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The behavior of laterally loaded monopile-pier system in clay soils

Laila Mohamed Hafez [1], Remon Isaac[2], Mohamed A. Eid[3] and Ahmed Mostafa[4]

[1] Professor concrete structure design– Faculty of Engineering – Minia University, Egypt
[2] Associate Professor – Faculty of Engineering – Minia University, Egypt remon.isaac@mu.edu.eg
[3] Associate Professor – Faculty of Engineering – Minia University, Egypt
M.Eid@mu.edu.eg
[4] Structural Engineer– EFJV for design and exciting Cairo metro, Egypt
ahmed_moustafa_shams@yahoo.com

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مقدمة:

يهدف هذا البحث إلى إظهار السلوك الخاص بالخازوق المفرد و هو خازوق متصل اتصال مباشر بالعمود والمزروع في التربة الطينية المعرضة لقيم مختلفة من الأحمال الأفقية.

أكثر ما يقلق المصممين هو الحصول على المقطع العرضي الأمثل الذي يفي بمعايير سلامة التصميم بأقل تكلفة. ويتم التطرق لهذه المشكلة في المشاريع الكبرى كالكباري حيث إن أساسات الكباري لها حلول مختلفة. أحدها هو ال خازوق المفرد الذي يمكن أن يكون أرخص من الأنواع الأخرى عن طريق تقليل المقطع العرضي. حيث إن تقليل المقطع العرضي يجعل الهيكل نحيفًا مع القصور الذاتي الصغير. وبناءً على ما سبق، لن يتم تجاهل تأثيرات الاجهادات الاضافية إذا كانت قيمة النحافة أعلى من الحد الأدنى للقيمة، وستزداد أيضًا قيم الإجهاد على الهيكل الذي سيجعل القطاع يصل إلى حالة الحد الأقصى. و يشير الكود الأوروبي في التصميم إلى أنه يجب مراعاة تأثيرات العزوم الإضافية المتولدة، حيث من المتوقع أن تؤثر بشكل كبير على الاستقرار العام للنظام وخاصة الأقسام الحرجة للوصول إلى حالة الحد الأقصى.

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Abstract.

Monopile-pier system is a pier directly connect to a single pile that is impeded in the ground. This paper aims to demonstrate the monopile behavior embedded in clay soil subjected to horizontal loads.

The most critical concern for engineers is to obtain the optimum cross section that satisfies design safety criteria at the lowest cost. This problem is presented in large bridge projects. Monopile foundations are greatly cheaper than the other types of bridge foundation due to the reduced cross section in addition to saving pile cap costs. The reduction of the cross section makes the structure slender with small inertia. Hence, second-order effects cannot be ignored if the slenderness ratio is higher than the minimum value, also straining action will increase on the structure which will make section reach the ultimate limit state.

This search is made by using parametric study for 9 cases of soil from soft clay to stiff clay using soil young modulus of pressure-meter test ranges. Maximum deflection, buckling length and ratio between moment due to second order analysis and first order analysis

INTRODUCTION

Monopile is a common foundation type that describes a pier that is directly connected to a single pile, without any pile cap, that is impeded in the soil. It transfers both horizontal loads and vertical loads from supper structure to the soil. The top of the pile is not connected to any pile cap, yet directly connected the pier to via a rigid connection. Thus, straining and deformation actions are fully transmitted through this connection. The stiffness of connection between pier and superstructure is changed by the type of the bearing device. This study is made using loads transmitted to the pier and applied directly to the top of the pier.

Bridges have various forms of supports. Monopiles may be preferred more than others as their cross-section respect construction safety requirements with the lowest cost, which is the target in large scall projects like bridges. Reducing the cross section of structure element compacts the structure and increases the value of stress in the element as described of second-order theories in Eurocode.

Eurocode indicates that second-order effects should be considered where they are expected to greatly impact on the overall stability of a system and in critical sections to reach the ultimate limit state.

The analysis methods of second order in Eurocode include a general method, based on non-linear second-order analysis, and the following two simplified methods: a method based on nominal stiffness and a method based on nominal curvature.

Simplified methods are used to get the ratio between second-order moment and first-order moment using simple equations based on Eurocode examples which show the different buckling modes and corresponding effective lengths for isolated members with regular supports.

Eurocode simplified methods indicate that horizontal load variation does not affect on the ratio between second-order moment and first-order moment for regular structure support. The behavior of soil support differs from the behavior of the regular structure support as soil decrease the displacement of the pile from the highest value at top of the ground to zero-displacement level unlike regular support has a clear condition

Non-linear analysis studies include the soil-structure interaction and estimates soil behavior, which have a major impact on the structure. Nonlinear analysis provides that equilibrium and compatibility are satisfied and an adequate non-linear behavior of the structure. [1-6]

Model

Model description

Numerical models of monopiles are typically presented in finite element programs as beam elements defined by circular cross section using general method of Eurocode based on non-linear second-order analysis. Main material parameter used in programs is the concrete characteristic compressive cylinder strength at 28 days, which is taken as 35(MPa) in this parametric study. Length from the top of soil to top of pier(L) is assumed to be 10 m as shown in Figure 2. The pier is fixed in the soil and free at the top. Loads are applied at the top of the structures. 9 soil cases are used with a constant vertical load and variant in horizontal loads for each soil. The monopile structure is divided into smaller segments of beams with 0.1-meter length.

Vertical Load is assumed to be constant for all models and equal to 7000kN and applied horizontal loads vary from 0kN to maximum value relative to soil type. The maximum horizontal load corresponds to the maximum allowable displacement at the top of the pier which is equals to L/300 = 33.3mm.[7, 8] Diameter is calculated depending on applied vertical load value to achieve acceptable slenderness ratio as per Eurocode equations by using maximum model fixed-free as a conservative model and nearest to our case. Equations are described below:

$$\lambda_{lim} = 20 \cdot A \cdot B \cdot C / \sqrt{n} \qquad (1)$$

$$\lambda = l_0 / i \qquad (2)$$

where:

A, B, C are constant values as A= 0.7, B = 1.1 and C = 0.7.
$n = N_{Ed} / (A_c f_{cd})$; is relative normal force.
N_{Ed} is vertical load
λ is slenderness ratio
l_0 is the effective length.
i is the radius of gyration of the uncracked concrete section.

The diameter should not exceed 2.64 m. when $\lambda_{lim} = \lambda = 46$. Chosen diameter, as a case study, is taken equal to 2.5 m, with a percentage ratio between slenderness and limit =117.4% (as slenderness is 51.2 and the limit is 43.61).

Nonlinear analysis is used to get the second-order moment and first order to compare between them. The analysis is carried out with models using a software program known as Sofistik. Sofistik is a finite element software that has different input methods and optimal interfaces. The first advantage of the software is Finite element analysis. The Finite Element Method (FEM) employed in Program is a displacement method, meaning that the un-knowns are deformation values at several selected points, that so-called nodes. Displacements can be obtained with an element-wise interpolation of the nodal values. The calculation of the mechanical behavior is based generally on an energy principle (minimization of the deformation work). The result is a so-called stiffness matrix. This matrix specifies the reaction forces at the nodes of an element from that the straining actions on elements are known. [9]

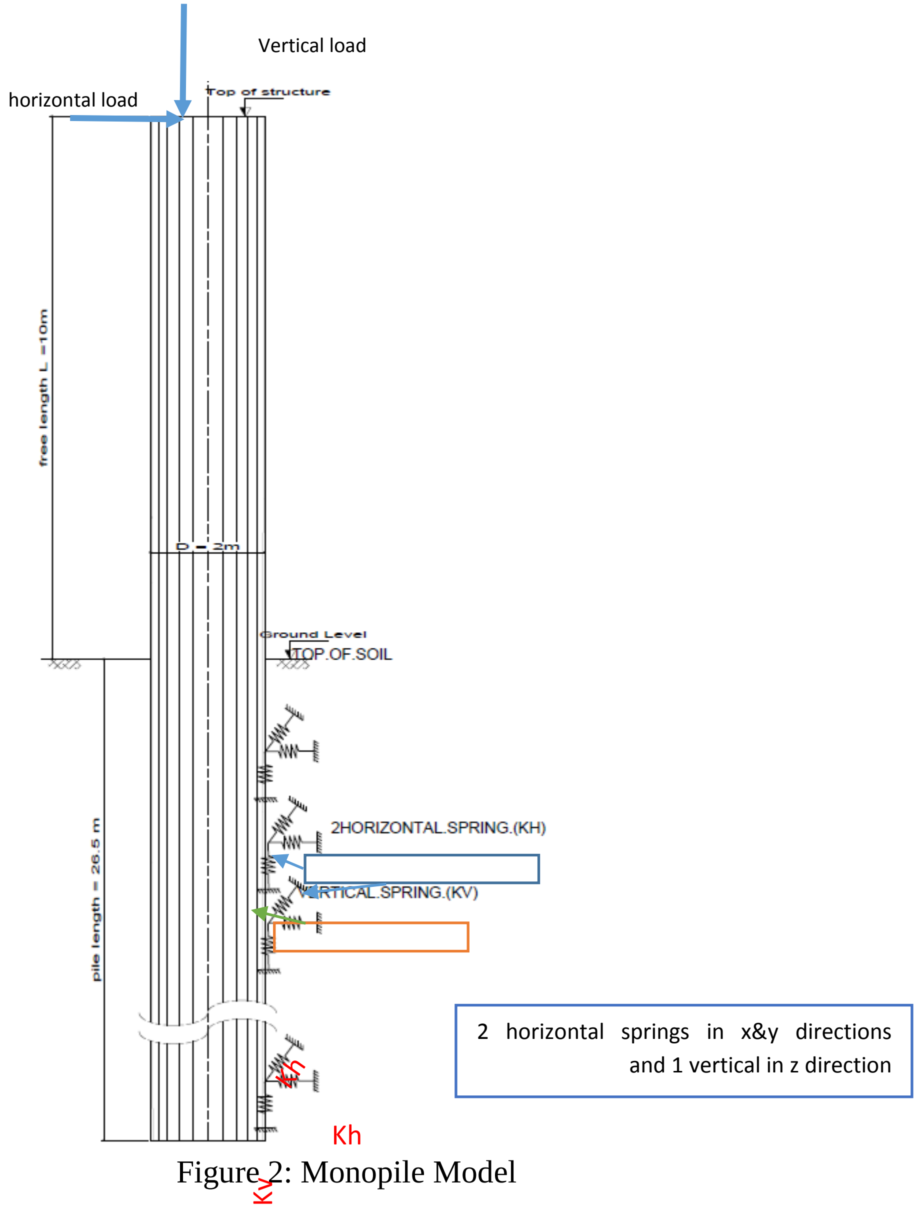

Figure 2: Monopile Model

Soil parameters

Soil is represented as Winkler model springs: two horizontal springs and a vertical spring. In each section of the element, the soil is assumed to have a perpendicular reaction to the axis of the element, which is a function with the relative displacement of the section.

Different Clay soils are used on these models. Soil young's modulus in a radial direction is commonly obtained by pressure-meter test. Different soil used within range defined in table1.

Table 2:Typical range of young's modulus for clay soils from pressure-meter test [10].

Serial no.	Types of soil	Em(MPa)
1	Soft clay	0.5–3.0
2	Medium clay	3–8
3	Stiff clay	8–40

The interaction law of soil reaction is a function with the displacement of the pile. it is defined by slope K_f between load /meter and displacement which is constant with depth in this parametric study. The evaluation of K_f from the Ménard pressure-meter modulus is calculated as follows:

-From Eurocode 7 French annex the Horizontal linear spring follow the equation [12]

$$Kf = \frac{12E_M}{\frac{4*B0}{3*B}(2.65*\frac{B}{B0})^{\alpha}+\alpha} \qquad (3)$$

E_M: Pressure-meter modulus

α: soil rheology coefficient

B: diameter of the foundation

B_0: a reference width taken equal to 0.60 m [12]

Kf is the value of horizontal subgrade reaction

Table 3:Range of young's modulus from pressure-meter test model (a) : model (i) [10].

					Diameter (m)	
					2.50	
	SOIL				STIFFNESSES	
					horizontal	vertical
case	soil	EM (MPa)	α	Type soil	Kf (kPa)	Kt (Kn/m3)
1	Soft clay	0.5	0.67	Fine	2644	400
2	Soft clay	1.5	0.67	Fine	7931	1200
3	Soft clay	2.5	0.67	Fine	13219	2000
4	Medium clay	3.5	0.67	Fine	18506	2800
5	Medium clay	5.5	0.67	Fine	29081	4400
6	Medium clay	7.5	0.67	Fine	39656	6000
7	Stiff clay	8.5	0.67	Fine	44944	6800
8	Stiff clay	15	0.67	Fine	79313	12000
9	Stiff clay	40	1	Fine	105882	32000

Models straining actions

The simplified methods in Eurocode describe that the variation of horizontal loads changes the moment of the structure without changing the ratio between the moment of the second-order analysis and first-order analysis for the normal structures. terse case study uses the general method, which depends on non-linear analysis, and by changing the horizontal loads.

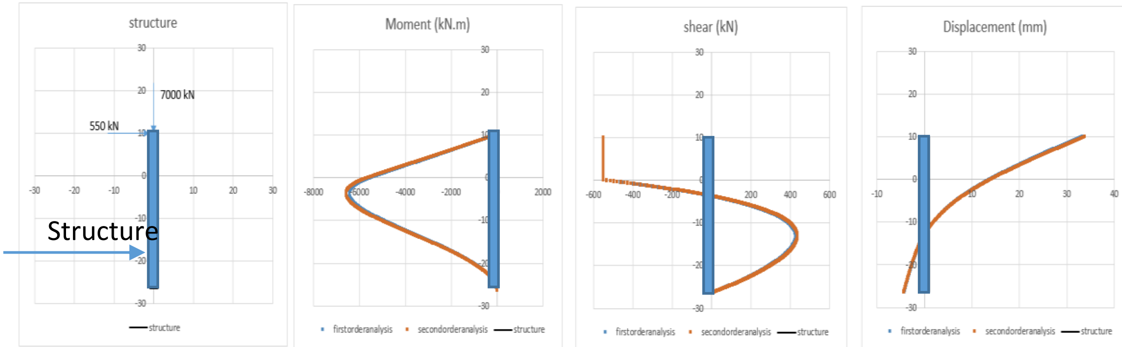

Figure 3 : Straining action of one parametric case of model (3)

Figure (3) shows the ratio between Max moment of the second-order analysis moment and the first order analysis is constant with the variation of horizontal load. These results are valid for clay soils with a constant value of young's modulus of soil. Figures also shows that the moment of second-order analysis and first-order analysis has the same slope and moment increase according to horizontal load increasing. These figures prove that the behavior of monopile and general methods has the same assumptions of simplified method of Eurocode [13, 14].

Nine soil used in this study with different properties defined in table 2

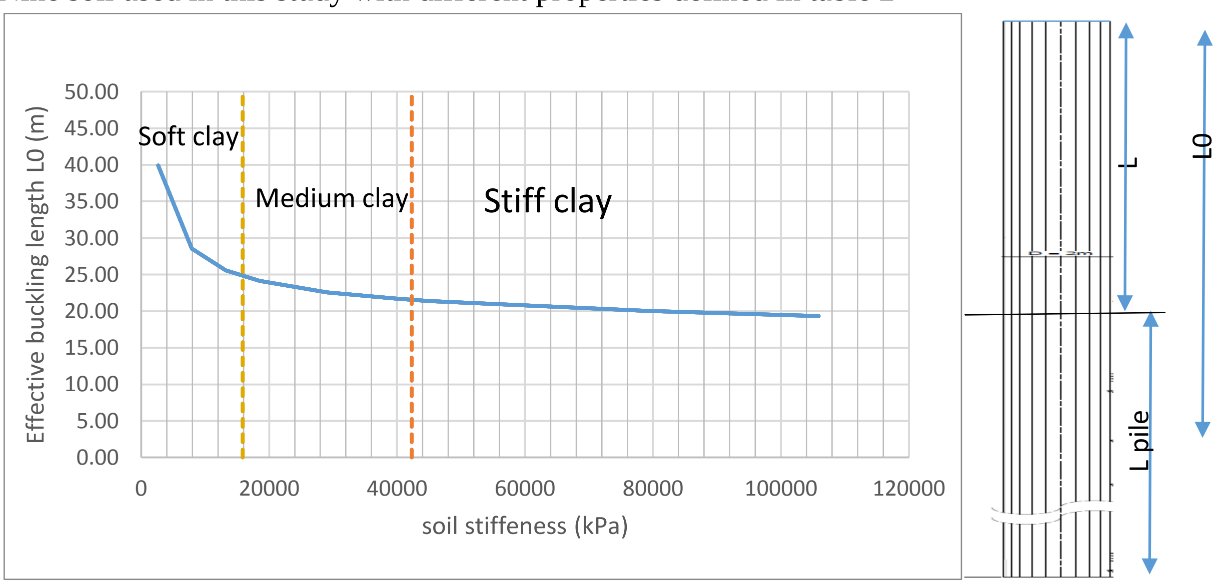

Figure 4 : Relation between stiffness and L0, which is the effective buckling length

Relation between ratio second order to first order moments and horizontal load for every model described on figure below

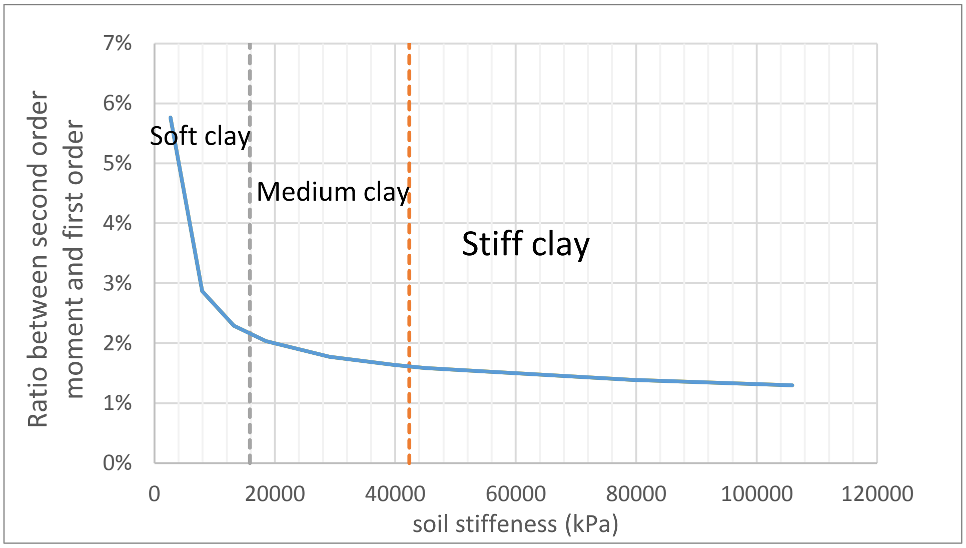

Figure 5: Soil Stiffness and Ratio between Max Moment obtained from Second order and First order analysis

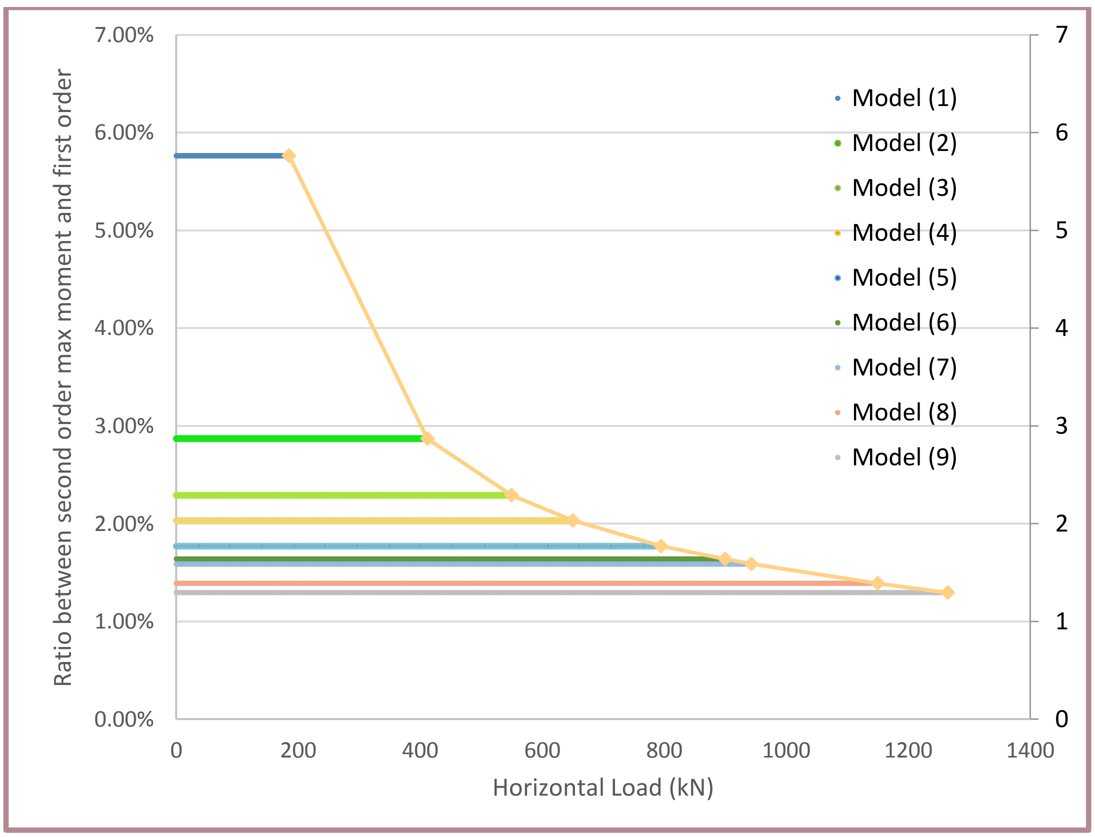

Figure 6 :Horizontal load and Ratio between Max Moment obtained from Second order and First order analysis

$$Moment\ ratio = \frac{Max\ 2nd\ order}{Max\ 1st\ order}\% = 10 \sim 101\%$$

Relation between horizontal has and maximum

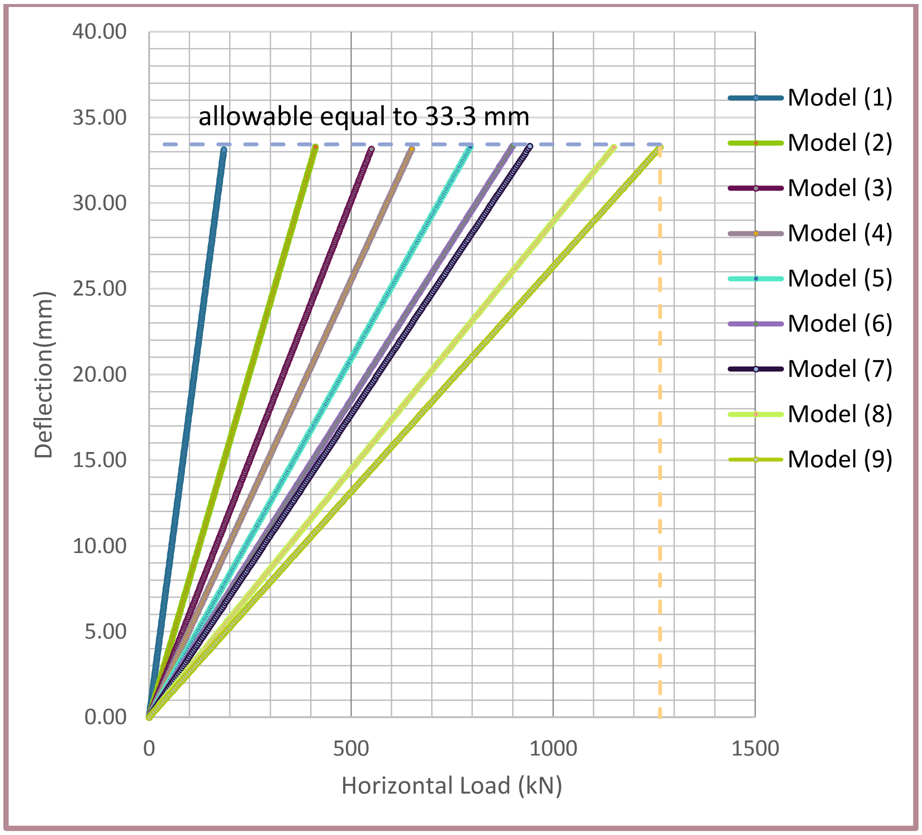

Figure 7 :Deflection (mm) and Ratio between Max Moment (kN) obtained from Second order and First order analysis

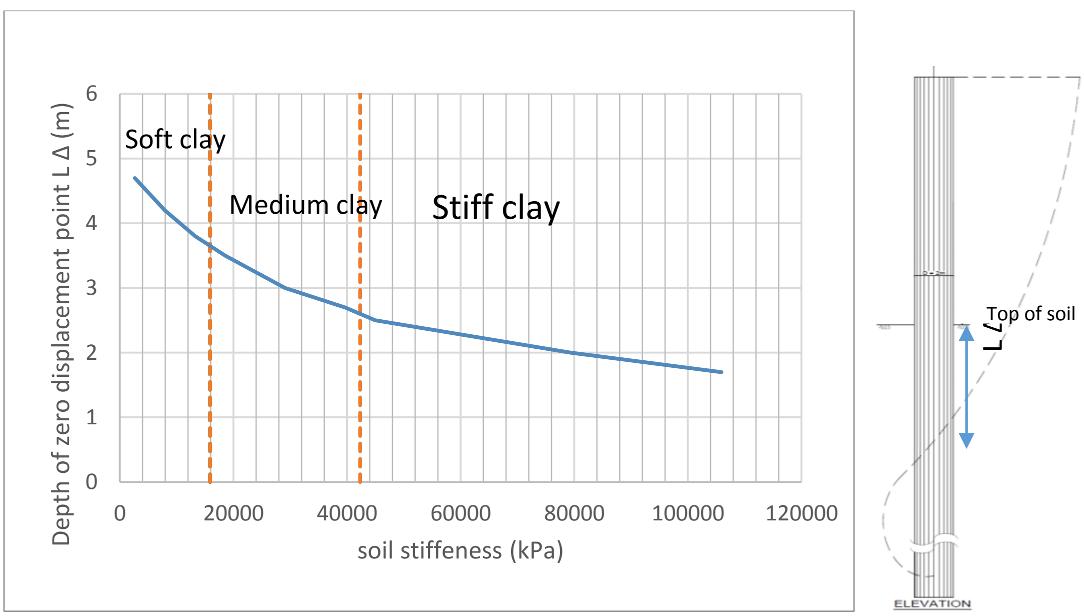

Figure 8:relation between depth of zero-displacement point and soil stiffness

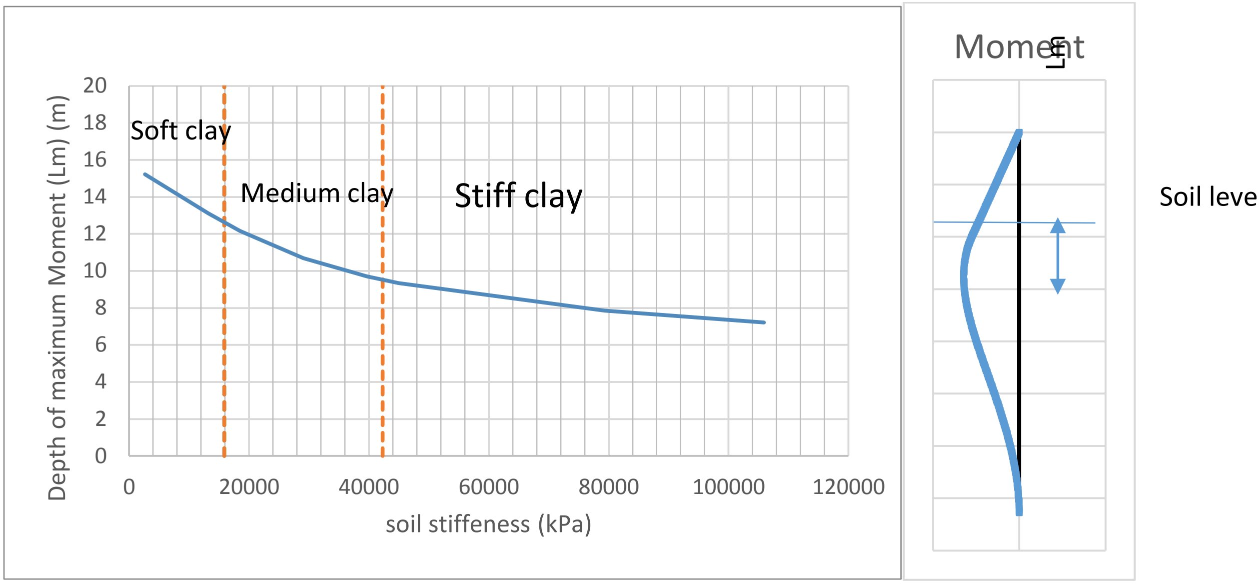

Figure 9:relation between depth of maximum moment point and soil stiffness

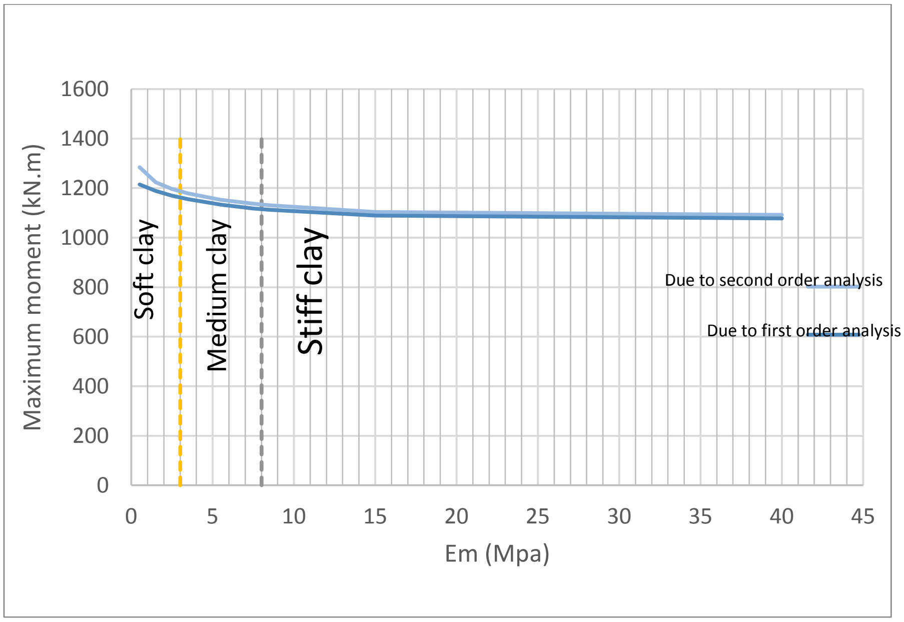

Figure 10:relation between maximum moment point and soil young modulus

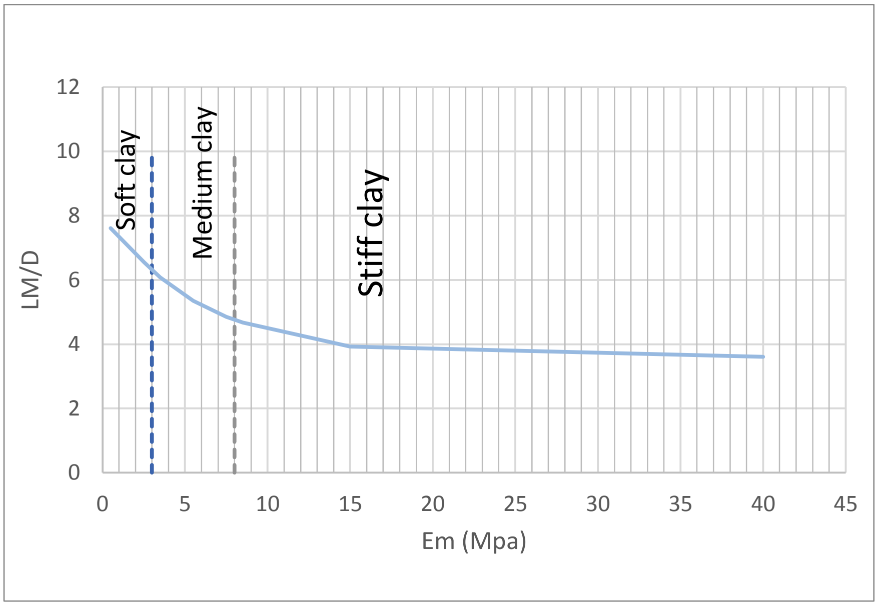

Figure 11:relation between depth of maximum moment divided by monopile diameter (D) and soil stiffness

Lm is depth with maximum moment; D is diameter of monopile

CONCLUSIONS

This study proves that the variation of Horizontal loads for the monopiles analyzed by Eurocode general method has the same effect of simplified method in case of clay soil used with constant young's modulus. The study proves also some concepts for design monopile as can be summarized as followings:

1- Changing Horizontal loads has no effect on the ratio between second-order analysis moment and first-order moment. The moment of the structure will be increased with a constant slop between moment and horizontal load.
2- ratio between second-order analysis moment and first-order moment has inverse relationship with soil stiffness.
3- Buckling length has inverse relationship with soil stiffness.
4- Lm (depth of maximum moment) has invers relationship with soil stiffness and constant for same soil
5- Depth of Zero deflection point (LΔ) is constant for same soil and has inverse relationship with soil stiffness.

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