$\delta = \frac{1}{3} \cdot \varphi'$	c'	E_{ref}	$E_{increament}$	y_{ref}	c_{ref}	ν
[kN/m³]	[°]	[kN/m²]	[MN/m²]	[kN/m²]	[kN/m²]	[-]	[-]
19.5	8.33	0.33	0.75 – 10.0	0.0	0.0	0. 0	0.35

Since the main aim of the study is to develop a soil stiffness dependent mobilization function of the earth resistance, the stiffness of the soil, namely the $E_{50}^{ref} = E_{oed}^{ref}$ is varied between *0.75 - 10 MN/m²* and the ratio $E_{ur}^{ref} / E_{50}^{ref} = 1$ is kept constant.

3 MODEL GEOMETRY

In order to limit the influence of the model geometry on the mobilization of the passive resistance, a preliminary analysis is performed by varying the width and height of the model as shown in Fig. 2. The smallest soil stiffness in Table 1 ($E_{50}^{ref} = E_{oed}^{ref} = 0.75 MN/m^2$) is taken in the preliminary study. The calculation is performed by applying a uniform prescribed displacement on the 8 m long rigid wall in the direction of the soil mass.



Model	α_h	α_v
1	2	1
2	3	1
3	4	1
4	5	1
5	2	2
6	3	2
7	4	2
8	5	2

Figure 2. Model geometry selection

The result of the preliminary FEM - calculations is presented in Fig. 3. The figure shows the passive force as a function of the displacement for the various model sizes, but for *t = 8 m* and $E_{50}^{ref} = E_{oed}^{ref} = 0.75 MN/m^2$. As it can be seen from Fig. 3, the passive resistance forces obtained from different model sizes lie in a very narrow band showing a negligible influence of the model size. After closed observation of the principal stress orientations and the displacement vectors near the boundaries, and based on Fig. 3, the model 8 is chosen for a further numerical study of the mobilization of the earth resistance.

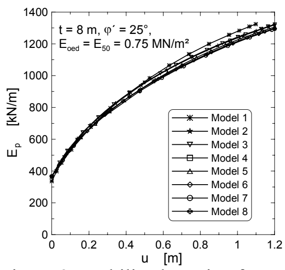


Figure 3. Mobilized passive force from different model sizes

4 MOBILIZATION OF THE EARTH RESISTANCE

Once the model geometry had been fixed and the soil model parameters were identified, the FEM-calculations are started by applying a prescribed displacement either uniformly in the case of parallel translation or in a triangular shape with zero at the top and maximum at the bottom in the case of rotation about the toe or again triangular shape but reversed in the case of rotation about the head. Two cases of the height of the wall t = 8 m and t = 4 m, seven variations of the stiffness of the soil $E_{50}^{ref} = E_{oed}^{ref}$*=0.75, 1.5, 3.0, 4.5, 6.0, 7.5, 10.0 MN/m²* are investigated. All in all 42 (3 × 2 × 7 = 42) FEM-calculations are performed.

The results of the parametric studies are shown in Fig. 4. A dimensionless presentation is preferred to avoid the effect of the height of the wall on the results and in order to treat the net resistance instead of the total passive force which includes the earth pressure at rest. The dimensionless mobilized net passive resistant is defined as:

$$K^*_{p(mob)} = \frac{(E_{ph} - E_0)}{(\frac{1}{2} \cdot \gamma \cdot t^2)} \tag{3}$$

where E_{ph} is the passive force at limit state and E_0 is the earth pressure at rest. The dimensionless displacement is also defined as u/t. As can be observed from Fig. 4, the mobilized resistance for t = 8 m and t = 4 m almost lie on the same line in all cases of the wall movement showing the advantage of using the dimensionless parameters.

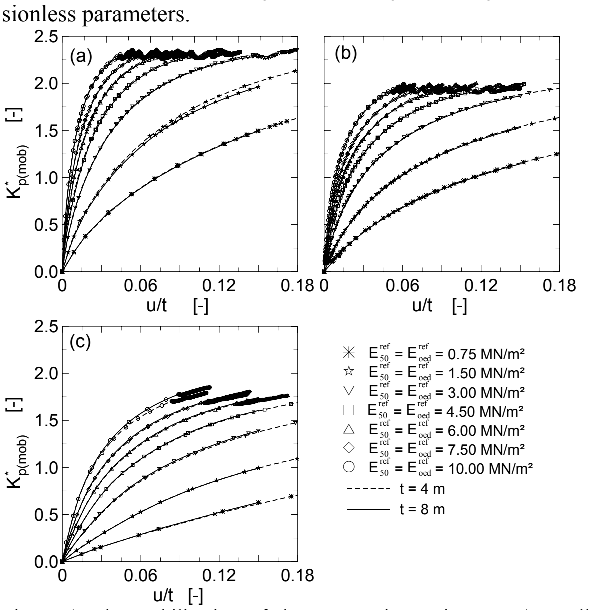


Figure 4. The mobilization of the net passive resistance: a) parallel translation, b) rotation about the head, and c) rotation about the toe

5 DERIVATION OF THE MOBILIZATION FUNCTION

The mobilization curves in Fig. 4 may be approximated by a hyperbolic function analogue to the Kondner and Zelasko (1963) hyperbolic equation as follows:

$$K^*_{p(mob)} = \frac{(u/t)}{[a + b \cdot (u/t)]} \tag{4}$$

or in a transformed form,

$$\frac{(u/t)}{K^*_{p(mob)}} = [a + b \cdot (u/t)] \tag{5}$$

where *a* and *b* are the intercept and the slope of the transformed straight lines in Fig. 5. The constants *a* and *b* may be obtained from the best fit line of the transformed lines, but the question remains weather there exists a definite relationship between these curve constants and the physical parameters of the soil. Fig. 6 shows that the curve parameter a may almost be 100% correlated with the normalized stiffness parameter of the soil using a potential function of the form

$$a = \alpha_1 \cdot \left[\frac{E_{oed}}{\gamma \cdot t} \right]^{\alpha_2} \tag{6}$$

The values of the constants α_1 and α_2 are given in Fig. 6 for the three cases of wall movement. The slope b is usually related to the deviatoric stress at failure in approximating the stress - strain behavior of soils with a hyperbolic function according to Duncan and Chang (1970). Analogue to this, b may be related to the passive resistance at limit state, namely the coefficient of the passive earth pressure K_{ph}. That is,

$$b = \frac{\beta}{K_{ph}} \tag{7}$$

Reading the value of the slope b from Fig. 5 and K_{ph} from standard tables for $\varphi'=25°$, the value of β may be calculated for different stiffness values of the soil. It appears that the values of β are fairly constant for a given range of stiffness of the soil. Therefore, its value may be fixed as an average value as shown in Table 3 for two ranges of the stiffness values.

Hence, substituting a and b from Eqs. 6 and 7 into Eq. 4, one may arrive at the mobilization function of the form:

$$K^*_{p(mob)} = \frac{(u/t)}{\left[\alpha_1 \cdot \left(\frac{E_{oed}}{\gamma \cdot t} \right)^{\alpha_2} + (u/t) \cdot \frac{\beta}{K_{ph}} \right]} \tag{8}$$

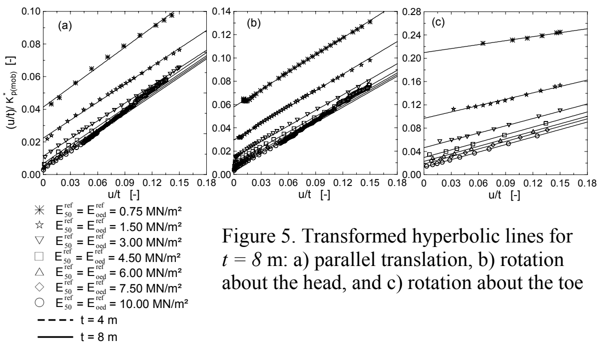


Figure 5. Transformed hyperbolic lines for $t = 8$ m: a) parallel translation, b) rotation about the head, and c) rotation about the toe

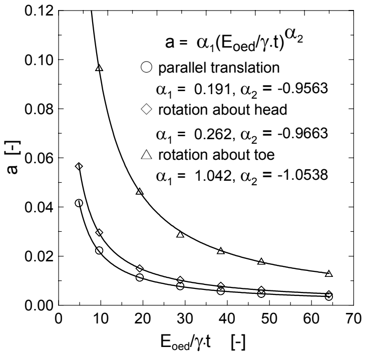


Figure 6. Relationships between the normalized constrained modulus E_{oed} and the curve constant a for $t = 8\ m$

Table 3: Values of the constant β for a range of stiffness of the soil

$E^{ref}_{50} = E^{ref}_{oed}$ [kN/m²]	Values of β		
	Parallel translation	Rotation about head	Rotation about toe
< 3000	1.1880	1.5268	0.9146
≥ 3000	1.1106	1.3518	1.3355

6 COMPARISON

Fig. 7 shows a comparison of the results of the analytical calculation using the mobilization function (Eq. 8) and the FEM for two selective stiffness values of the soil, namely $E^{ref}_{50} = E^{ref}_{oed} = 3.0\ and\ 4.5\,MN/m^2$ and for the case of parallel translation of the wall. The two results match fairly well for the case of $t = 8\ m$ and $\varphi' = 25°$ (Fig. 7a) and for the case of $t = 8\ m$ and $\varphi' = 20°$ (Fig. 7c). However, for values of $t = 4\ m$ and $\varphi' = 25°$ (Fig. 7b), the two results do not match each other. This is mainly due to the fact that the E_{oed} is normalized with $t = 8\ m$ in finding a correlation with the constant a (Eq. 6). Hence inserting $t = 4\ m$ into Eq. 8 results in a lower value of the intercept a and in turn a higher value of the mobilized resistance.

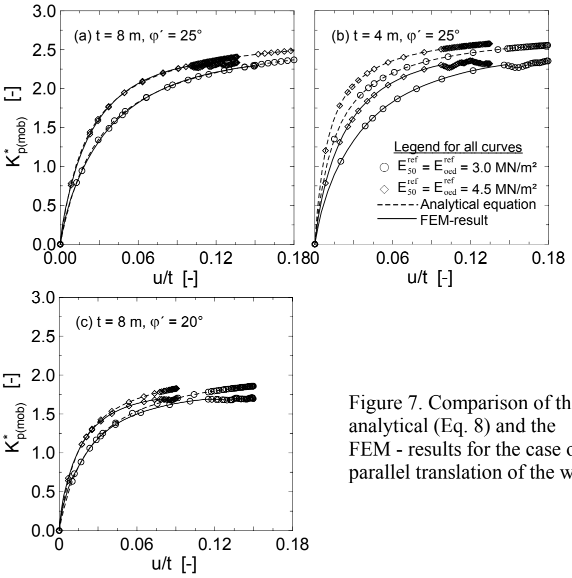


Figure 7. Comparison of the analytical (Eq. 8) and the FEM - results for the case of parallel translation of the wall

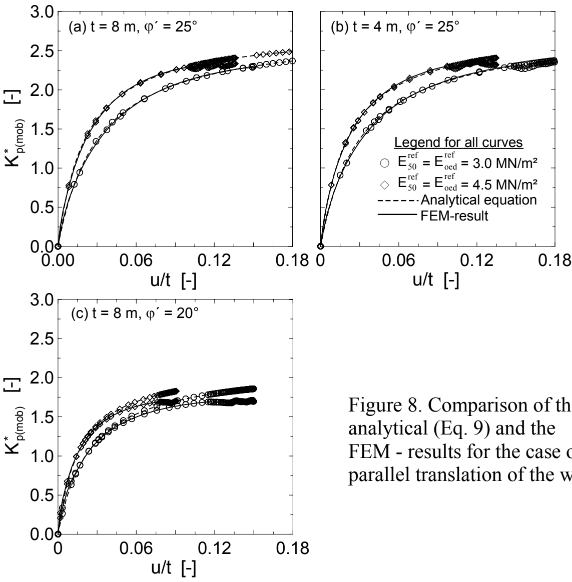


Figure 8. Comparison of the analytical (Eq. 9) and the FEM - results for the case of parallel translation of the wall

To correct this deviation, a dimensionless factor f was introduced into Eq. 8, so that the term $(E_{oed}/\gamma \cdot t)$ remains constant for all values of t. The corrected mobilization function is given by Eq. 9.

$$K^*_{p(mob)} = \frac{(u/t)}{\left[\alpha_1 \cdot \left(\frac{E_{oed}}{f \cdot \gamma \cdot t}\right)^{\alpha_2} + (u/t) \cdot \frac{\beta}{K_{ph}}\right]} \quad (9)$$

where $(f = 8/t)$ and t is the wall height in m.

The comparison of the FEM - results with the analytical results from Eq. 9 are given in Figs. 8, 9 and 10 for the cases of parallel translation of the wall, rotation about the head and rotation about toe respectively. It appears from these figures that the results of the FEM and the analytical agree very well. Therefore, the mobilization of the passive resistance may fairly be approximated using Eq. 9.

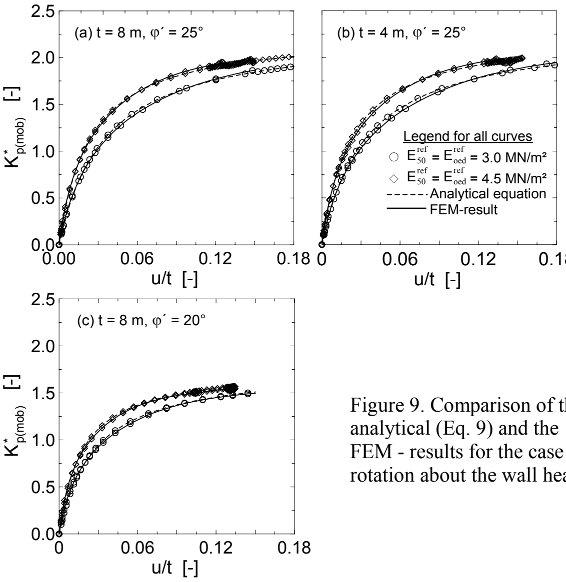


Figure 9. Comparison of the analytical (Eq. 9) and the FEM - results for the case of rotation about the wall head

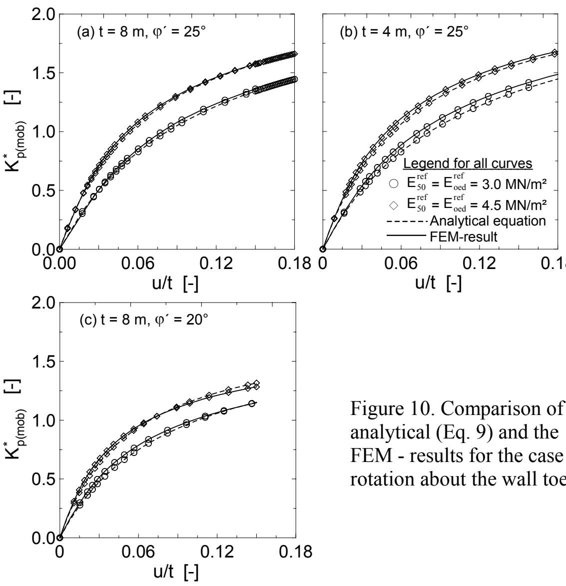


Figure 10. Comparison of the analytical (Eq. 9) and the FEM - results for the case of rotation about the wall toe

7 CONCLUSION

This is a first attempt to formulate a passive mobilization function for soft soils based on the FEM. Using the developed formula, one can easily estimate the mobilized passive resistance knowing the expected movement of the wall. However, it should be noted that the computations were performed using a particular type of soil model, namely the hardening soil model. Hence, a broad investigation is required to check the validity of the developed equations using other soil models. Even within the HSM parameters, other parameters may also have a significant influence on the deformation behavior, whereas a constant value of all HSM parameters except the stiffness of the soil was assumed in developing the mobilization functions in this paper. Model tests to validate the analytical function would be worth while.

8 SYMBOLS AND ABBREVIATIONS

E_{50}^{ref} = secant modulus at 50% of the failure stress and at effective reference pressure of p^{ref}
E_{oed}^{ref} = constrained modulus at 50% of the failure stress and at effective reference pressure of p^{ref}
E_{ur}^{ref} = un/reloading modulus at effective reference pressure of p^{ref}
E = modulus of elasticity
A = Area of cross section
I = moment of inertia
γ_{sat} = saturated unit weight of soil
φ' = effective angle of internal friction
δ = wall friction
c' = effective cohesion
R_f = the ratio of the stress at failure and the ultimate stress
K_0^{NC} = the coefficient of the earth pressure at rest for normally consolidated soils
ν_{ur} = the Poisson's ratio for un/reloading
ν = the Poisson's ratio
t = the height of the wall
u = horizontal displacement of the wall
R_f = the ratio of the stress at failure and the ultimate stress
$K^*_{p(mob)}$ = the mobilized net passive resistance
E_{ph} = the passive earth pressure
E_0 = the earth pressure at rest
a = slope of the transformed curves
b = intercept of the transformed curves
α_1, α_2, and β = curve constants
HSM = Hardening Soil Model
MCM = Mohr-Coulomb Model

9 REFERENCES

Besler, D. 1998. Wirklichkeitsnahe Erfassung der Fussauflagerung und des Verformungsverhaltens von geschützten Baugrubenwänden. *Schriftenreihe des Lehrstuhls Baugrund-Grundbau der Universität Dortmund, Heft 22.*

Duncan, J.M. and Chang, C.Y. 1970. Non-linear analysis of stress and strain in soils. *Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 92, SM5, pp. 1629 – 1653.*

Gebreselassie, B. 2003. Experimental, analytical and numerical investigations of excavations in normally consolidated Soft Soils. *Schriftenreihe Geotechnik. Universität Kassel, Heft 14.*

Kondner, R.L. 1963. Hyperbolic stress-strain response: cohesive soils. *Journal of the Soil Mechanics and Foundation Division, ASCE, 89(SM1), pp. 115 – 143*

Brinkgreve R.B.J. 2002. PLAXIS, Finite Element Code for Soil and Rock Analyses; *Balkema, Rotterdam-Brookfield.*