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A new simplified meta-model to evaluate the transmission of ground movements to structures integrating the elastoplastic soil behavior

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Abstract

Many buildings may suffer damage due to ground movements associated to underground excavations like tunneling, mines or urban excavations. The level of damage depends upon the rate of ground movements transmitted to structures that is affected by the Soil-Structure Interaction (SSI) conditions and parameters such as the soil elastoplastic behavior. The purpose of this paper is to integrate the soil elastoplasticity while investigating the response of a structure sitting on a soil subjected to a ground movement. Analytical and numerical approaches are applied to examine the effect of the non-linear soil behavior. The analytical approach is based on modified Winkler and Pasternak elastic models under the assumption of limiting the soil reaction by its bearing capacity ; the numerical approach is based on finite element models, using Plaxis 2D that consider an elastoplastic soil behavior. Results display the discrepancy in the structural response between considering an elastic or an elastoplastic soil behavior. Based on a significant number of iterations, the artificial neural network technique is used to propose a new simplified meta-model that integrates the soil elastoplasticity to evaluate the transmission of ground movements to structures. In addition, a procedure, which can be used by engineers and designers, is developed to evaluate the transmission ratio for any structure sitting on any type of soil.

Keywords

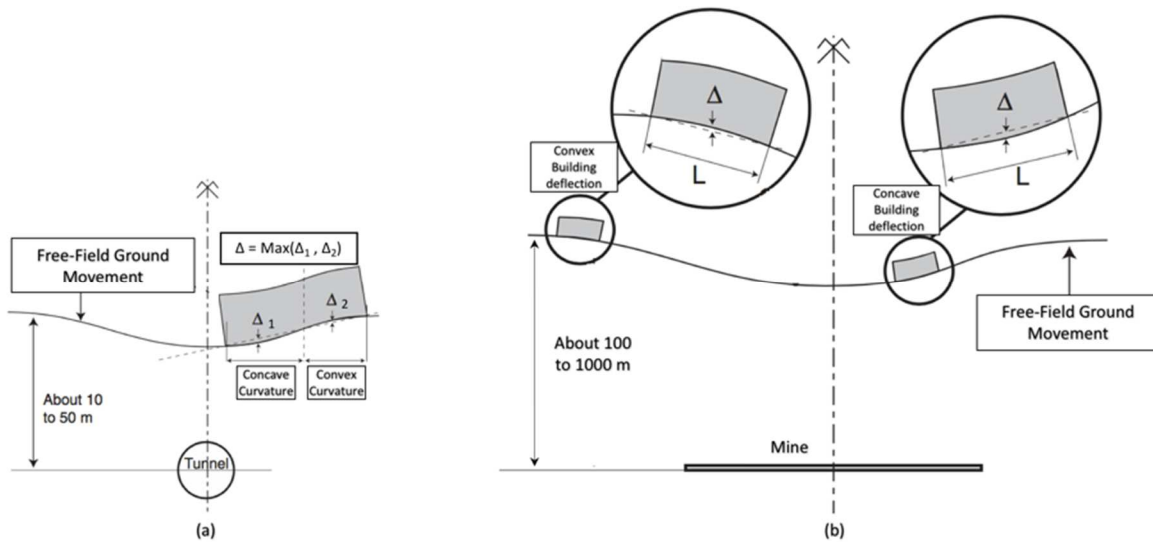
Meta-model, elastoplastic soil behavior, Pasternak model, Winkler model, soil-structure interaction, ground movements, artificial neural network.

1. Introduction

Ground movements designate a sequence of soil displacements, 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 of the soil settlements and displacements. The soil displacement may occur even in the absence of any structure on top of it; this case represents the free-field ground movement. Conversely,

38 if the soil is underneath an existing structure, the ground movement is transmitted to the building
 39 foundations (Figure 1). An important parameter is the stiffness and the building stiffness could
 40 be underestimated if it is only based on the foundation geometry. Consequently, the building
 41 with its foundation is assimilated to a beam with an equivalent stiffness. The computed
 42 deflection represents the deflection transmitted to both the building and its foundation which
 43 may cause a structural damage [1, 2]. It is not proper to consider that these movements in the free-
 44 field are transmitted entirely to the building since the transmission may be considerably affected by
 45 the soil-structure interaction (SSI) phenomenon which is strongly dependent upon the structure and
 46 the soil conditions and the associated parameters [3-5].

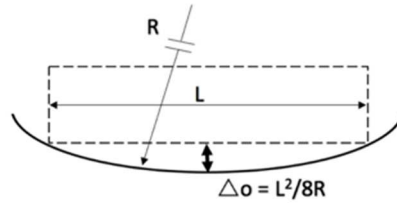
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48

49 Figure 1. Building deflection caused by ground movements: (a) Case of tunneling. (b) Case of
 50 underground mine.

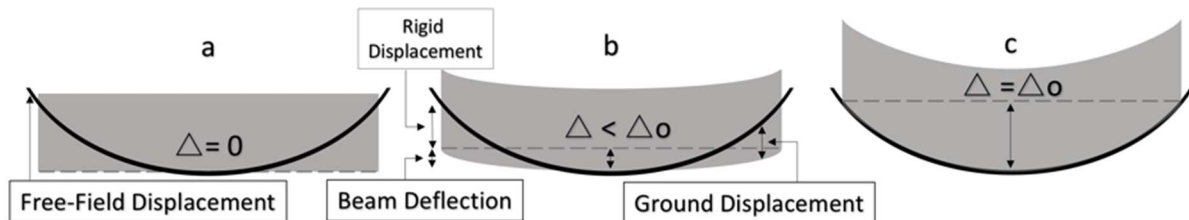
51 By neglecting the impact of the interaction between the soil and the structure, the free-field ground
 52 movements are integrally transmitted to the building. Under this assumption, Δ_0 represents the
 53 maximum deflection of the building. Assuming that the free-field ground movement is symmetrical
 54 and roughly circular under the building, Δ_0 represents the maximum free-field deflection under the
 55 building (for an integrally transmitted movement); it depends upon the ground radius of curvature R
 56 and the building length L (Figure 2).



57
58

Figure 2. Free-field deflection Δ_0 .

59 By considering the impact of the SSI, the soil, located under an existing structure and subjected to a
 60 ground movement, will influence the structure differently due to the interdependence of the
 61 mechanical behavior between the soil under the foundations and the structure sitting on these
 62 foundations. This interdependence is strongly dependent on the stiffness of the structure as well as
 63 that of the soil [2, 4, 6]. Due to the influence of the SSI, the ground movement may be partially
 64 transmitted to the structure which results in a building deflection characterized by its maximum value
 65 Δ with $\Delta \leq \Delta_0$. As shown in Figure 3, if the structure is stiff, it can resist the ground movement and the
 66 induced transmitted deflection is limited ($\Delta < \Delta_0$); if it is flexible, then it perfectly follows the
 67 settlement of the soil and $\Delta = \Delta_0$.



68

69 Figure 3. Behavior of structures subjected to ground movement. (a) High-stiffness structure on soft
 70 ground. (b) Intermediate ground and structure stiffness. (c) Flexible structure on stiff ground.

71

72 For a symmetrical free-field movement with respect to the structure, the deflection Δ corresponds to
 73 the maximum differential settlement under the building. For a non-symmetrical free-field movement
 74 case, Δ represents the maximum deflection of the building, **whether** the structure has a concave or a
 75 convex deformation (Figure 1-a).

76 The Δ / L ratio, called the deflection rate, is frequently used to assess the behavior of structures
 77 subject to differential settlement and to evaluate their damage [6, 7]. Since the damage depends upon

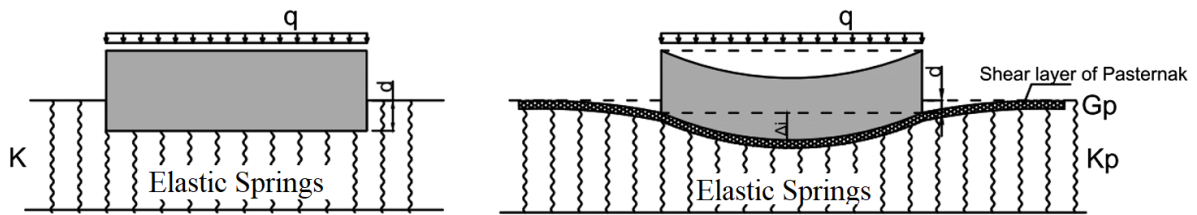
78 the rate of movement transmitted to the building, the structure response to the ground movement is
79 usually evaluated through the deflection transmission ratio, defined as Δ/Δ_0 [8, 9].

80 Different methods (analytical, numerical, experimental, empirical field data results) have been
81 developed to predict the building deflection in response to the ground movements [6-15]. **Except**
82 **empirical methods that are based on observations of real existing structures, all of these methods do**
83 **not consider a specific study of a particular case but they are applied to simplified structures, such as**
84 **beams, in order to assess the global trend of ground movements induced phenomena.**

85 Among the approaches developed to study the SSI phenomenon, only numerical methods offer great
86 flexibility for taking into account the complexity of the SSI conditions [11, 16]. Although it is
87 relatively simple to consider complex soil and structure behaviors in numerical models, their use may
88 be criticized by the justification of the numerical values of all parameters and conditions. In addition,
89 numerical models present difficulties to generalize results, because of the need to reproduce the same
90 scenario numerous times, by varying a particular SSI parameter in each repetition to cover the extent
91 of the variation range of all parameters. Thus, they can be considered as time-consuming processes
92 [7].

93 To avoid these difficulties, it is possible to obtain results through analytical methods that develop
94 simple equations that represent the structural deflection. Analytical methods may be considered as a
95 complementary tool to the numerical ones, allowing quick calculations for a wide **variation** range of
96 parameters, without considering complex configurations [6]. In these analytical models, the soil is
97 modelled with simple elastic stiffness elements as elastic springs. Winkler model is the simplest soil
98 model and has been used by many investigators and by Deck and Singh (2010) [7] to address the
99 question of the building deflection induced by ground movements and the assessment of Δ/Δ_0 . Such a
100 SSI model can be criticized because it neglects any interaction between the springs and because it
101 assumes a purely elastic behavior of the ground [17]. As a consequence, it does not take into account
102 the influence of soil settlement outside the loaded area, which leads to discontinuities in the settlement
103 profile when the applied load is also discontinuous; the displacements of the soil outside the building
104 are supposed null, which is not correct. Basmaji et al. (2017) [6] developed a similar SSI model by
105 replacing the Winkler by Pasternak model in order to introduce some interactions between the springs

106 (Figure 4). This SSI model corrects some critical points of the previous one, but it does not take into
 107 consideration the soil elastoplastic behavior.



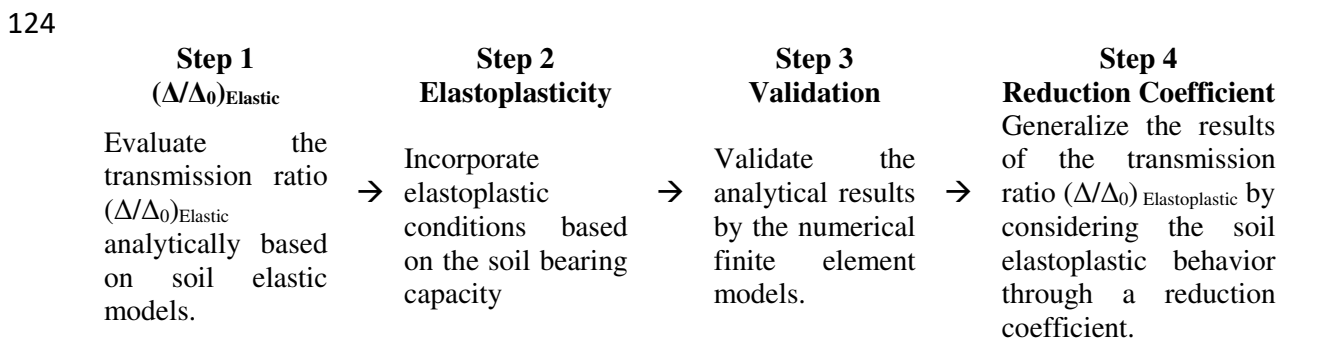
The ground is modelled by the elements of Winkler
 The parameter of Winkler is K

The ground is modelled by the elements of Pasternak
 The parameters of Pasternak are K_p and G_p

108
 109 Figure 4. Structure on a soil modelled analytically with the one parameter Winkler's elastic model or
 110 the two parameters Pasternak's elastic model.

111 Thus, soil analytical models do not take into account the influence of the soil elastoplastic behavior
 112 even-though this factor significantly affects the transmission of ground movements to structures [6-9].

113 As shown in Figure 5, the target of this paper is to investigate the influence of soil elastoplasticity on
 114 the transmission of ground movements affecting the soil-structure interaction. Based on the elastic
 115 analytical models, a simplified elastoplastic meta-model is proposed, via statistical regressions, to
 116 evaluate the structural response. A modification is added to the analytical elastic models that
 117 assimilate the soil to a juxtaposition of elastic springs; the modification incorporates elastoplastic
 118 conditions based on the soil bearing capacity. Results of the analytical approach are then compared to
 119 the results obtained by numerical finite element models. In order to generalize the obtained results, a
 120 large database of the deflection transmission ratio is evaluated for different combinations of the SSI
 121 parameters and the soil bearing capacity. Based on this database, a new correlation is proposed to
 122 evaluate the transmission of ground movements to structures considering the elastoplastic soil
 123 behavior, in an effort to improve the investigation of the structure response to ground movements.



125
 126 Figure 5. Diagram representing the study plan.

127 2. Procedure & Modeling

128

129 Previous research on this subject **addresses** the question of building stiffness compared to ground
130 stiffness, which is known as "relative stiffness", and suggests to assess the transmission ratio Δ/Δ_0 as
131 a function of a relative stiffness parameter ρ^* between the soil and the structure [7, 11, 18].

132 Most of these studies rely on Eq. (1) to evaluate the relative stiffness parameter ρ^* based on the
133 structure length L , inertia I , Young's modulus E and the soil Young's modulus E_s . Since it is a 2D
134 study done per linear meter (EI [$N.m^2/m$]), Eq. (1) has the advantage of being non-dimensional and of
135 being well adapted to a synthetic representation of Δ/Δ_0 .

$$\rho^* = \frac{EI}{E_s L^3} \quad (1)$$

136 **In order to propose a simplified meta-model that evaluates the transmission ratio Δ/Δ_0 as a function of**
137 **the relative stiffness ρ^* , an appropriate SSI model has to be considered. While there is a significant**
138 **number of SSI models proposed in the literature [6-8, 10-11, 18-23], a comparison between two**
139 **elastic models, representing the transmission ratio Δ/Δ_0 versus the relative stiffness ρ^* for a wide**
140 **variation range of SSI parameters, is performed.**

141 2.1. Elastic Deck & Singh SSI analytical model

142

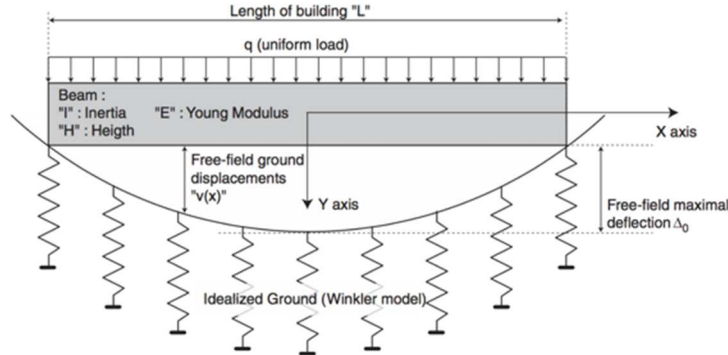
143 Deck and Singh (2010) [7] developed a SSI analytical model to calculate the deflection transmission
144 ratio Δ/Δ_0 as a function of the ground and building mechanical properties. As shown in Figure 6, the
145 building is assimilated to an **elastic** Euler–Bernoulli beam and the ground is represented by the
146 Winkler model, which consists on assimilating the soil to a juxtaposition of vertical springs
147 characterized by their stiffness K without any interaction between them. Considering that $p(x)$ and
148 $w(x)$ represent the ground reaction and displacement respectively, Winkler model is evaluated using
149 Eq. (2). The ground is modelled with an initial shape corresponding to Δ_0 and a polynomial equation
150 $v(x)$ (Eq. (3)) that represents the free-field movement shape. The final building deflection Δ is then
151 calculated based on the final position and deformation of the beam required to get a static equilibrium
152 under its own weight q and the vertical ground reaction $p(x)$ (Eq. (4)).

$$p(x) = Kw(x) \quad (2)$$

$$v(x) = \Delta_0 (1 - 4x^2 / L^2) \quad \text{for} \quad -L/2 < x < L/2 \quad (3)$$

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

153 Where L and EI are the building length [m] and elastic stiffness [N.m²/m] (since it is a 2D study done
154 per linear meter).



155
156 Figure 6. Deck & Singh (2010) analytical model for the SSI and the building deflection induced by
157 ground movements.

158 On the other hand, Deck & Singh (2010) [7] introduced their own relative stiffness definition to plot
159 the results of Δ/Δ_0 (Eq. (5)) that is suitable to the Winkler model, since the ground stiffness is defined
160 with the Winkler parameter K instead of Es used in Eq. (1).

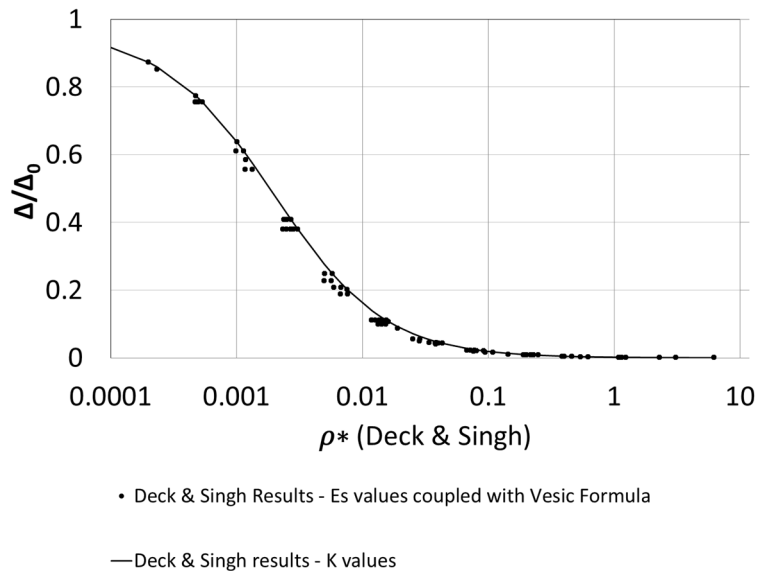
$$\rho * (Deck \& \text{Singh}) = \frac{EI}{KL^4} \quad (5)$$

161 Where K is the Winkler elastic modulus [N/m³].

162 This equation is comparable to other relative stiffness ratios defined in the literature; it presents the
163 advantage of being a non-dimensional parameter and suitable to have a synthetic representation of
164 Δ/Δ_0 based on Winkler model. In order to show the consistency between Eq. (1) and Eq. (5), Vesic
165 (1963) [24] formula (Eq. (6)) is used to define values for K in the case of a foundation with length L,
166 width B (with L>B) and a ground characterized by a Young's modulus Es and a Poisson's ratio ν . In
167 this case B is taken equal to 1m, which approximatively corresponds to the width of a building
168 foundation. Noting that various formulas link the Winkler modulus to the soil Young modulus [24-
169 28], Vesic formula is chosen since it takes into account the presence of a beam (through the "EI"
170 term) contrary to other formulas.

$$K = \frac{0.65Es}{B(1 - \nu^2)} \sqrt[12]{\frac{EsB^4}{EI}} \quad (6)$$

171 Figure 7 shows the Deck & Singh (2010) results for the transmission ratio plotted against the relative
 172 stiffness ρ^* (Deck & Singh) defined in Eq. (5). A comparison is done between the Δ/Δ_0 values
 173 evaluated according to specific values of K and Δ/Δ_0 values evaluated according to specific values of
 174 Es and converted to K according to Vesic formula (Eq. (6)). The difference between the results is
 175 slight (Figure 7) which validates the consistency between Eq. (1) and Eq. (5) using Vesic formula.



176
 177 Figure 7. Results of the deflection transmission ratio Δ/Δ_0 versus the relative stiffness ratio ρ^* (Deck
 178 & Singh) obtained for K values and for Es values coupled with Vesic formula.

179

180 2.2. Elastic Basmaji et al. SSI analytical model

181

182 Based on Deck & Singh (2010) model, Basmaji et al. (2017) [6] developed their analytical model
 183 where the soil is represented by the Pasternak model, a two parameters soil model that takes into
 184 account the interaction between adjacent springs, in addition to the influence of shear deformation in
 185 the soil (Figure 4). The two parameters are the shear modulus G_p , and the stiffness modulus K_p . The
 186 soil reaction can be written as follows:

$$187 \quad p(x) = K_p \cdot B \cdot w(x) - G_p \cdot B \cdot w''(x) \quad (7)$$

188 When G_p is taken to be zero, the Pasternak model is equivalent to the Winkler model. The Winkler
 189 parameter K is used instead of K_p . It should be noted that if a given geotechnical problem is modelled
 190 with each of the two models, i.e., Pasternak and Winkler, the values of K_p and K will be different,
 unless G_p is assumed to be equal to zero [6].

191 As shown in Figure 4, due to the influence of the shear layer, Pasternak model displays a differential
192 settlement under the building without any discontinuities contrary to Winkler model that displays a
193 uniform settlement with a discontinuity at the edge. Thus, when a local force F acts on a point (x) of a
194 soil modelled by Pasternak model, the slope curve $w'(x)$ presents a discontinuity. Conversely, any
195 discontinuity of $w'(x)$ must be associated to a local force. To overcome this problem, Eq. (7) must be
196 completed with Eq. (8).

$$F = w'_{left}(x) - w'_{right}(x) \quad (8)$$

197 Where w'_{left} and w'_{right} are the limit of the first derivatives of $w(x)$ for x_{0-} and x_{0+} respectively and F
198 is the associated local force (Figure 8).

199 To highlight the effect of the shear deformation, Basmaji et al. (2017) compared Pasternak and
200 Winkler models. In order to make a suitable comparison, the transmitted ratio Δ/Δ_0 has to be plotted
201 versus the same definition of the relative stiffness ρ^* . To do so, the parameters used in the soil models
202 have to be calculated according to the same methodology in order to correspond to the same soil in
203 terms of Young's modulus and Poisson's ratio. Due to the lack of existing analytical relations to assess
204 the two parameters used in the Pasternak's model (G_p and K_p), Basmaji et al. (2017) [6] implemented
205 a new methodology based on Flamant's theoretical solution of induced vertical settlement. They
206 adjusted the displacement for both methods according to Flamant's theoretical solution in order to
207 justify the parameter values for Winkler and Pasternak. Consequently, they proposed abacuses to
208 select the Winkler and Pasternak values based on the half width of the loaded zone and the thickness
209 of the compressive ground for $E_s = 1\text{MPa}$ and $\nu = 0.3$. However, the comparison of the transmitted
210 ratio Δ/Δ_0 versus the relative stiffness ratio ρ^* defined in Eq. (1), between Pasternak and Winkler
211 models, reveal a discrepancy between both methods which is related to the influence of shear
212 deformation into the soil (Figure 10).

213

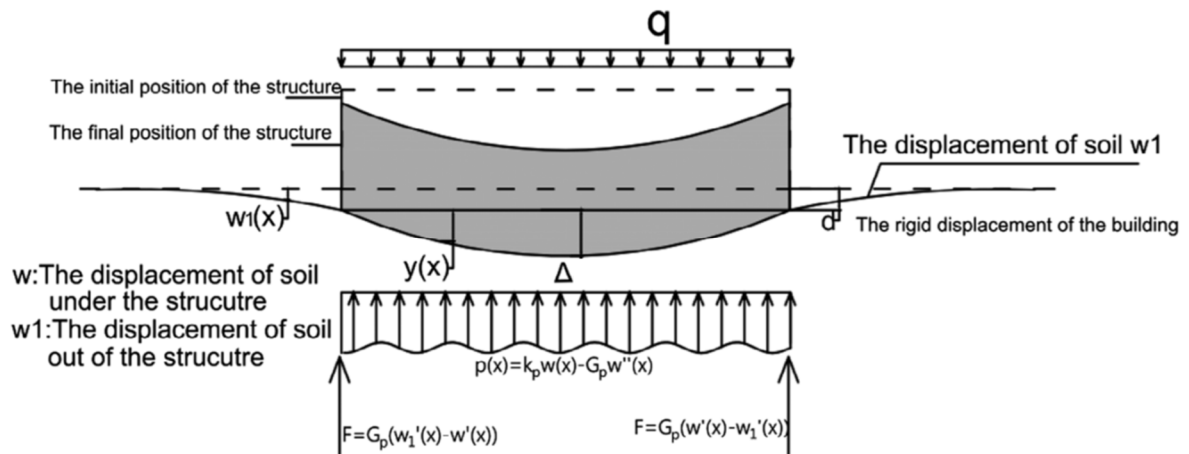


Figure 8. Definition of parameters used to model the beam deflection according to Pasternak model.

2.3. Validation of elastic analytical models

A significant number of SSI models (analytical, numerical, experimental, etc.) were proposed in the literature. In order to investigate the influence of soil elastoplasticity on the transmission of ground movements, the elastic analytical models have to be validated, since a simplified elastoplastic meta-model will be proposed based on the elastic analytical results. Two validation techniques are evaluated in this paper: (a) Validation with a finite-element model; (b) Validation with numerical, experimental and field data results from previous research.

2.3.1. Validation with a finite-element model

A finite element model (FEM) is developed to compare the elastic analytical results with a set of numerical simulations. The objective of the FEM is to model the ground curvature induced by ground movements and calculate the transmission ratio of the free-field deflection. In fact, Basmaji et al. (2017) [6] and Deck & Singh (2010) [7] validated their analytical results with numerical models; however, they considered an elastoplastic ground behavior in their studies, and they modeled the subsidence by a uniformly distributed load imposed on the lower boundary. On the contrary, the numerical model presented in this paper intends to fully reproduce the analytical conditions in order to well verify the effectiveness of the analytical results. Subsequently, this FEM model considers an elastic ground behavior and the subsidence is imposed without adding a uniform load on the lower boundary.

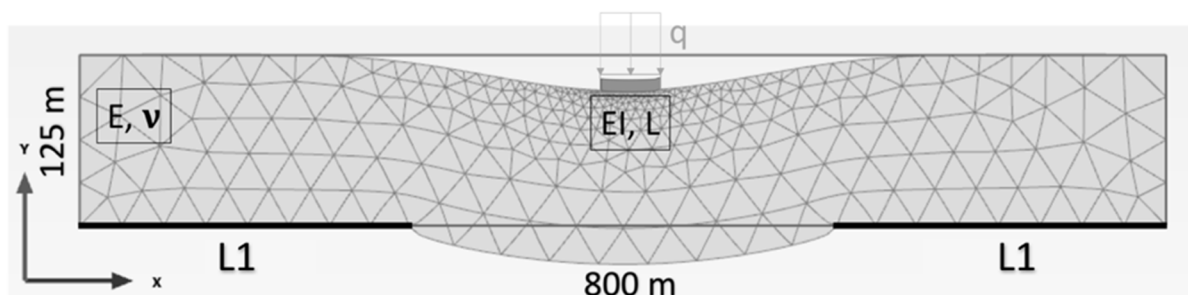
238 The numerical model is performed with a finite element software (Plaxis 2D) under the plane strain
239 hypothesis. The model consists of an elastic soil layer, 125 m thick and 800 m long, with a building
240 located at the center (Figure 9). For the boundary conditions, the horizontal displacement is fixed on
241 the right and left boundaries and the vertical displacement is fixed only at the bottom boundary right
242 and left sides (L1) while the central region of the bottom boundary is free. So, to model the
243 subsidence and the free-field displacement, the length of L1 is selected in order to reach a value of
244 Δ_0 that is equivalent to the analytical model.

245 The soil Poisson's ratio ν is 0.3 and the unit weight is 20 KN/m^3 . The structure is modeled by a beam
246 that is loaded with a vertical uniformly distributed load q . Mechanical properties and buildings
247 dimensions are chosen **in order to get values that are identical to** the ones considered in the analytical
248 approach (EI and L).

249 (a) A first computation is performed by fixing the vertical displacement on all the lower
250 boundary in order to generate the initial ground situation under the soil weight; all the
251 evaluated displacements are then set to zero.

252 (b) A second computation is performed by fixing the vertical displacement on L1, without
253 considering the structure, in order to assess the free-field displacement Δ_0 of the subsidence;
254 Δ_0 is evaluated and the displacements are set to zero.

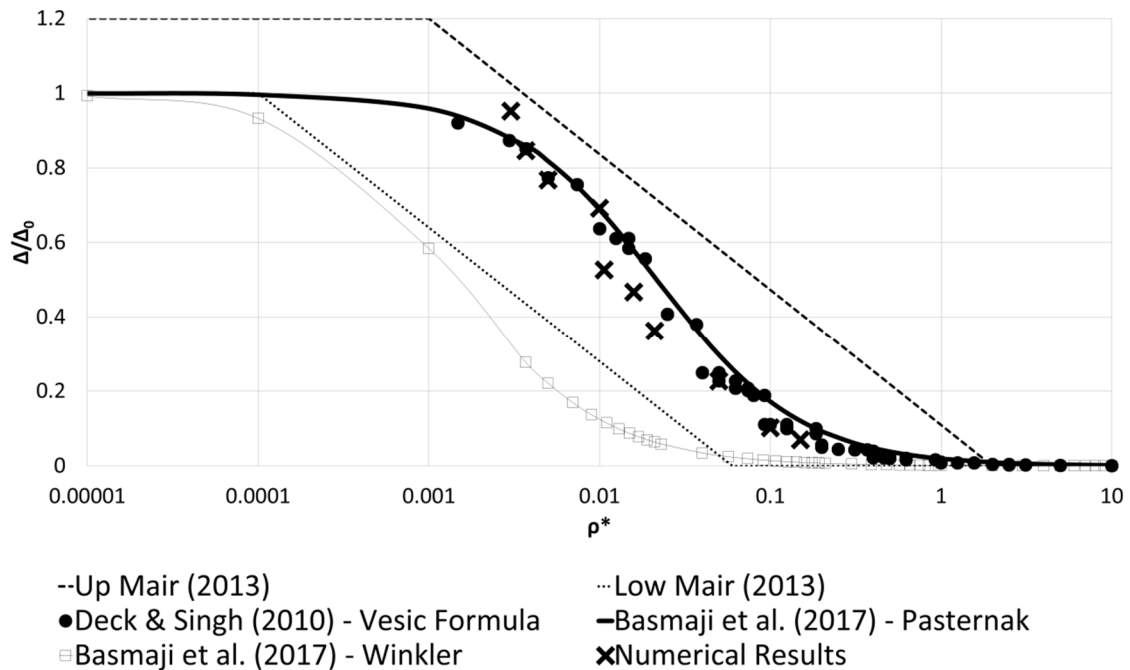
255 (c) A third computation is performed with the presence of both the structure (with the vertical
256 uniformly distributed load) and the subsidence in order to assess the final building deflection
257 Δ considering the soil-structure interaction.



258
259 Figure 9. Description of the finite element model used to compare analytical results of the deflection
260 transmission ratio with numerical results.
261

262 A set of 10 simulations are performed that cover the distribution range of the relative stiffness ρ^* , for

263 different values of EI/B , E_s , L , q and Δ_0 . Globally, numerical results presented in Figure 10 are
 264 superimposed with the curve of the transmission ratio calculated with the elastic analytical models of
 265 Deck & Singh (2010) Winkler model combined with Vesic (1963) formula and Basmaji et al. (2017)
 266 with Pasternak model; consequently, these two analytical approaches seem to be sufficient to predict
 267 the trend of the transmission ratio.



268 Figure 10. Comparison between Mair, 2013; Deck & Singh, 2010; Pasternak-Basmaji et al., 2017;
 269 Winkler-Basmaji et al., 2017 and numerical results.
 270
 271

272 2.3.2. Validation with numerical, experimental and field data from previous 273 research

274
 275 In addition to the finite-element model validation, Mair (2013) [2] envelope is used to validate the
 276 elastic analytical results. In fact, Mair (2013) [2] compared the transmission ratio, derived from the
 277 finite-element analyses of Potts and Addenbrook (1997) [11] and Franzius et al. (2006) [29] with
 278 respect to the relative stiffness. Also, he considered the results of the finite element parametric
 279 analyses, of deep excavations in soft clay on adjacent buildings, using the Modified Cam Clay soil
 280 model done by Goh (2010) [30]. The comparison of these studies shows that the obtained results fall
 281 into a relatively narrow envelope known as Mair (2013) [2] envelope (Figure 10).

282 As shown in Figure 10, the elastic analytical models of Deck & Singh (2010) with Winkler model [7]
 283 combined with Vesic (1963) formula and Basmaji et al. (2017) with Pasternak model [6] fit well

284 within Mair (2013) envelope, while an important discrepancy is shown between these results and
285 Basmaji et al. (2017) with Winkler model [6]. Accordingly, even-though Deck & Singh (2010)
286 Winkler model does not consider the shear deformation and the displacement outside the building,
287 results show that the influence of these properties is indirectly taken into consideration or
288 compensated by evaluating the Winkler modulus according to Vesic (1963) formula. In fact, Vesic
289 (1963) has adopted the principle of equivalence between two solutions to find the soil reaction
290 modulus for an infinite length beam in contact with the ground, modeled by the Winkler model. The
291 same principle has been adopted by Basmaji et al. (2017) to calculate the Pasternak parameters; it was
292 done for the case of a distributed load applied on a length L on a soil modeled by the Pasternak
293 model. Thus, the results of Deck & Singh (2010) Winkler model combined with Vesic (1963) formula
294 and Basmaji et al. (2017) with Pasternak model are comparable.

295 3. Results & Discussion

296 3.1. $(\Delta/\Delta_0)_{\text{Elastic}}$

297 Based on Eq. (4), the Deck & Singh analytical model is based on evaluating the deflection of the
298 building using Euler–Bernoulli fourth order differential equation. To solve the problem, six boundary
299 conditions are used which present computation difficulties and time consumption to generalize the
300 results for a significant number of iterations. On the other hand, as shown in Figure 8, Pasternak
301 model presents punctual forces at the building extremities; thus, a higher number of boundary
302 conditions is needed for Basmaji et al. (2017) model leading to additional computation time
303 difficulties.

304 In order to simplify the evaluation of Δ/Δ_0 , this paper proposes simple meta-model equations, based
305 on the results shown in Figures 7 and 10, depending upon the relative stiffness ρ^* parameters, namely
306 the structure stiffness EI and length L and the soil stiffness E_s that can be substituted by the soil
307 modulus K evaluated according to the Vesic formula (Eq. (6)). **A significant number of iterations of
308 the ρ^* parameters is evaluated, covering its variation range in the analytical models of Deck & Singh
309 (2010) and Basmaji et al. (2017). Since these original models are heavy to implement and expensive
310 in computation time, polynomial meta-models are proposed to evaluate $(\Delta/\Delta_0)_{\text{Elastic}}$. The predictability**

313 and general applicability of the equation are evaluated by comparing the predictions of these meta-
 314 models with analytical results of the original models. Thus, the meta-models allow having, in any
 315 point of the design space, an estimate of the value of the elastic transmission ratio $(\Delta/\Delta_0)_{\text{Elastic}}$ while
 316 reducing the computation time for designers and engineers. Based on Figure 7 and Figure 10, Eq. (9)
 317 and Eq. (10) correspond to $(\Delta/\Delta_0)_{\text{Elastic}}$.

$$\frac{\Delta}{\Delta_0} \text{Elastic}(EI, K, L) = 0.5 - 0.5 \text{Tanh}[2.99373 + 0.46898 \left(\frac{EI}{KL^4}\right)] \quad (9)$$

(K evaluated according to the Vesic formula)

$$\frac{\Delta}{\Delta_0} (EI, Es, L) = 0.5 - 0.5 \text{Tanh}[1.96633 + 0.512843 \left(\frac{EI}{EsL^3}\right)] \quad (10)$$

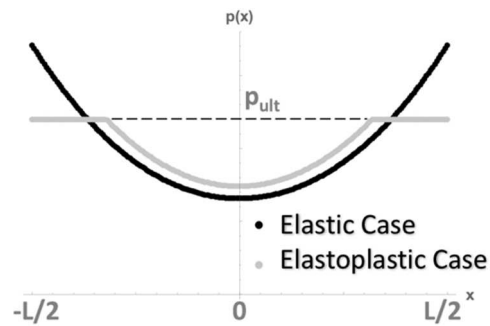
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319 **3.2. Integrate the elastoplastic soil behavior**

320

321 The objective is to develop an analytical SSI model that takes into account the influence of plasticity
 322 in the soil. To consider the influence of the elastoplastic soil behavior, a comparison between the
 323 stresses applied to the soil and its bearing capacity will be used as a criterion to judge whether the soil
 324 is in a plastic state or not. If it is in a plastic state, a new relation is proposed based on assuming that
 325 the vertical stresses in the soil must not exceed the bearing capacity of the soil (Figure 11). If the
 326 applied forces exceed the soil bearing capacity, a spring continues to deform but it cannot carry any
 327 additional stress. The overloads are thus transferred to nearby springs which are still in the elastic
 328 range. The applied procedure is iterative given the nonlinear behavior of the ground.

329 As presented in Figure 11, at the beam edges where the constraints are greater than p_{ult} , $p(x)=p_{\text{ult}}$ is
 330 imposed. Note that, since the integral of $p(x)$ before and after taking into account the plasticity is
 331 always equal to the external loads applied to the building, the values of $p(x)$ are increased in the
 332 middle of the beam for the elastoplastic behavior, as shown in Figure 11.



333

334

Figure 11. Presentation of the applied procedure.

335

The concept of considering the elastoplastic soil behavior is **divided into two cases (elastic and**

336

elastoplastic) as follows:

Elastic Case:	Winkler	$p(x) = K \cdot w(x)$	(2)
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	Pasternak	$p(x) = K_P \cdot B \cdot w(x) - G_P \cdot B \cdot w''(x)$	(7)
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Elastoplastic Case:		$p(x) = p_{ult}$	(11)
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Where p_{ult} is the soil bearing **capacity**; p_{ult} is the **maximum stress that the springs can carry**. **First, the**

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elastic conditions of Winkler and/or Pasternak are considered (Eq. (2) or Eq. (7)). Then, the beam

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deformation and the stresses applied to the ground are evaluated. Two cases are then possible:

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- 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 evaluated according to Winkler and/or Pasternak equations**.

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- Some of the stresses applied **in a certain zone under the building (at the edges), known as the “plastic zone”, are greater than p_{ult}** . In this case, an iterative procedure is applied to find the solution **in the plastic zone** and determine the **soil reaction based on Eq. (11)**.

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3.2.1. Winkler model

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An example is presented to show the influence of considering soil plasticity. This example is based on

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the model considered by Basmaji et al. (2017) [6] with an additional parameter (the soil bearing

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capacity), in order to integrate the elastoplastic conditions. Given a beam of unit width and length

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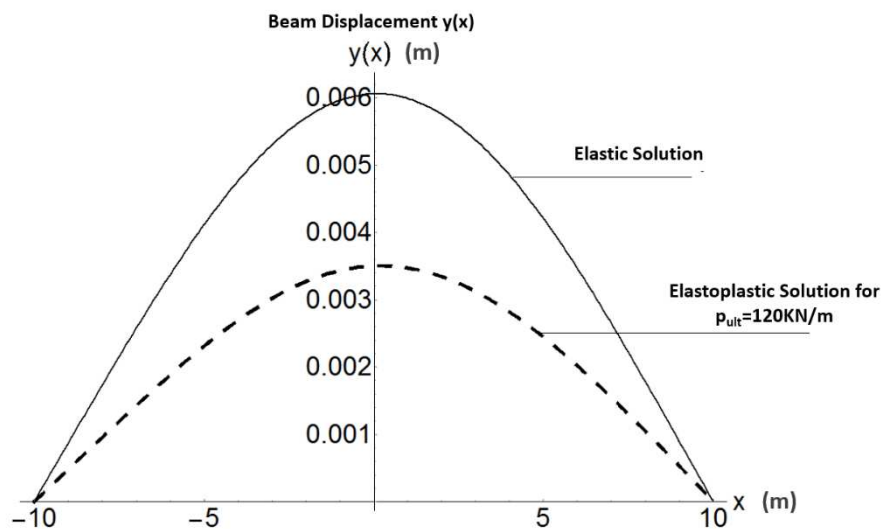
$L=20\text{m}$, stiffness $EI=5350\text{MN.m}^2$, loaded with 100KN/m , bearing capacity $p_{ult}=120\text{KN/m}$, Winkler

353 reaction modulus $K=3850\text{KN/m}^3$ and a radius of curvature of the free field ground movement
354 $R=1500\text{m}$, the solution of the problem is found by solving the equations and boundary conditions
355 using Mathematica.

356 Figure 12 first shows the elastic solution for which there is no limitation on the soil reaction due to
357 assuming an elastic behavior for the soil. For this case, the maximum displacement in the middle of
358 the building is equal to 0.6 cm. However, at the boundaries there is an area where $p(x) > p_{ult}$, then the
359 soil plasticity must be considered. Consequently, by applying the iterative process of resolution (Eq.
360 (2) and Eq. (11)), it is noted that the maximum deflection of the beam Δ is reduced from 0.6 cm to
361 0.35 cm after considering plasticity.

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Figure 12. Vertical displacements at the soil-structure interface according to the elastic and elastoplastic behavior of the ground.

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3.2.2. Pasternak model

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A procedure similar to that applied to Winkler model, to find the solution of a beam on an elastoplastic ground, is applied to find a solution for Pasternak model. However, since there is a soil displacement in Pasternak model outside the structure length L , the solution must take into account the movements of the soil throughout the whole system. The system is composed of the ground under the structure of length L , and the ground outside the structure over a length of $5L$. It is assumed that the displacement of the ground at a distance of $5L$ from the structure is zero, this distance being

375 infinite in the case of an analytical solution. The length 5L was chosen after numerous tests, as a
 376 reasonable compromise to obtain a satisfactory solution without an excessive computation time.

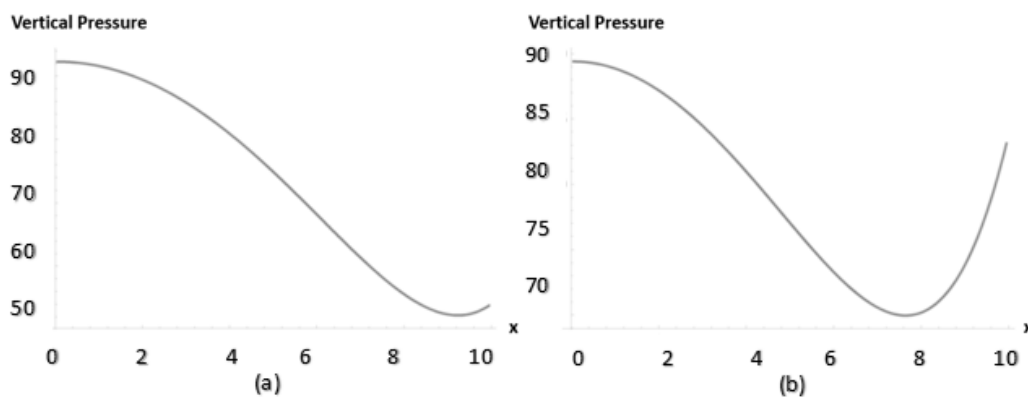
377 A preliminary example according to the Pasternak model has been applied and results show an
 378 inconsistency and a discontinuity in the values of the punctual forces at the building edges. According
 379 to the simulations evaluated by Mathematica, the soil reaction is concentrated in the two punctual
 380 forces generated at the building extremities. The value of F is significantly higher than the total sum
 381 of the reaction $p(x)$ distributed under the building (Figure 8) which confirms the necessity of adding a
 382 limitation of the maximum punctual forces admissible at the building extremities. To do so, the shear
 383 modulus G_p is modified locally as per Eq. (12) so that the formula of the punctual force F shown in
 384 Figure 8 is limited by multiplying it by a coefficient α .

$$F_{lim} = \alpha G_p (w'(x) - w'_1(x)) \quad (12)$$

385 The criterion of validation of the results is the verification of the stability of the system (statistical
 386 equilibrium of the system) for each iteration, **as per the following equation:**

$$qL = \int_{-L/2}^{L/2} p(x) + 2F \quad (13)$$

387 As shown in Figure 13, it is found that, without plasticity, the soil reaction $p(x)$ decreases with the
 388 increasing values of x toward the beam edges where the punctual force F is located. However, after
 389 considering the influence of plasticity, the $p(x)$ decreases at the beam center and increases at the beam
 390 edges in comparison with the first case. These results confirm the statistical balance and the
 391 equivalence between the sum of the reactions of $p(x)$ and F from one side and the loads applied to the
 392 beam from the other side.



393

394 Figure 13. Vertical pressure along the half beam (a) without plasticity; (b) with plasticity.

395 In order to find the exact value of F_{lim} , the parameter α is varied from 0.1 to 0.7 with a step of 0.1 to

396 find the suitable value of F where the sum of the soil reaction $p(x)$ and F is exactly equal to the loads

397 applied to the beam. The results obtained showed that a value of $\alpha= 0.4$ seems to be the most adequate

398 for the Basmaji et al. (2017) example shown in Figure 12.

399 However, even-though the elastoplastic soil conditions can be integrated to the Pasternak model, the

400 applied procedure presents several difficulties since the coefficient α has to be evaluated for every

401 case separately and to check the system stability and the equivalence between the sum of the reactions

402 and the applied loads by varying the value of α progressively. Thus, the process of integrating

403 elastoplastic conditions to the Pasternak model is time consuming and presents difficulties to be

404 generalized. Since the objective is to propose a ‘generalized’ meta-model that integrates the soil

405 elastoplasticity, this paper will proceed by considering the Deck & Singh (2010) Winkler model

406 combined with Vesic (1963) formula.

407 3.3. Validation with finite-element models

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409 Based on the elastic finite element model explained previously, a new elastoplastic model is

410 developed on Plaxis 2D. This model consists of dividing the soil into two layers; the upper layer of

411 thickness $h_1 = 100$ m is modelled as elastoplastic with a Mohr–Coulomb criterion, whereas the lower

412 layer of thickness $h_2 = 25$ m is assumed to be elastic. The function of the upper layer is to represent

413 the elastoplastic conditions with a cohesion and a friction angle that vary with respect to p_{ult} value

414 determined by the Terzaghi formula:

$$p_{ult} = cN_c + 0.5B\gamma_1N_\gamma + (q + \gamma_2D)N_q \quad (14)$$

415 with γ_1 the soil density under the foundation, γ_2 the soil density lateral to the foundation, q the lateral

416 vertical overload to the foundation, c the cohesion of the soil under the base of the foundation, B the

417 width of the foundation, D the embedment depth of the foundation and N_c , N_q , N_γ the bearing

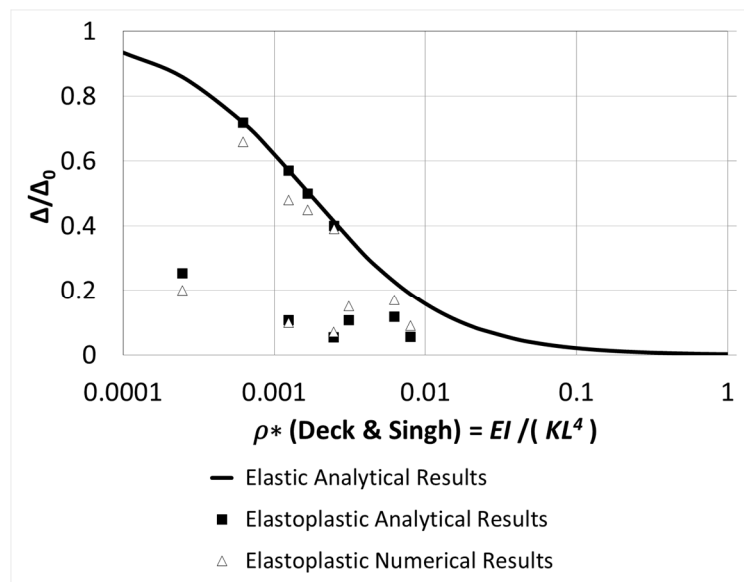
418 capacity factors.

419 The function of the lower layer ($h_2 = 25$ m) is to avoid large deformations and large mass losses that

420 occur near the lower limit due to the fact that such a loss could compromise the convergence of

421 calculations and the accuracy of results; also stress-strain results are only interpreted for the upper
 422 ground layer. Considering an elastoplastic soil layer in contact with the building, a sliding interface is
 423 modelled between the ground and the structure in order to investigate only the influence of the ground
 424 curvature and not the influence of horizontal strains and the associated shear stresses induced by the
 425 subsidence. The same boundary conditions are applied and the model is realized in three stages as for
 426 the elastic case.

427 The set of 10 finite-element models that were generated for the elastic conditions are evaluated for
 428 elastoplastic conditions considering a particular value of the bearing capacity p_{ult} (cohesion and
 429 friction angle as per Eq. (14)) for every case. The numerical results presented in Figure 14 are
 430 superimposed with the elastoplastic analytical results of the same considered combinations of the SSI
 431 parameters (same p_{ult} , EI, K, L, q and Δ_0 values) for the transmission ratio calculated with the Deck &
 432 Singh (2010) Winkler model combined with Vesic (1963) formula. Consequently, the analytical
 433 methodology developed to consider the soil elastoplastic behavior is validated numerically and can be
 434 used to predict the value of the elastoplastic transmission ratio $(\Delta/\Delta_0)_{Elastoplastic}$.



435
 436 Figure 14. Results of the comparison between analytical and numerical results of the deflection
 437 transmission ratio.

438 3.4. Reduction coefficient

439
 440 In order to study the effect of soil plasticity on the transmission ratio Δ/Δ_0 , the elastoplastic analytical
 441 model was evaluated using Mathematica, by investigating 18,900 possible combinations of p_{ult} , EI, K,

442 L, R and q, as shown in Table 1.

443 The building length is taken between 10 and 30 m to model small and intermediate buildings [8]. The
444 beam loading represents the building self-weight and service loading. 100 kN/m is approximately the
445 weight of a 5 m high wall with a thickness of 0.5 m with service loading, 200 kN/m is approximately
446 the weight of a 10 m high wall with a thickness of 0.5 m and 400 kN/m is about the weight of a whole
447 building with three 5 m tall walls with a thickness of 0.5 m including service loading.

448 The beam bending stiffness EI is between 20 and 500 GN.m². The smallest value represents the
449 stiffness of a 0.5 m masonry wall thickness with 5 m height and a 3000 MPa equivalent Young's
450 modulus for the masonry. The largest value represents the stiffness of a 0.2 m thick concrete wall, 12
451 m tall with a 20000 MPa equivalent Young's modulus.

452 The ground stiffness values vary between 20 and 500 MPa, according to Eq. (6), for values of soil
453 Young modulus between 40 MPa (soft ground) and 500 MPa (stiff ground) and a Poisson's ratio of
454 0.3. The free-field ground radius of curvature is set between 250 and 5000m to represent a wide range
455 of scenarios [7].

456 Considering that the structures are usually constructed with shallow foundations of length L and width
457 B with $L \gg B$, the bearing capacity can be obtained by Terzaghi's formula which depends essentially
458 on the angle of internal friction and the cohesion of the ground under the foundation. To show the
459 essential role that the limitation of the soil bearing capacity can have on the deflection of the building,
460 the soil bearing capacity is considered variable between q and 4 q. Nevertheless, given the partial
461 safety factors used in construction codes (Eurocode, etc.) for the design of the foundations at the
462 Ultimate and Serviceability Limit States ULS and SLS (1.35 or 1.5), the considered cases ($p_{ult} = Xq$
463 with $X = 1, 1.5, \dots, 4$) can be representative to approximate to standard situations [4].

464

Table 1: Model Parameters.

Symbol (Unit)	Description	Values
$L(m)$	Beam Length	10, 20, 30
$q(KN/m)$	Beam Load	100, 200, 300, 400
p_{ult}	Soil Bearing Capacity	$q, 1.5q, 2q, 2.5q, 3q, 3.5q, 4q$
$EI(GN.m^2)$	Beam Stiffness	20, 50, 100, 250, 500
$K(MPa/m)$	Ground Stiffness	20, 50, 100, 250, 500
$R(m)$	Free-Field Ground Radius of Curvature	250, 500, 750, 1000, 1500, 2000, 3000, 4000, 5000

465

466 Based on the results shown in Figure 15 for the 18,900 investigated combinations, a new relation can
467 be proposed for the elastoplastic deflection transmission ratio using a reduction coefficient "a" as
468 follows:

$$\frac{\Delta}{\Delta_0}(\text{Elastoplastic}) = a \frac{\Delta}{\Delta_0}(\text{Elastic}) \quad (15)$$

469

$$\text{With } 0 \leq a \leq 1$$

470 If $a=1$, p_{ult} is not reached with the soil still in the elastic range, and there is no difference between
471 considering an elastic or an elastoplastic soil behavior. However, when "a" decreases below 1, p_{ult} is
472 reached. In order to establish a new correlation that evaluates "a" as a function of p_{ult} , q , R , K , EI and
473 L , the influence of every factor on "a" is evaluated and presented in Table 2.

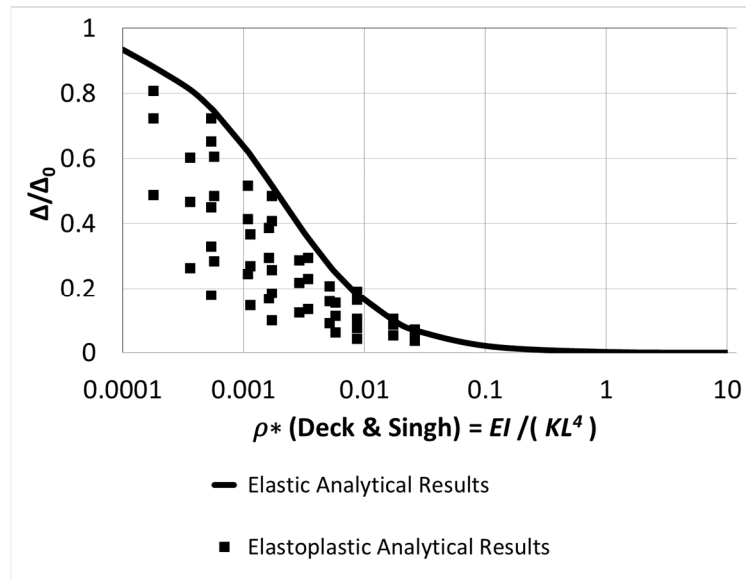
474

Table 2: Effect of every increasing factor on a.

Factor	Comments	a
$p_{ult} \uparrow$	The soil does not reach the plastic phase and behaves as an elastic soil.	\uparrow
$q \uparrow$	Due to static equilibrium, the soil reaction $p(x)$ increases and may reach p_{ult} at a certain position under the structure.	\downarrow
$R \uparrow$	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.	\uparrow
$K \uparrow$	The soil reaction increases as per Winkler formula and becomes closer to p_{ult} .	\downarrow
$EI \uparrow$	The building has more stiffness and can sink in the soil which will increase the soil reaction until reaching p_{ult} .	\downarrow
$L \uparrow$	The structure is more flexible and the soil reaction under the structure is more homogeneous and exceeds less often p_{ult} .	\uparrow

475

476 After evaluating 18,900 combinations (Table 1) and calculating Δ/Δ_0 for an elastic and an elastoplastic
477 soil behavior, a new correlation (Eq. (16)) is proposed for the reduction factor "a" using artificial
478 neural networks via JMP software which is a software used for statistical analysis.



479

480 Figure 15: Deflection transmission ratio Δ/Δ_0 versus the relative stiffness ρ^* for elastic/elastoplastic
 481 behavior of soil for various soil bearing capacities.

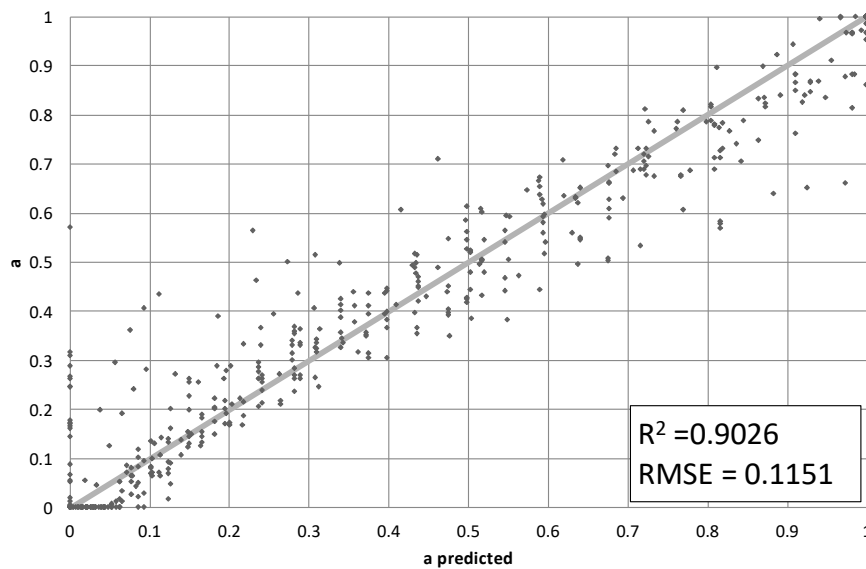
482 To obtain the analytic expression of a, several data analyzes were performed. Attempts to express this
 483 parameter by various combinations of the model input parameters have not lead to satisfactory results.
 484 For this reason, the technique of neural networks has been used [4, 31].

485 The artificial neural network is composed of a collection of artificial neurons by computing a
 486 weighted sum of the inputs (18,900 combinations of p_{ult} , q , R , K , EI and L). Many variations exist in
 487 the way neurons are organized into a network, but all neural networks are composed of multiple
 488 layers; an input layer, an output layer, and intermediate layers, called hidden layers. The proposed
 489 model seeks to match the relationship between the obtained values of Δ/Δ_0 and the inputs. For good
 490 generalization performance, a balance must be found between an artificial neural network with
 491 insufficient neurons that miss trends, and an artificial neural network with too many neurons that
 492 suffer from over fitting to the training data. The latter occurs when the minimization procedure tunes
 493 the weights in such a way that it almost perfectly captures the provided data, but is inaccurate when
 494 applied to new data, not used in the training procedure. To detect over fitting, the data is divided into
 495 three sets: a training, validation and test set. The network is built with a validation rate of 0.1 meaning
 496 that a proportion of 10% is therefore retained for validation. The final network obtained is composed
 497 of one layer and 3 neurons H1, H2 and H3 evaluated by minimizing the variance of the residues (Eq.
 498 (16)).

$$a = -7.19258 - 0.97155H1 - 0.52479H2 - 8.10706H3 \quad (16)$$

$$H1 = \text{TanH} \left(0.5 \begin{pmatrix} -5.55733 \\ +0.00045K_w \\ -0.00062R \\ +0.00037q \\ +0.00040p_{ult} \\ +0.20247L \\ +0.010897EI \end{pmatrix} \right); H2 = \text{TanH} \left(0.5 \begin{pmatrix} 44.10233 \\ +0.02106K_w \\ -0.00035R \\ +0.00033q \\ -0.00102p_{ult} \\ -1.77733L \\ -0.076137EI \end{pmatrix} \right); H3 = \text{TanH} \left(0.5 \begin{pmatrix} -2.44438 \\ +0.000078K_w \\ +0.000071R \\ +0.001837q \\ -0.001939p_{ult} \\ -0.009696L \\ -0.001588EI \end{pmatrix} \right) \quad (17)$$

499 Figure 16 shows the actual values as a function of the expected values of the coefficient a. Thus, it is
500 possible to visualize the residues. The coefficient of correlation is $R^2 = 0.9026$ and the root mean
501 square error (RMSE) is relatively low (0.12). Figure 16 shows that the formulation of “a” has a
502 general tendency to overestimate the large values of “a” and to underestimate the small values of “a”.



503

504

Figure 16: Graph of observed values versus expected values.

505 It should be noted that the network has been reconstructed with other values of the validation rate (0.2
506 and 0.3) and the results are roughly the same, the RMSE is always close to 0 and it slightly increases
507 with the increase of this rate. Thus, results show that the application of Eq. (16) can approximate the
508 influence of plasticity when evaluating the transmission ratio. Consequently, this correlation can be
509 directly adopted by the engineering society for design purposes to approximate the Δ/Δ_0 value when
510 considering the elastoplastic behavior of the soil.

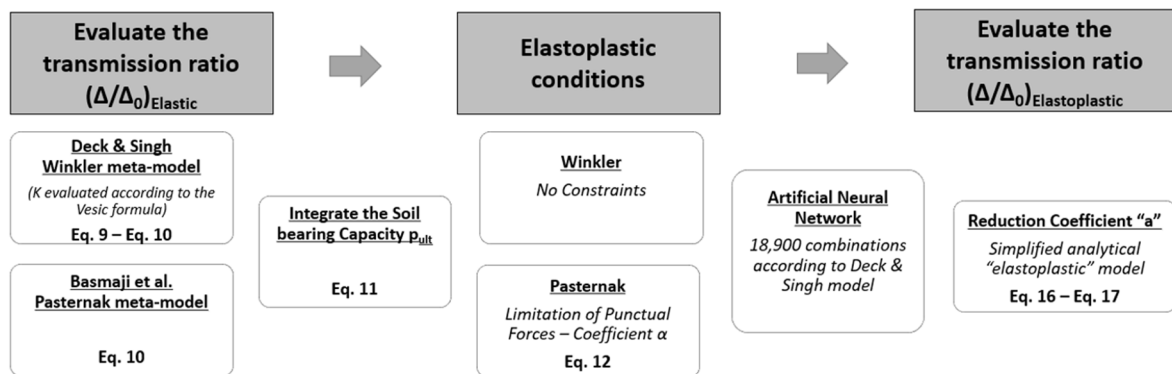
511 4. Conclusions

512

513 This paper presents a new correlation to incorporate the elastoplastic soil behavior when evaluating

514 the transmission of ground movements to structures induced by tunneling and mining subsidence.
 515 Based on the SSI analytical elastic approaches that are based on Pasternak and Winkler models, a new
 516 methodology is implemented that consists of limiting the soil reaction to its bearing capacity in order
 517 to consider soil elastoplastic conditions.
 518 As shown in Figure 17, simplified equations are initially proposed to evaluate the elastic transmission
 519 ratio $(\Delta/\Delta_0)_{\text{Elastic}}$ for (a) Deck & Singh (2010) Winkler model coupled with Vesic formula and (b)
 520 Basmaji et al. (2017) Pasternak approaches. **These two approaches are validated by elastic numerical**
 521 **finite element models and numerical, experimental and field data results from previous research.**
 522 Then, the influence of soil plasticity on the transmission ratio Δ/Δ_0 is investigated by integrating the
 523 soil bearing capacity p_{ult} . Results show a significant difference in the transmission ratio between the
 524 elastic and the elastoplastic soil behavior. The elastic behavior results create an envelope that engulfs
 525 the elastoplastic results.

Evaluate the transmission of ground movements to structures integrating the elastoplastic soil behavior



526

527 Figure 17: Methodology of evaluation of the new simplified meta-model to calculate the transmission
 528 of ground movements to structures integrating the elastoplastic soil behavior.

529 On one hand, the proposed procedure applied for Pasternak model shows an inconsistency and a
 530 discontinuity in the values of the punctual forces at the building edges. Thus, a coefficient α is
 531 imposed to modify the shear modulus G_p locally and limit the maximum admissible punctual forces.
 532 To find the value of α , it is required to check the statistical balance and the equivalence between the
 533 sum of the reactions and loads applied to the beam for every combination. Thus, the proposed
 534 procedure applied for Pasternak model is time consuming and presents difficulties to be generalized.

535 On the other hand, the proposed procedure applied for Winkler model (Deck & Singh model coupled
536 with Vesic formula) does not show constraints and is validated by finite element-models.
537 Based on Deck & Singh Winkler model, a new meta-model is proposed that associates the elastic with
538 the elastoplastic results of the transmission of the ground movement ($(\Delta/\Delta_0)_{\text{Elastoplastic}}$); the statistical
539 meta-model is realized using artificial neural networks based on 18,900 combinations of SSI
540 parameters and soil bearing capacities p_{ult} . A reduction coefficient “a” is proposed to associate the
541 elastic ($(\Delta/\Delta_0)_{\text{Elastic}}$) with the elastoplastic ($(\Delta/\Delta_0)_{\text{Elastoplastic}}$) transmission ratios.
542 In conclusion, to improve the investigation of the structure response to ground movements and the
543 evaluation of its damage, the effect of a significant SSI factor, the soil elastoplastic behavior, can be
544 directly evaluated via the proposed simplified meta-model that is based on the elastic values of $(\Delta/\Delta_0)_{\text{Elastic}}$.
545 To reduce time and calculation difficulties, this paper proposes simple equations (as shown in
546 Figure 17) that are sufficient and can be directly used by geotechnical engineers and designers to
547 consider the elastoplastic soil behavior and evaluate transmission of ground movements to structures.

548 **Acknowledgment**

549
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621

622

Graphical Abstract

Evaluate the transmission of ground movements to structures integrating the elastoplastic soil behavior

