Studying the influence of soil plasticity on the transmission of ground movements affecting the soil-structure interaction

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Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-1042

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

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Étude de l'influence de la plasticité du sol sur la transmission des mouvements du sol affectant l'interaction sol-structure

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ABSTRACT: Many buildings may suffer damage due to ground movements associated to underground excavations like tunnelling, mines or urban excavations. Assessment of the transmitted ground movement is then one of the major concerns and soil plasticity may have a significant influence on structural behaviour due to the Soil-Structure Interaction (SSI). The purpose of this study is to investigate the behaviour of an existing structure sitting on a soil subjected to a ground movement with considering soil plasticity. Analytical approach is applied to examine the effect of the non-linear behaviour of soil based on a modified Winkler elastic model. Results reveal the influence of considering an elastoplastic behaviour on the evaluation of the transmission of ground movements, and display the discrepancy in the response of the structure whether the soil is elastic or elastoplastic; this directly affects the prediction of structural damage. In addition, a new correlation is proposed to evaluate the structural response considering SSI parameters for an elastoplastic soil.

RÉSUMÉ: De nombreux bâtiments peuvent être endommagés par des mouvements de terrain associés à des excavations souterraines, des tunnels, des mines ou des excavations urbaines. L'évaluation du mouvement du terrain transmis est alors l'une des préoccupations majeures et la plasticité du sol peut avoir une influence significative sur le comportement de la structure dû à l'Interaction Sol-Structure (ISS). Le but de cette étude est d'étudier le comportement d'une structure existante assise sur un sol soumis à un mouvement de terrain en tenant compte de la plasticité du sol. Une approche analytique est appliquée pour examiner l'effet du comportement non linéaire du sol basée sur un modèle élastique modifié de Winkler. Les résultats révèlent l'influence de la prise en compte d'un comportement élasto-plastique sur l'évaluation de la transmission des mouvements du terrain et montrent la divergence dans la réponse de la structure, que le sol soit élastique ou élasto-plastique; cela affecte directement la prévision des dommages structurels. De plus, une nouvelle corrélation est proposée pour évaluer la réponse structurelle en tenant compte des paramètres d'ISS pour un sol élasto-plastique.

Keywords: Analytical model; elastoplastic correlation; soil-structure interaction; soil plasticity; Winkler model.

1 INTRODUCTION

Plasticity designates the permanent deformation that stays after the application of a force on a solid material. This concept was initially introduced on metals, then it was developed to include other domains, in particular the soil plasticity (Bardet, 1984).

In fact, from earliest times, the main target was to evaluate the soil stability by the determination of the loads which cause the ultimate failure state of a certain soil mass. When no failure is involved, the main target is to deal with the soil stress and deformation based on the linear elastic law. However, between the elastic phase and the ultimate failure point, there is an intermediate phase corresponding to a transition phase which has an elastoplastic behaviour known as the plasticity phase (Lefevre, 1966).

Ground movements designate a sequence of displacements of the soil, of natural or anthropogenic origin such as shrink-swell phenomenon of clayey soils, influence of nearby excavations (tunnels) and presence of underground voids such as mining subsidence and sinkholes. These ground movements are responsible to the soil settlements and displacements. This soil displacement may occur in the absence of any structure on top of it; this case represents the free-field ground movement. Conversely, if the soil is underneath an existing structure, the ground movement is transmitted to the building (ElKahi, et al., 2018). Since it is not proper to consider that these movements in the free-field are transmitted entirely to the building (Mair, 2013), it is necessary to take into account the SSI. Consequently, the soil settlement produced by the free-field ground movements will cause structural movement and consequently can cause structural damage (Ricceri & Soranzo, 1985).

Different methods were developed to predict the deflection caused by ground movements. These prediction methods are affected by many factors related to soil mechanical and geological properties. In fact, to study the influence of soil movement on the stresses under a building, many of the models that were developed showed that a significant plasticity could appear in the soil below (Deck, 2002). Due to SSI, the structure is influenced by the ground movement and consequently by soil plasticity.

The target of this article is to investigate the influence of soil plasticity on the transmission of ground movements affecting the soil-structure interaction.

2 ANALYTICAL APPROACH

Various approaches have been developed to study the behaviour of structures subjected to differential settlement. These can be gathered into five main groups (Aissaoui, 1999): numerical, empirical, semi-empirical, physical and analytical. Among the proposed methods to study the deformation of a building in a zone of ground movement, only numerical methods offer a great deal of flexibility in taking into account complex soil behaviour (Potts & Addenbrooke, 1997). Even if the choice of a complex behaviour model is relatively easy and efficient using numerical models, several considerations are always problematic when using these models such as the choice of interface properties, meshing or dimensioning of the model and especially the choice of the mechanical properties of the ground. However, since analytical methods use the simplest behaviours to achieve the most general results possible, the analytical modelling allows rapid calculations for a wide range and sensitivity of model parameters (Deck & Singh, 2010).

This study is developed using an analytical approach; however, analytical models of soils (such as Winkler) do not take into account the influence of soil plasticity. The soil structure interaction associated with the ground movement raises serious questions about the need to take into account non-linear behaviour of the soil, and the possibility of being plasticized as a result of the redistribution of applied loads due to the movement of the ground.

Therefore, the innovation of this study is to develop an analytical approach, taking into account the elastoplastic behaviour of the soil which provides an understanding of the behaviour of the building and of the soil during a ground movement.

2.1 Soil modelling

Winkler assumes that the reaction of the soil at each point under the foundation is proportional to the deflection of the foundation at this point (Rashidifar & Rashidifar, 2013).

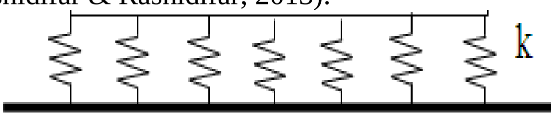

Figure 1. Winkler model (Rashidifar & Rashidifar, 2013).

As shown in Figure 1, this hypothesis amounts to modelling the soil by a juxtaposition of the elastic springs. The proportionality constant of these springs is known as the soil reaction modulus K_w. Considering that p(x) and w(x) represents the ground reaction and displacement respectively, Winkler model is characterized by equation (1):

$$p(x) = K_w.w(x) \quad (1)$$

By modelling the ground by Winkler springs and in the case of ground movement, the springs undergoes variable deformations depending on the stiffness of the building and the intensity of ground movement. If the soil behaviour is elastic, the springs can undergo unlimited deformations and stresses, which is not true in the real case because the ground or the springs can deform but the stresses are limited to the bearing capacity of the soil. The stresses applied to the ground cannot therefore exceed its bearing capacity; if the stresses are greater than the soil bearing capacity, redistribution under the building must be made to ensure that the constraints in each element do not exceed the capacity allowed in that element.

2.2 Structure modelling

Generally, the analytical approaches developed to study the SSI phenomenon model the building by an elastic Euler-Bernoulli beam of length "L", height "H", width "B", inertia "I" and Young's modulus "E". The beam is loaded by a uniform vertical load "q" as shown in Figure 2.

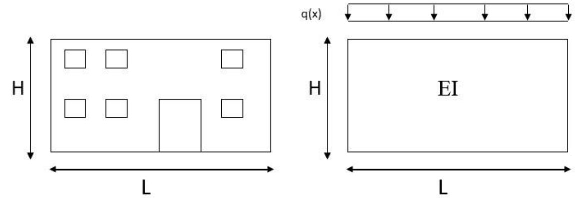

Figure 2. Building modelled similar to an elastic Euler-Bernoulli beam (ElKahi, et al., 2018).

The deflection of the beam is determined using equation (2):

$$y''(x) = -M(x)/EI \quad (2)$$

2.3 Characteristic differential equation

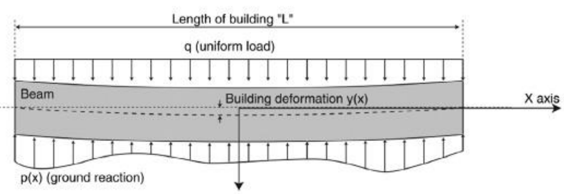

Figure 3. Presentation of the building load q, ground reaction p(x) and building deflection y(x) (Basmaji, et al., 2017).

As shown in Figure 3, the beam is loaded both sides, by a uniform vertical load q from above, and by the ground reaction p(x) from below. The relationships between the shear forces V(x), the bending moments M(x), the external pressure p(x) and the building load q, can be stated as follows:

$$V(x) = -dM(x)/dx \quad (3)$$

$$\frac{dV(x)}{dx} = q - p(x) \quad (4)$$

Combining (2), (3) and (4), the differential equation of the building displacement can be written as follows:

$$y^{(4)}(x) = \frac{q - p(x)}{EI} \quad (5)$$

Considering that the displacements of the ground and the building are in static equilibrium, it follows that there is a continuous contact between the ground and the beam. As illustrated in Figure 4, the building undergoes a rigid vertical displacement "d" with a deflection y(x).

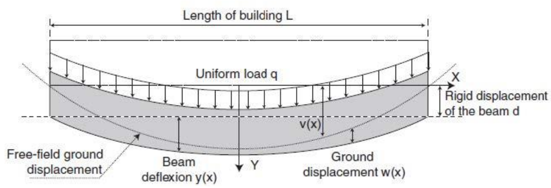

Figure 4. Displacements of the ground and the building under static equilibrium (Basmaji, et al., 2017).

If the polynomial function v(x) represents the free-field ground displacement for $-L/2 \leq x \leq L/2$, the condition of no interpenetration is given as follows:

$$v(x) = \Delta_0(1 - 4x^2/L^2) \qquad (6)$$

$$y(x) + d = v(x) + w(x) \qquad (7)$$

Where Δ_0 is defined later by equation (9).

Based on (1), (5) and (7), the characteristic differential equation of the beam deflection per linear meter is given by (8):

$$y^{(4)}(x) = \frac{q - K_w(y(x) + d(x) - v(x))}{EI} \qquad (8)$$

To solve the problem, six boundary conditions are used (Deck & Singh, 2010). The building deflection y, bending moment y`` and shear force y``` are equal to zero at the extremities of the beam (-L/2 and L/2).

2.4 *Transmission ratio & Relative stiffness*

The transmission ratio is used to quantify the building damage analytically. It is the ratio of the maximum deflection of the building foundation Δ over the free-field deflection Δ_0. The value of Δ_0 depends on the ground movement origin, the beam length and the geological/geotechnical conditions. If one assumes that the free-field ground movement is roughly circular under the building with a radius of curvature R, a geometric relationship can be determined to calculate Δ_0 by combining R with the length of the building L, as shown in Figure 5.

$$\Delta_0 = L^2/8R \qquad (9)$$

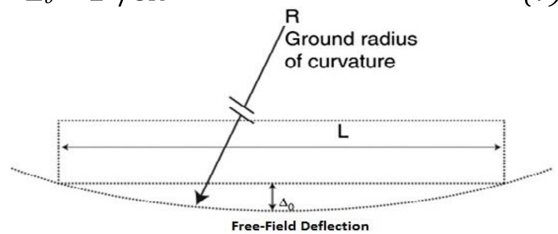

Figure 5. Presentation of the free-field deflection Δ_0 (ElKahi, et al., 2018).

The assessment of Δ is a key point because the free-field ground movements vary depending on the soil as well as the structure stiffness properties. As shown in Figure 6, by taking the SSI into consideration, Δ should be less than Δ_0 and the values of the transmission ratio Δ/Δ_0 are be between 0 and 1.

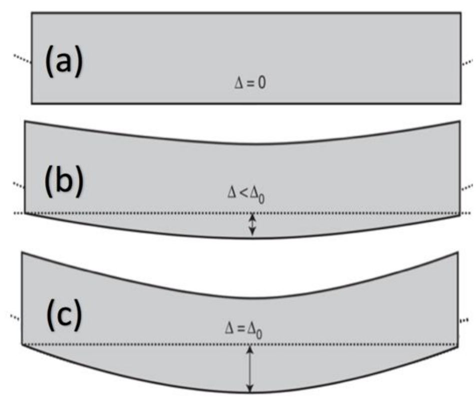

Figure 6. Behaviour of structures subjected to ground movement. (a) High-stiffness structure on soft ground. (b) Intermediate stiffness structure on intermediate ground. (c) Flexible structure on stiff ground.

To predict the building deflections due to ground movements, the question of building stiffness compared to ground stiffness is addressed, which is known as "relative stiffness" (Boscardin & Cording, 1989). In the literature, different stiffness ratios are defined, and the transmission ratio of the free-field ground movements is investigated with analytical and numerical models according to the predefined stiffness ratios. This study considers the relative stiffness ratio ρ* defined in the analytical model of Deck & Singh (2010):

$$\rho * = \frac{EI}{K_w B L^4} \qquad (10)$$

2.5 Soil elastoplastic behaviour

The objective is to develop an analytical model of the soil-structure interaction that takes into account the influence of plasticity in the soil. The new distribution of stresses in the ground could, under certain conditions, lead to the generation of non-reversible plastic deformations.
To consider the influence of the elastoplastic behaviour of the soil, a new relation will be developed to interpret the behaviour of soil under the building. The comparison between the stresses applied to the soil and its bearing capacity will be used as a criterion to judge whether the soil is in a plastic state or not, assuming that the vertical stresses in the soil must not exceed the bearing capacity of the soil. The concept of soil behaviour is based on Winkler's model and considers the elastoplastic behaviour as follows:

$$Elastic\ Case\text{:}\quad p(x) = K_w.w(x) \qquad (1)$$
$$Plastic\ Case\text{:}\quad p(x) = p_{ult} \qquad (11)$$

The soil bearing capacity p_{ult} is considered to be the maximum stress that the springs can take. If the applied forces exceed the load capacity of the ground, a spring continues to deform and it cannot carry any additional stress. The overloads are thus transferred to the nearby springs which are still in the elastic range.
The resolution of equations (1) and (11) is iterative given the nonlinear behaviour of the ground. The solution of these equations (in the elastic zone at first) with the corresponding boundary conditions, will lead to finding the deformation of the beam and the stresses applied to the ground. After obtaining the solution, there are two possible cases:

1- The stresses applied to the ground are less than p_{ult} (the soil is still in the elastic range); in this case the maximum deformation of the building can be directly calculated.
2- Some of the stresses applied to the ground will be greater than p_{ult}; in this case an iterative procedure is applied to find the solution and determine the plastic limit.

As presented in Figure 7, at the extremities of the beam where the constraints are greater than p_{ult}, $p(x) = p_{ult}$ is imposed.

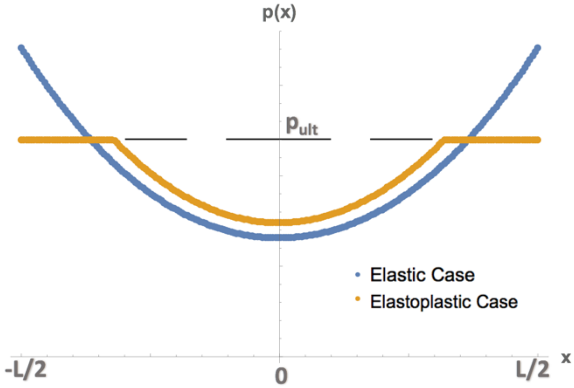

Figure 7. Presentation of the applied procedure.

Note that, since the integral of p(x) before and after taking into account the plasticity is always equal to the external load applied to the building, the values of p(x) are increased in the middle of the beam for the elastoplastic behaviour, as shown in Figure 7.

3 RESULTS & DISCUSSION

An example is presented to show the influence of considering soil plasticity. Given a beam of unit width and length L = 20 m, stiffness EI = 5333 MN.m^2, loaded with 100 KN/m, bearing capacity p_{ult} = 120 KN/m, Young's modulus = 100 MPa, Winkler reaction modulus K_w = 3850 KN/m^3 and a radius of curvature of the free field ground movement R = 1500 m, the solution of the problem is found by solving the equations and boundary conditions using Mathematica.

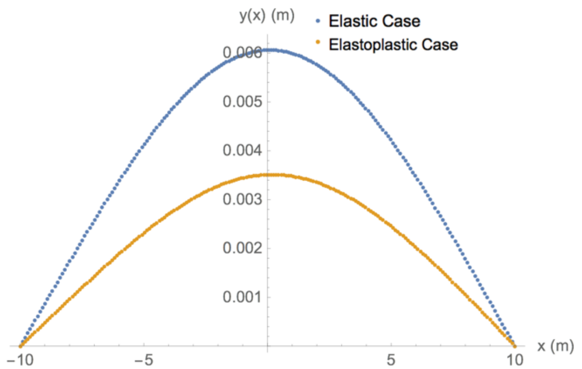

Figure 8. Vertical displacements at the soil-structure interface according to the elastic and elastoplastic behaviour of the ground.

Figure 8 first shows the elastic solution for the case represented in blue; note that there is no limitation on the contact pressure due to assuming an elastic behaviour for the soil. For this case, the maximum displacement in the middle of the building is equal to 0.6 cm. However, at the boundaries of the building there is an area where $p(x) > p_{ult}$, then the soil plasticity must be considered. Consequently, by applying the iterative process of resolution (equations (1) and (11)), it is noted that the maximum deflection of the beam Δ is reduced from 0.6 cm to 0.35 cm after considering plasticity.

In order to study the effect of soil plasticity on the deflection transmission ratio Δ/Δ_0, an analytical model was developed using Mathematica, by investigating 18,900 possible combinations of p_{ult}, EI, K_wB, L, R and q, as shown in Table 1.

Table 1. Model parameters.

Symbol	Values
R (m)	250, 500, 750, 1000, 1500, 2000, 3000, 4000, 5000
K_wB (MPa)	20, 50, 100, 250, 500
EI (GN.m^2)	20, 50, 100, 250, 500
L (m)	10, 20, 30
q (KN/m)	100, 200, 300, 400
p_{ult} (KN/m)	q, 1.5q, 2q, 2.5q, 3q, 3.5q, 4q

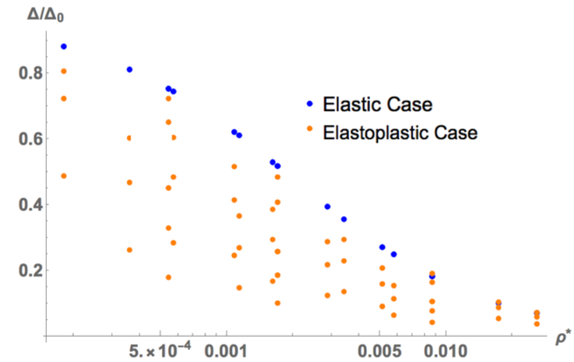

Figure 9. Deflection transmission ratio Δ/Δ_0 versus the relative stiffness ρ^* for elastic/elastoplastic behaviour of soil for various soil bearing capacities.

Results presented in Figure 9 show that taking into account the elastoplastic behaviour in the soil reduces the calculated maximum deflection for the building.

Accordingly, a new relation can be proposed for the elastoplastic deflection transmission ratio using a reduction coefficient "a" as follows:

$$\Delta/\Delta_{0\,(Elastoplastic)} = a.\Delta/\Delta_{0\,(Elastic)} \qquad (12)$$

With $0 \leq a \leq 1$.

If a =1, p_{ult} is not reached; the soil still has an elastic behaviour, consequently, there is no difference between considering an elastic or an elastoplastic soil behaviour. However, when a decreases below 1, p_{ult} is reached.

In order to establish a new correlation that evaluates a as a function of p_{ult}, q, R, K_w, EI and L, the influence of every factor on a is investigated. Table 2 summarizes the effect of every increasing factor on a.

Table 2. Effect of every increasing factor on a.

Factor	Comments	a
p_{ult} ↑	The soil does not reach the plastic phase and behaves as an elastic soil.	↑
q ↑	Due to the static equilibrium, the soil reaction p(x) increases and may reach p_{ult} at a certain position under the structure.	↓
R ↑	The soil reaction difference at the ends of the structure is limited. The soil reaction p(x) then remains low and does not exceed p_{ult}, in most cases.	↑

K_w ↑	The soil reaction increases as per equation (1) and becomes closer to p_{ult}.	↑
EI ↑	The building has more stiffness and can sink in the soil which will increase the soil reaction until reaching p_{ult}.	↑
L ↑	The soil reaction difference under the structure is significant and may reach and exceed p_{ult}.	↑

After evaluating 18,900 combinations (Table 1) and calculating Δ/Δ_0 for elastic and elastoplastic soil behaviour, a new correlation (equation (13)) is proposed for the reduction factor a using artificial neural networks via JMP software which is a software used for statistical analysis.

$$a = -7.19258 - 0.97155H1 - 0.52479H2 - 8.10706H3 \quad (13)$$

$$H1 = TanH\left(0.5\begin{pmatrix}-5.55733\\+0.00045K_w\\-0.00062R\\+0.00037q\\+0.00040p_{ult}\\+0.20247L\\+0.010897EI\end{pmatrix}\right) \quad (14)$$

$$H2 = TanH\left(0.5\begin{pmatrix}44.10233\\+0.02106K_w\\-0.00035R\\+0.00033q\\-0.00102p_{ult}\\-1.77733L\\-0.076137EI\end{pmatrix}\right) \quad (15)$$

$$H3 = TanH\left(0.5\begin{pmatrix}-2.44438\\+0.000078K_w\\+0.000071R\\+0.001837q\\-0.001939p_{ult}\\-0.009696L\\-0.001588EI\end{pmatrix}\right) \quad (16)$$

This correlation can be directly adopted by the engineering society for design purposes to assume the Δ/Δ_0 value when considering the elastoplastic behavior of the soil.

4 CONCLUSIONS

This study develops an analytical approach based on Winkler's elastic model to assess the influence of soil plasticity on the transmission of the ground movements affecting the soil-structure interaction. This is done by limiting the maximum value of the soil reaction not to exceed the soil bearing capacity.

To study the effect of soil plasticity on the deflection of a structure, an application on a building, modelled as an individual beam, was developed with the existence of a plastic zone under it. By applying the soil reaction limitation methodology, results show that the building deflection decreases when considering an elastoplastic soil behaviour. On the other hand, the stresses in the soil are limited to the ultimate bearing capacity in the plastic areas at the boundaries of the building, and tend to increase in the middle relative to the elastic case to respect the condition that the integral of p(x) before and after taking into account the plasticity is always equal to the external load applied to the building, as shown in Figure 7.

The influence of the soil plasticity on the deflection transmission ratio Δ/Δ_0 versus the relative stiffness ρ* was also investigated by evaluating a wide range of SSI parameters and soil bearing capacities p_{ult}. Results show a significant difference in the deflection transmission rate between the elastic and the elastoplastic soil behaviour. The elastic behaviour results create an envelope that engulfs the elastoplastic results.

Consequently, a new correlation is proposed that associates the elastic with the elastoplastic results of the transmission of the ground movement. Based on the 18,900 empirical estimated values corresponding to different values of the soil bearing capacity, beam length, stiffness, load and the free-field radius of curvature, a statistical model is realized by neural networks. Consequently, the effect of the soil elastoplastic behaviour on the soil-structure interaction can be directly evaluated via the proposed correlation that is based on the elastic values of Δ/Δ_0; this proposed equation can be used by geotechnical engineers and designers to consider elastoplastic behaviour.

5 AKNOWLEDGMENT

The work presented in this paper was supported by a research grant from the National Council for Scientific Research-Lebanon (CNRS-L) and the Lebanese University.

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