

A Comparative and Parametric Study of Reaction Coefficients: The Balay, Schmitt and Chadeisson Methods for Diaphragm Walls

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ABSTRACT

The increase in the number of excavation projects in highly dense urban areas, coupled with advances in numerical analysis, has sparked engineers' interest in using soil-structure interaction to calculate diaphragm walls. However, the calculation of the soil reaction coefficient k_h , which is an input parameter for most models (whether single-parameter or two-parameters), remains a point of disagreement among several authors. This article aims to conduct a comparative and parametric study of the k_h calculation formulas proposed by Chadeisson, Balay and Schmitt. The aim is to fix one parameter and study the relative variation of the other two. The results obtained show significant differences in approach and indicate that the choice of formula for calculating k_h depends on the type of diaphragm walls to be designed, the nature of the in-situ soil, and the desired level of accuracy.

Keywords: diaphragm wall, soil-structure interaction, reaction coefficient, parametric study, Chadeisson, Balay, Schmitt.

INTRODUCTION

With dense urbanisation in major cities, the increase in the number of deep-excavation projects and the interactions between structures and their environment highlight the importance of understanding the behaviour of diaphragm walls. The limitations observed in the use of conventional rigid-plastic calculation methods, together with advances in numerical analysis, have enabled engineers and scientists to refine their calculations by rigorously accounting for soil-structure interaction. This involves the use of soil-structure interaction models such as: [1], [2], [3], [4], [5]. All these models (single-parameter or two-parameters) share the introduction of a parameter linking diaphragm walls displacement to soil reaction: the reaction coefficient k_h . Despite its significant influence on calculation results, the choice of the value of k_h remains a point of disagreement among several authors: [6], [7], [8].

In this article, we carry out a parametric study of the formulas for calculating k_h proposed by [6], [7] and [8].

LITERATURE REVIEW

To model the behavior of a diaphragm walls, [1] proposes an equation relating

displacement, earth pressure and the mechanical properties of the wall:

$$EI \frac{d^2 w}{dz^2} + k_h w = q(z) \quad (1)$$

where:

EI: moment of inertia of the diaphragm wall

w: horizontal displacement of the diaphragm wall

k_h : soil reaction coefficient

$q(z)$: triangular soil pressure on the diaphragm wall

Equation (1) amounts to treating the soil behavior as a set of independent springs of stiffness k_h . The displacement of the diaphragm wall at depth z is related to the soil reaction by the following equation:

$$p = k_h \cdot w \quad (2)$$

Karl Terzaghi [9] formalized the use of the reaction coefficient k_h by classifying soil behavior based on their particle size distribution:

- Grainy soils (sands): The modulus k_h is assumed to increase linearly with depth z due to the increase in effective stress. The standard formula is:

$$k_h(z) = n_h \cdot \frac{z}{B} \quad (3)$$

Where n_h is the initial stiffness parameter of the sand (which depends on its density) and B is the width of the screen (often simplified to one for continuous walls).

$$k_h = \left[20EI \left(\frac{K_p \gamma \left(1 - \frac{K_0}{K_p} \right)}{0.015} \right)^4 \right]^{\frac{1}{5}} + A_p c' \frac{\tanh \left(\frac{c'}{30} \right)}{0.015} \quad (5)$$

where:

E: diaphragm wall elasticity modulus

I: diaphragm wall inertia

K_0 : coefficient of earth pressure at rest

K_p : coefficient of bearing capacity at rest

c' : effective soil cohesion in kPa

A_p : cohesion influence coefficient

- Cohesive soils (stiff clays): Karl Terzaghi[9] considers that k_h is independent of depth and depends primarily on the consistency of the clay (undrained cohesion c_u):

$$k_h = \text{constante} \quad (4)$$

Chadeisson [6] proposed an empirical approach, represented by charts. These curves establish a direct link between k_h and the soil's shear strength properties, namely cohesion c and the angle of internal friction φ .

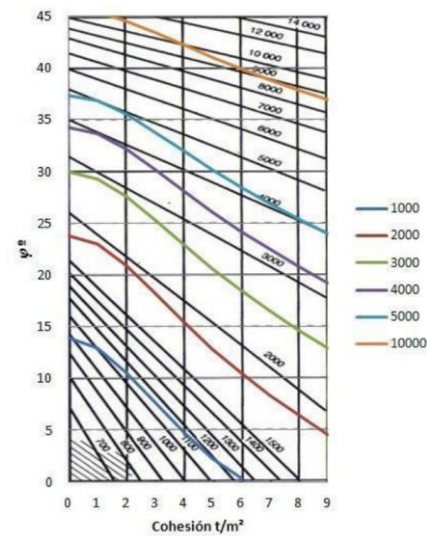


Fig. 1: Chadeisson chart [6]

Monnet [10] proposed a comprehensive analytical formulation that enables the automated extraction of k_h values from these charts for screens of intermediate stiffness.

Ménard and Bourdon [11] applies the theory of elasticity to the pressure bulb of the screen. They break down soil deformation into a deviatoric component (shear) and a spherical component (consolidation):

$$k_h = \frac{E_M}{\frac{\alpha a}{2} + 0.133x(9a)^\alpha} \quad (6)$$

where:

E_M : Ménard's pressure-strain module

a : Effective length

α : Rheological coefficient depending on the nature of the soil.

Balay [7] extended and validated this formulation, refining the definition of the effective length a according to the stages of earthworks and the presence of anchors.

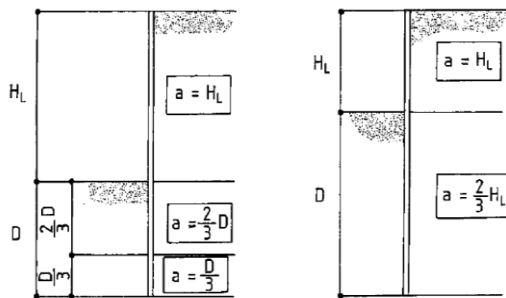


Fig.2: Definition of the effective length for self-supporting diaphragm wall, Balay [7]

Schmitt [8] demonstrated that Ménard and Bourdon [11] equation underestimated the soil response for highly rigid structures (such as reinforced concrete diaphragm walls). By explicitly incorporating the wall's flexural stiffness (EI), he proposed a formulation that couples the soil's deformability with that of the structure:

$$k_h = 2,1 \times \left(\frac{\left(\frac{E_M}{\alpha} \right)^{\frac{4}{3}}}{(EI)^{\frac{1}{3}}} \right) \quad (7)$$

where:

E_M : Ménard's pressure-strain module

α : Rheological coefficient depending on the nature of the soil.

EI : moment of inertia of the diaphragm wall

Eurocode 7 [12] has adopted Schmitt's [8] formula, adapting it as follows:

$$k_h = 2 \times \left(\frac{\left(\frac{E_M}{\alpha} \right)^{\frac{4}{3}}}{\left(\frac{EI}{B_0} \right)^{\frac{1}{3}}} \right) \quad (8)$$

where:

E_M : Ménard's pressure-strain module

α : Rheological coefficient depending on the nature of the soil.

EI : moment of inertia of the diaphragm wall

B_0 : reference length: 1 m

MATERIALS & METHODS

To understand the relationship between the reaction coefficient k_h and the properties of the diaphragm wall and the soil, we conducted a parametric study using the Python Jupyter Notebook interface. The input data for the Balay [7] and Schmitt [8] formulas, are listed in the tables below.

The methodology involves fixing one parameter of the soil or the diaphragm wall and studying how k_h varies as a function of a second parameter.

For Balay [7] formula, below the parameters considered:

Table 1: $k_h = f(E_M, a/H) - \alpha = 1/3$

E_M (MPa)	1	2	5	10
a/H	from 0 to 1			
α	1/3			

Table 2: $k_h = f(a/H, E_M) - \alpha = 1/3$

E_M (MPa)	from 0 to 4.5MPa by a step of 0.5 MPa			
a/H	0.1	0.2	0.5	1
α	1/3			

Table 3: $k_h = f(a/H, \alpha) - E_M = 5 \text{ MPa}$

E_M (MPa)	5			
α	1/3	1/2	2/3	1
a/H	from 0 à 1 (step of 0.1)			

For Schmitt's [8] formula, below the parameters considered:

Table 4: $k_h = f\left(\frac{E_M}{\alpha}, EI\right)$

$\frac{E_M}{\alpha}$ (MPa)	1	2	5
EI (MN.m ² /ml)	10 - 121 (step of 20)		

Table 5: $k_h = f\left(\frac{E_M}{\alpha}, e\right) - f_{ck}=25\text{MPa}$

$\frac{E_M}{\alpha}$ (MPa)	0 - 22 (step of 3)				
e(m)	0,4	0,5	0,6	0,7	0,8
EI (MN.m ² /ml)	165	323	558	886	1323

Table 6: $k_h = f\left(\frac{E_M}{\alpha}, f_{ck}\right) - e=0,5\text{m}$

$\frac{E_M}{\alpha}$ (MPa)	0 - 22 (step of 3)				
strength of the concrete	C20/25	C25/30	C30/37	C35/45	C40/50
EI (MN.m ² /ml)	302	323	333	354	365

In Table 6, we have used equations (9) and (10) to relate the moment of inertia to the characteristic strength of the concrete and the thickness e of the diaphragm wall:

$$E_{cm} = 22 \times \left(\frac{f_{ck} + 8}{10} \right)^{0.3} \quad (9)$$

$$I = \frac{1 \times e^3}{12} \quad (10)$$

RESULT

A graphical representation of the data in Tables 1 to 6 in Jupiter Notebook yields the following results shown in Figures 3 to 8:

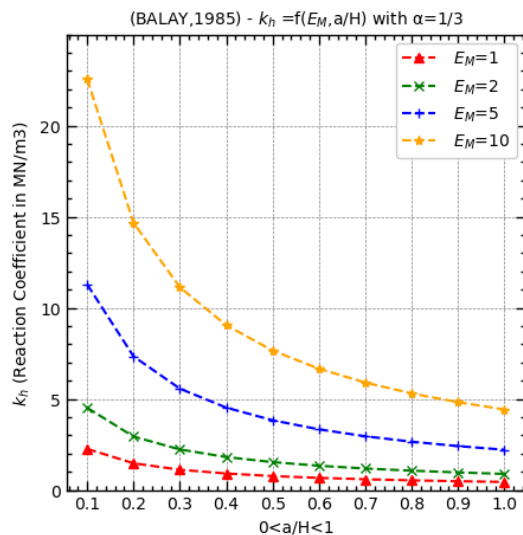


Fig. 3: k_h as a function of E_M for various values of $0 < a/H < 1$ ($\alpha=1/3$) according to [7]

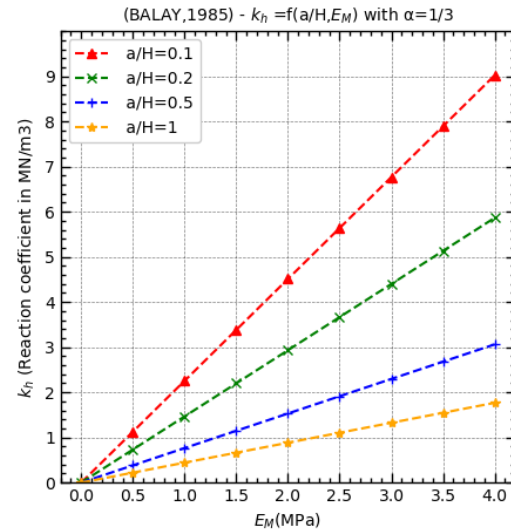


Fig. 4: k_h as a function of a/H for different values of E_M ($\alpha=1/3$) according to [7]

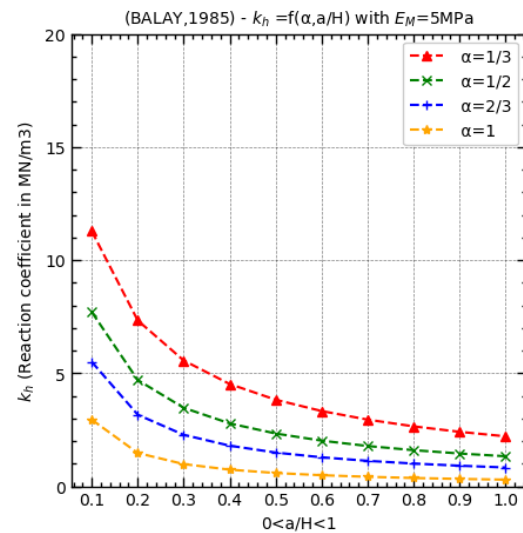


Fig. 5: k_h as a function of a for different values of a/H ($E_M=5\text{MPa}$) according to [7]

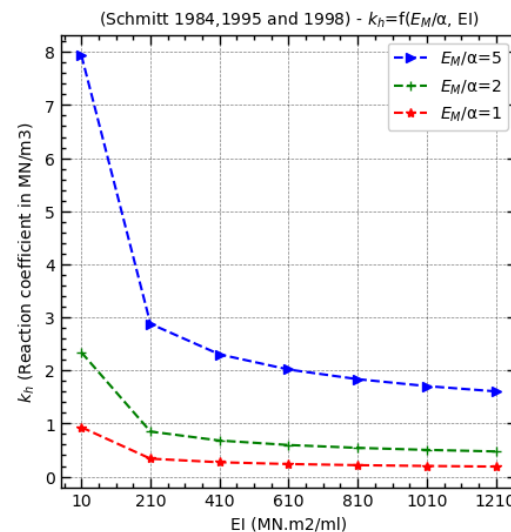


Fig. 6: k_h as a function of E_M/α for different values of EI , according to [8]

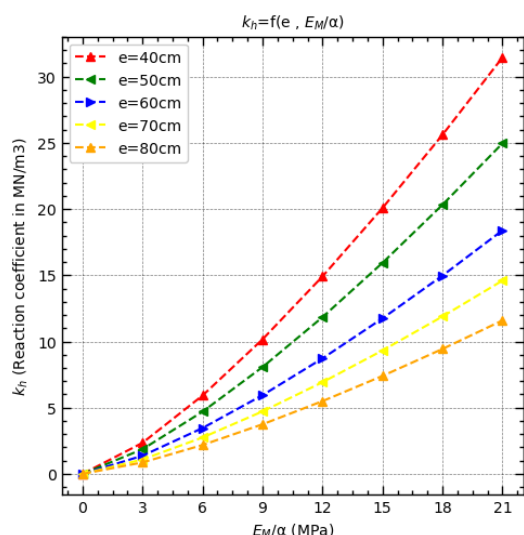


Fig. 7: k_h as a function of thickness e for different values of (E_M/α) according to [8].

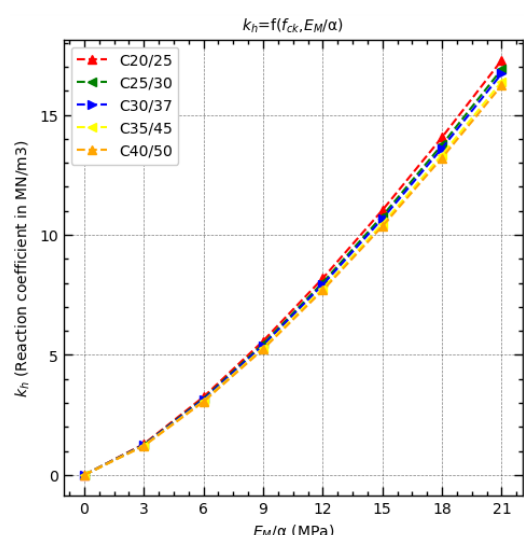


Fig. 8: k_h as a function of f_{ck} for different values of E_M/α , according to [8].

According to the Balay [7] formula, **Fig. 3** shows that the higher the E_M value, the higher the k_h value, as the a/H ratio decreases. **Fig. 4** shows that the relation between the reaction coefficient k_h and the pressure modulus E_M is linear. **Fig. 5** shows that the lower α is, the higher the reaction coefficient k_h is. Relating to the Schmitt [8] formula, **Fig. 6** shows that the higher the Young's modulus E_M/α , the greater the reaction coefficient k_h becomes, as the diaphragm wall becomes increasingly flexible. **Fig. 7** shows that the thinner the screen, the higher the reaction coefficient k_h becomes, as Young's modulus increases.

Fig. 8 shows that the lower the concrete strength class, the higher the soil reaction coefficient, and this becomes increasingly true as the soil's Young's modulus increases. We also observe that when the soil's Young's modulus is between 0 and 6 MPa, the reaction coefficient is essentially identical for all concrete strength classes.

DISCUSSION

The aim of this study was to conduct a parametric analysis of the Balay [7] and Schmitt [8] formulas. With regard to the Balay [7] formula, our results show that the higher the E_M value, the higher the k_h value, as the a/H ratio decreases. Furthermore, as the a/H ratio varies at each stage of excavation, it is therefore necessary to recalculate k_h for each stage of the calculation. It can also be noted that k_h is higher at the toe of the excavation than at the level of the free height. Also, Balay [7] formula shows that the lower α is, the higher the reaction coefficient k_h is. Thus, normally consolidated clay will yield a higher reaction coefficient than over consolidated clay. Balay [7] formula therefore takes the nature of the soil into account but it does not take into account the properties of the material used in the retaining wall. This remains one of the limitations of the method in opposition to the Schmitt [8] formula.

It can also be observed that as the a/H ratio approaches 1, we tend towards convergence (a reduced difference between k_h values). Consequently, a uniform reaction coefficient k_h may be considered.

Regarding Schmitt [8] formula, our analysis shows that the higher the Young's modulus E_M/α , the greater the reaction coefficient k_h becomes, as the diaphragm wall becomes increasingly flexible. Consequently, for a given site, a sheet pile wall or Berlin-type wall will result in a higher k_h than a diaphragm wall (which generally has greater inertia). This finding may seem surprising, as logic would suggest that the more flexible (less rigid) the diaphragm wall, the more it will tend to deform and thus reduce reaction coefficient.

Schmitt [8] formula analysis shows also that the lower the concrete strength class, the higher the soil reaction coefficient, and this becomes increasingly true as the soil's Young's modulus increases (when the soil's Young's modulus is between 0 and 6 MPa, the reaction coefficient is essentially identical for all concrete strength classes). Consequently, for a retaining wall to be constructed in soil with a Young's modulus of less than 6 MPa, it is possible to consider a strength class of C20/25 or C25/30 (bearing in mind that higher strength classes will yield the same reaction coefficient value, all other influencing parameters being equal), provided that a verification of the average and maximum concrete stresses in the retaining wall is carried out, which must fall within the permissible limits defined in NF P94-282[13].

We can see that Schmitt [8] formula does not take diaphragm wall height into account. The reaction coefficient k_h remains constant for a diaphragm wall 5m high and another 25m high (for the same type of soil). This is one of his limits.

We also can note that according to A.Monnet [10], k_h depends primarily on the soil's shear parameters (cohesion and angle of internal friction). Furthermore, its value increases as the diaphragm wall becomes stiffer (higher EI). This conclusion contradicts Schmitt's [8] hypothesis; whose formula indicates a higher k_h for an increasingly flexible diaphragm wall.

CONCLUSION

This parametric and comparative study has highlighted the fundamental differences between the methods for calculating the soil reaction coefficient k_h proposed by Chadeisson [6], Balay [7] and Schmitt [8]. Analysis of the results shows that the choice of formulation has a considerable influence on the calculation of the coefficient and depends heavily on the type of retaining wall to be designed, the nature of the in-situ soil, and the level of accuracy required.

The main conclusions drawn from this analysis are as follows:

Balay's method

- The coefficient k_h is found to be highly dependent on the earthwork's phases due to variations in the ratio a/H , making it necessary to recalculate it at each stage of the calculation.
- It has also been observed that the value of k_h is higher at the bottom of the excavation than at ground level.
- Although this method takes appropriate account of the nature of the soil — for example, normally consolidated clay yielding a higher coefficient than overconsolidated clay — it has the major limitation of disregarding the mechanical properties and materials of the retaining structure.

Schmitt method:

- Unlike Balay's [7] approach, Schmitt's formulation explicitly takes into account the flexural stiffness EI of the wall.
- The analyses highlight a peculiar behavior: the coefficient k_h increases as the wall becomes increasingly flexible.
- Furthermore, when the soil modulus is low (between 0 and 6 MPa), the concrete strength class has virtually no influence on the reaction coefficient obtained.
- The main limitation of this method lies in the fact that it does not take the screen height into account.

The Chadeisson and Monnet method

- Based primarily on soil shear parameters (cohesion and angle of internal friction), this approach contrasts with Schmitt's assumptions because according to equation (5) the coefficient k_h increases here with the stiffness of the screen.

Ultimately, the determination of the parameter k_h remains a major point of contention within the geotechnical engineering community. The designer must therefore select the most appropriate method by rigorously analyzing the specific constraints of their excavation project.

In view of the discrepancies observed and the inherent limitations of each analytical formulation (such as Balay's failure to take

material properties into account, or Schmitt's omission of the screen height), several avenues for future research are emerging. In particular, it would be useful to compare these parametric results with two- or three-dimensional finite-element numerical simulations in order to assess the actual accuracy of each analytical method when applied to a complex continuum model. Furthermore, conducting a comparative study based on actual in-situ displacement measurements collected at excavation sites in dense urban environments would be an essential step towards empirically validating the analytical approach that best simulates the actual behavior of soil-structure interaction.

Declaration by Authors

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