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Sensitivity Analysis of Nonlinear Response of Buildings Subjected to an Adjacent Un-braced Excavation via Fully Coupled FEM

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ABSTRACT

In this paper the nonlinear and fully coupled soil-structure interaction (SSI) response of building structures subject to nearby un-braced excavation is examined via a fully coupled Finite Element Method (FEM) utilising partitioned approach. The problem under consideration represents a typical urban situation, where ground excavation can often induce significant movements and damage to nearby structures. This study, analyses the response sensitivity of steel frame resting on flexible soil subjected to ground excavation, where nonlinear elasto-plastic constitutive behaviour of the soil, as well as both geometric and material nonlinearity of the structure, are taken into account. The results demonstrate the fully coupled SSI response both in soil and structure sub-domains as well as the response sensitivity to various scenarios with respect to the applied loading to the structure, the excavation depth (He) and the distance of the structure from the excavation wall (Le). Furthermore, the results highlight the merits of the used fully coupled soil-structure model in providing effective and realistic predictions towards minimizing the associated structural damage in such problems.

1. Introduction

As a consequence of development of urban areas, excavations and open cuts adjacent to existing structures are rapidly growing in number due to both the limitations on availability of space and also the need for construction of new structures. This denotes a common problem that in principle involve making suitable decisions in terms of response prediction by both the structural and geotechnical engineers. In this respect, damages to buildings/structures nearby excavation sites are still occasionally reported despite the advances in construction and design procedures employed (Tung-Chin, 2012). Obviously, the favourable outcome of an excavation work would in principle necessitate guaranteeing the safety and serviceability of not only the excavation but also the adjacent structures (O'Rourke *et al.*, 1977; Clough and O'Rourke 1990; Burland, 1995, Boone, 1996; Boone, 2008, Tung-Chin 2012). Indeed, this characterizes

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a nonlinear Soil-Structure Interaction (SSI) problem, in which the ground movements induced by the excavation could inadvertently affect the functionality and/or safety of adjacent structures behind the excavation wall. The main challenges in the design stage of such SSI problems are due to the great extent of uncertainty of SSI conditions especially geotechnical parameters (Tung-Chin 2012) and also the necessity and complexity of fully coupled modelling of the SSI phenomenon.

In this respect, the response evaluation of the associated damage to nearby buildings is well connected to the excavation-induced deformation state in the adjacent structures (Boone, 2001; Son and Cording, 2005). Indeed, in practice, the excavation-induced deformation state in the structure would normally be the controlling factor in the design stage often referred to as serviceability-based design (Son & Cording, 2005; Aye *et al.*, 2006; Boone *et al.*, 1999; Seok *et al.*, 2001, Tung-Chin 2012).

Response prediction of excavations has been explored by various researches such as the work done by Kung *et al.* (2007), Wong and Brom (1989), Ou *et al.* (2000), Ou *et al.* (1998) and Finno *et al.* (2002);. Accordingly, the excavation-induced damage of adjacent structures has also been the focus of several works such as the researches by Son and Cording (2005), Boscardin and Cording (1989), Boone (1996) and Schuster *et al.* (2009). As mentioned before the fundamental requirement of such studies is the evaluation of the deformation state of the structure. Accordingly, SSI excavation problem has been studied by means of numerical and FEM analysis by various researchers namely; Potts and Addenbrooke (1997), Burd *et al.* (2000), Hsieh *et al.* (2003), Finno *et al.* (2002), Kung *et al.* (2007).

Numerical analysis, typically using the finite element method (FEM), is currently the most advanced tool available to facilitate such soil-structure interaction analysis. Notwithstanding the noteworthy improvements made in FEM modelling of such problems; further improvement is still needed for better simulation of the excavation-induced building response. Most cases that have been analysed so far have used field elimination and rarely a fully coupled nonlinear treatment. This usually means that structural analysis simplifies soil behaviour, while geotechnical analysis simplifies structural behaviour using field elimination techniques. It is therefore a real challenge to achieve the same amount of sophistication in nonlinear modelling of both the soil and the structure in a single soil-structure interaction analysis. In this respect, this paper adopts the fully coupled partitioned FEM approach proposed by Jahromi *et al.* (2009) and Jahromi *et al.* (2007) for nonlinear response modelling of buildings subjected to an adjacent un-braced excavation. The study under consideration in this paper represents the aforementioned typical urban situation, where ground excavation can often induce significant movements and damage to the nearby structures. The study, analyses the response sensitivity of steel frame resting on flexible soil subjected to ground excavation, where nonlinear elasto-plastic constitutive behaviour of the soil, as well as both geometric and material nonlinearity of the structure, are taken into account. The results highlight the fully coupled nonlinear response both in soil and structure sub-domains as well as the response sensitivity to various action scenarios with respect to the applied loading to the structure, the excavation depth (He) and the distance of the structure from the excavation wall (Le).

It is shown that by utilizing a fully coupled FEM soil-structure interaction model using the partitioned/domain decomposition treatment (Jahromi *et al.*, 2008; Jahromi *et* *al.* 2009), such nonlinear behaviour of both structure and soil could be accurately captured to the desired degree of accuracy. Besides, the results highlight the merits, and the high potential of using a fully coupled nonlinear FEM soil-structure model towards providing effective and realistic evaluation in prediction of the associated damage.

2. Fully Coupled FEM Modelling of SSI

In the fully coupled FEM modelling of SSI via partitioned treatment, the partitioned sub-domains of the coupled mechanical system (i.e. soil and structure) are computationally treated as isolated entities, and the response of the coupled system is calculated using already developed solvers (Figure 1). A partitioned treatment with different partitioned sub-domains modelled as separate computational entities, amongst which interaction effects are exchanged, can offer major benefits in the context of nonlinear soil-structure interaction. Such benefits include i) allowing field-specific discretisation and solution procedures that have proven performance for each partitioned sub-domain, ii) facilitating the reuse of existing nonlinear analysis solvers with all the resource savings that this brings, and iii) enabling parallel computations through problem partitioning (Jahromi *et al.* 2007; Jahromi *et al.* 2009; Lai, 1994; Felippa *et al.*, 2001).

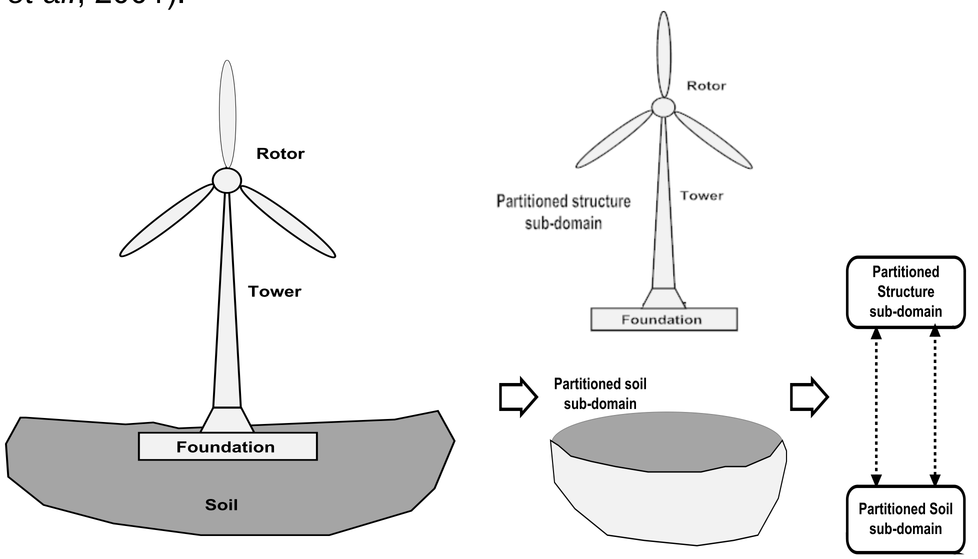


Figure 1: Fully coupled FEM modelling of SSI via partitioned treatment

The simulation of soil-structure interaction via the partitioned approach is carried out in this work through the coupling of two powerful FEM codes, ADAPTIC (Izzuddin, 1991) and ICFEP (Potts and Zdravkovic, 1999) that have been developed at Imperial College London for advanced nonlinear structural and geotechnical analysis, respectively. The proposed solution scheme couples the response of the partitioned and independently modelled soil and structure sub-domains by enforcing explicitly compatibility and equilibrium conditions at the interface through successive iterations as shown in Figure 2 (Jahromi *et al.* 2007).

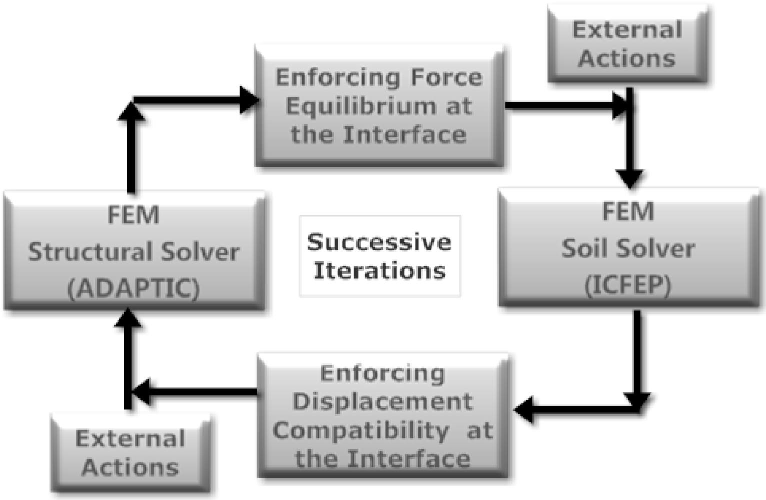


Figure 2: Schematics of the SSI Simulation Environment

3. Building Response to an Adjacent Excavation

The case under consideration in this section represents a typical urban situation, where ground excavation can often induce significant movements and damage to the nearby structures. It is shown that by utilizing a fully coupled soil-structure interaction model using the partitioned treatment, such nonlinear behaviour of both structure and soil could be accurately captured. This shows the high potential of using a fully coupled soil-structure model towards providing reliable assessment and minimizing the associated damage in such problems.

The example considers a steel frame resting on a soil subjected to ground excavation, where nonlinear elasto-plastic constitutive behaviour of the soil, as well as geometric and material nonlinearity of the structure, are taken into account. Figure 3a depicts the problem, where the left hand side boundary is assumed to be consistent with an axis of symmetry. The plan view of the analysed building frame and the geometric configuration of considered frame are also shown in Figures 3b and 3c respectively.

The soil-structure interaction analysis is carried out assuming plane strain conditions in the soil using an effective out-of-plane width of 1m, where the aforementioned partitioned approach is employed utilising ADAPTIC and ICFEP. The considered soil-structure system is partitioned physically into two sub-domains, soil and structure, where each sub-domain is discretised separately according to its characteristics as shown in Table 1.

The frame structure is modelled with ADAPTIC using cubic elasto-plastic beam-column elements (Izzuddin & Elnashai, 1993) using 10 elements per member for both columns and beams, and the material behaviour is assumed to be bilinear elasto-plastic with kinematic strain hardening. The footings are discretised using 4 elements per member.

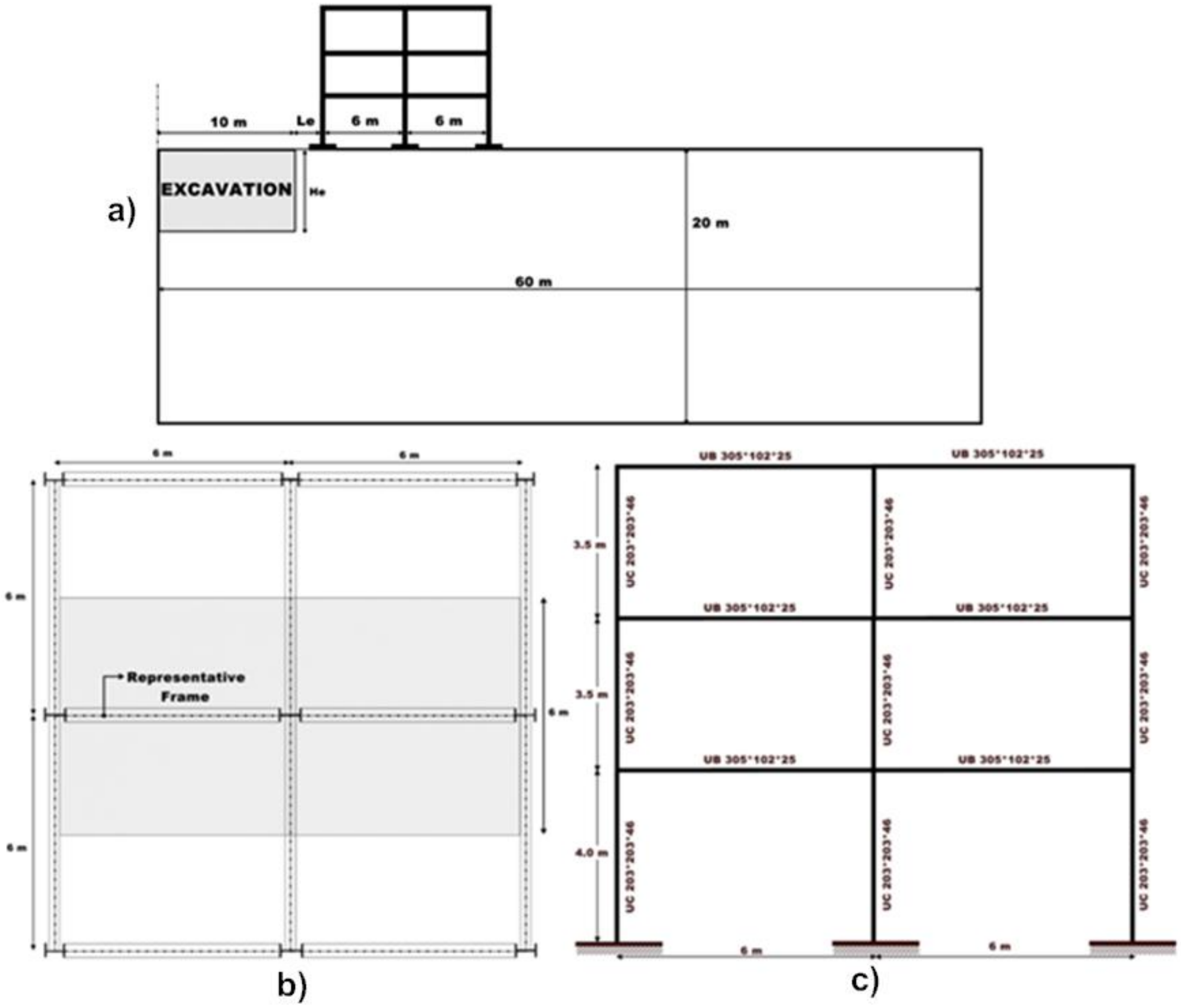


Figure 3: SSI case overview a) Plane frame resting on soil subject to ground excavation b) Plan view of considered building c) Geometric configuration of considered frame

The soil sub-domain and the un-braced excavation are modelled with ICFEP using an elasto-plastic Mohr-Coulomb constitutive model, with parameters chosen to represent the behaviour of London clay (Table1). The nonlinear solution procedure employed for analysing the soil sub-domain is based on a Modified Newton-Raphson technique, with an error controlled sub-stepping stress point algorithm.

The soil continuum is discretised using 8-noded isoparametric quadrilateral elements. The interface degrees of freedom are assumed to be at nodes that belong to both the footings and soil underneath. The total number of interface degrees of freedom is 30 for this case. The above problem is analysed for various scenarios with respect to the loading applied to the structure (which is assumed to be loaded equally on each floor with a total gravity load equal to $\lambda \times 5$ kN/m2), the excavation depth (He) and the distance of the structure from the excavation wall (Le).

Structure Sub-domain	Material Properties
All beams and columns (steel)	Steel Grade = S355 Elastic Modules = 210 GPa Strength = 355 MPa Bilinear elasto-plastic with strain Hardening Factor =1%
Foundation Beam (concrete)	Elastic Modulus = 30 GPa Linear material Size: 2m×0.5m
Soil Sub-domain	**Material Properties**
Soil and excavation	Angle of Shear resistance $(\Phi') = 22^{\circ}$ Dilation angle $(\nu') = 11^{\circ}$ Effective out of plane depth = 1m Cohesion = 20 kPa Young's modulus varies linearly with depth from 10000 kPa at the ground surface (dE/dZ=5000 kPa/m) Excavation width=20m He (excavation depth) (=1, 2, 3, 4, 5, 6, 7, 8, 9, 10 (m) Le (distance from the structure =2, 4, 6, 8, 10 (m) Elasto-plastic Mohr-Coulomb constitutive model

Table 1: Geometric and material properties of the partitioned soil-structure system

4. Case Scenarios: Loading and Excavation Sequences

Table 2 lists various loading scenarios considered for analysing the above problem with respect to the load factor (λ) applied in structure sub-domain, and the excavation depth (He) in the soil sub-domain. Considering Table 2, the loads on the structure are applied in the first six increments, and from increment 7 to 16 the soil is excavated while the loading in the structure is assumed to be constant.

Model Case	Increment number of the coupled analysis (16 increments in total)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	values for λ (no excavation)						Values for He (m) (λ=constant)									
Case 1	1	1	1	1	1	1	1	2	3	4	5	6	7	8	9	10
Case 2	1	2	2	2	2	2	1	2	3	4	5	6	7	8	9	10
Case 3	1	2	3	3	3	3	1	2	3	4	5	6	7	8	9	10
Case 4	1	2	3	4	4	4	1	2	3	4	5	6	7	8	9	10
Case 5	1	2	3	4	5	5	1	2	3	4	5	6	7	8	9	10
Case 6	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10

Table 2: Case scenarios

5. Ground Surface, Excavation Wall and Vertical Settlement Displacement Pattern: Effect of Structural Loadings

The vertical displacement of the ground surface for the various case scenarios is depicted in Figure 4, where it is assumed Le=2m.

Figures 4a, 4b and 4c, show the vertical settlement at the centre of the left, middle and right footings of the analysed frame (see Figure 3a), respectively, for the various loading scenarios, where it is assumed Le=2m. Although a common practice in estimating the ground movement adjacent to an excavation is to regard both the settlement of the ground and the building as identical to avoid complications in geotechnical analysis, considering the footing settlements depicted for various cases in Figures 4a, 4b and 4c, it is clear from Figure 5b that these are considerably underestimated by the free field response. The effect of the structural loads on the horizontal displacement of the excavation wall is also depicted in Figure 5a. It is a consequence of these lateral ground movements that the structure undergoes additional settlements due to its weight.

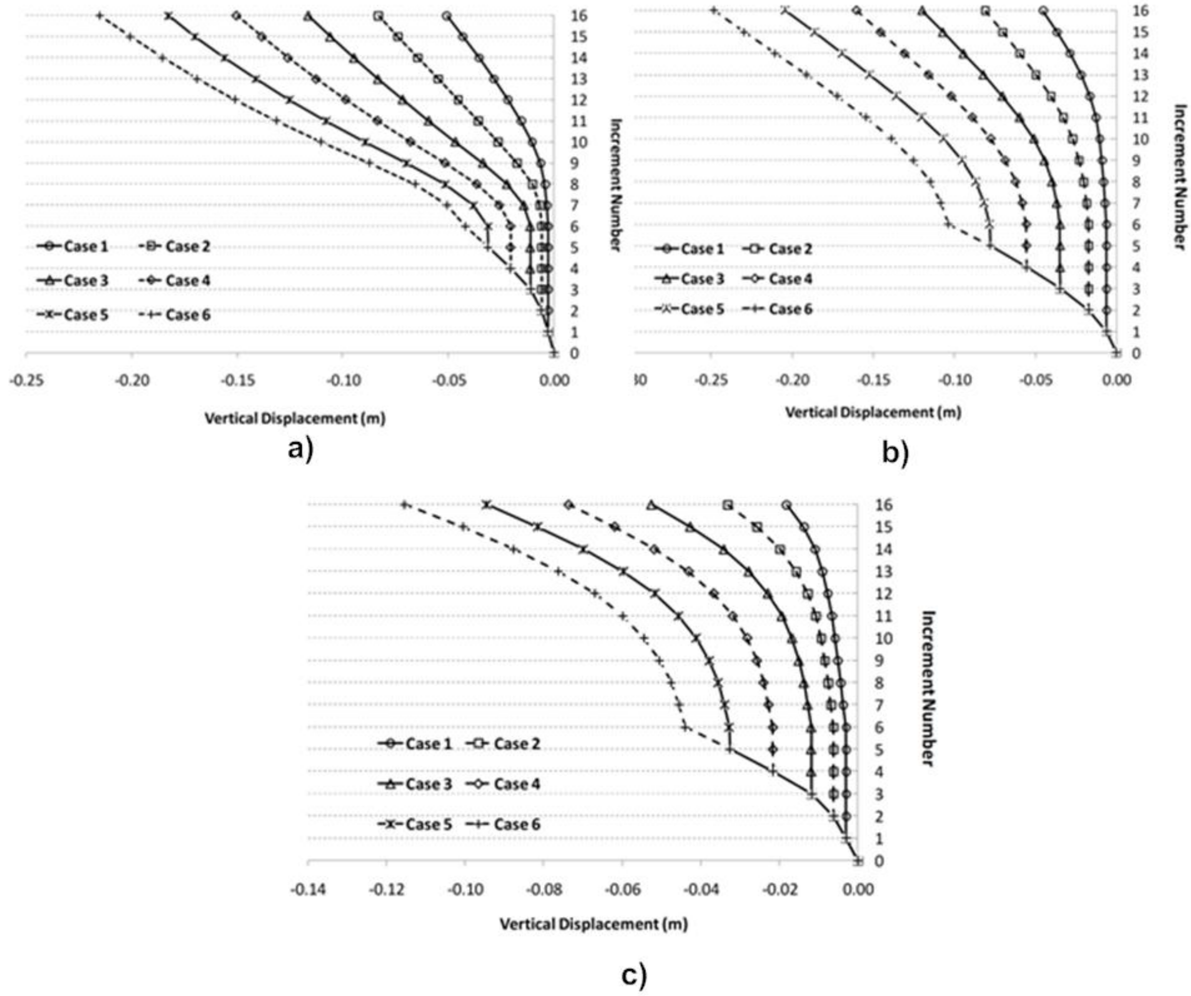
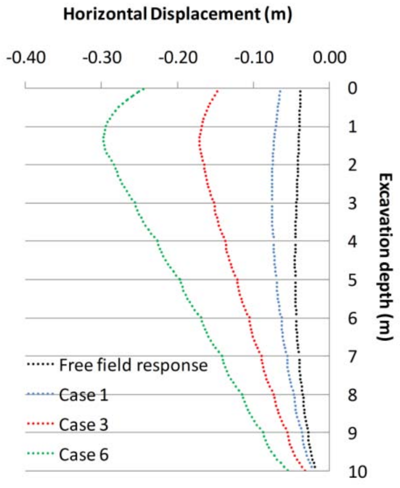
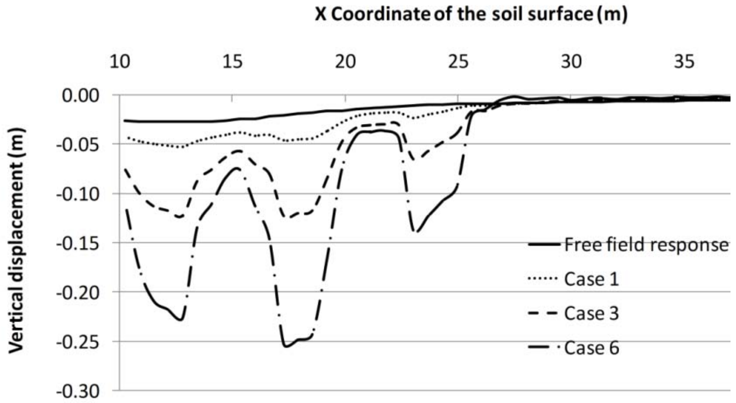


Figure 4: Vertical settlement of a) the left footing, b) middle footing and c) the right footing for different load cases



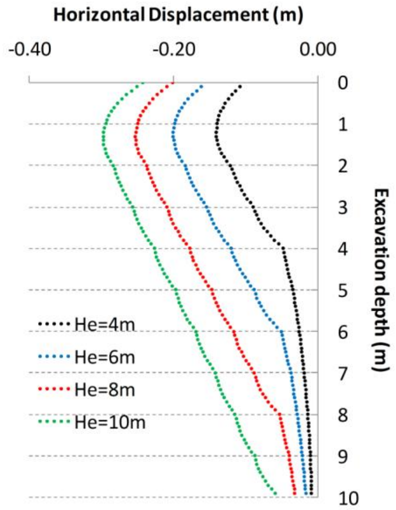


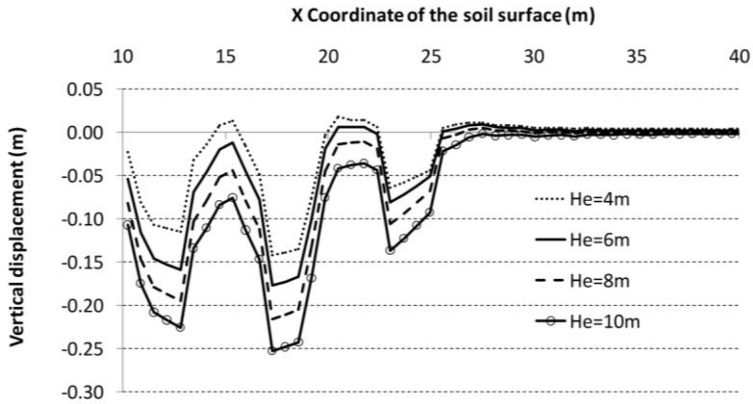
a) **b)**

Figure 5: Cumulative a) horizontal displacement of the excavation wall and b) vertical displacement of the ground surface for the last increment

6. Ground Surface, Excavation Wall Displacement Pattern: Effect of the Excavation Depth (He)

The effect of the excavation depth on the vertical deformation profile of the soil surface and the horizontal displacement of the excavation wall is also depicted in Figures 6a and 6b, respectively, for Case 6 (Table 2).





a) **b)**

Figure 6: Cumulative a) Horizontal displacement of the excavation wall and b) vertical displacement of the ground surface for different excavation depths (Case 6)

7. Vertical Settlement Displacement Pattern: distance of the structure from the excavation (Le)

The effect of distance of the structure from the excavation (Le) on the vertical settlements of the footings is also depicted in Figures 7a, 7b and 7c for model Case 6.

As expected by increasing Le the additional settlements of the structure due to the excavation decreases. The results further emphasise the importance of using a fully coupled soil-structure interaction analysis for such cases.

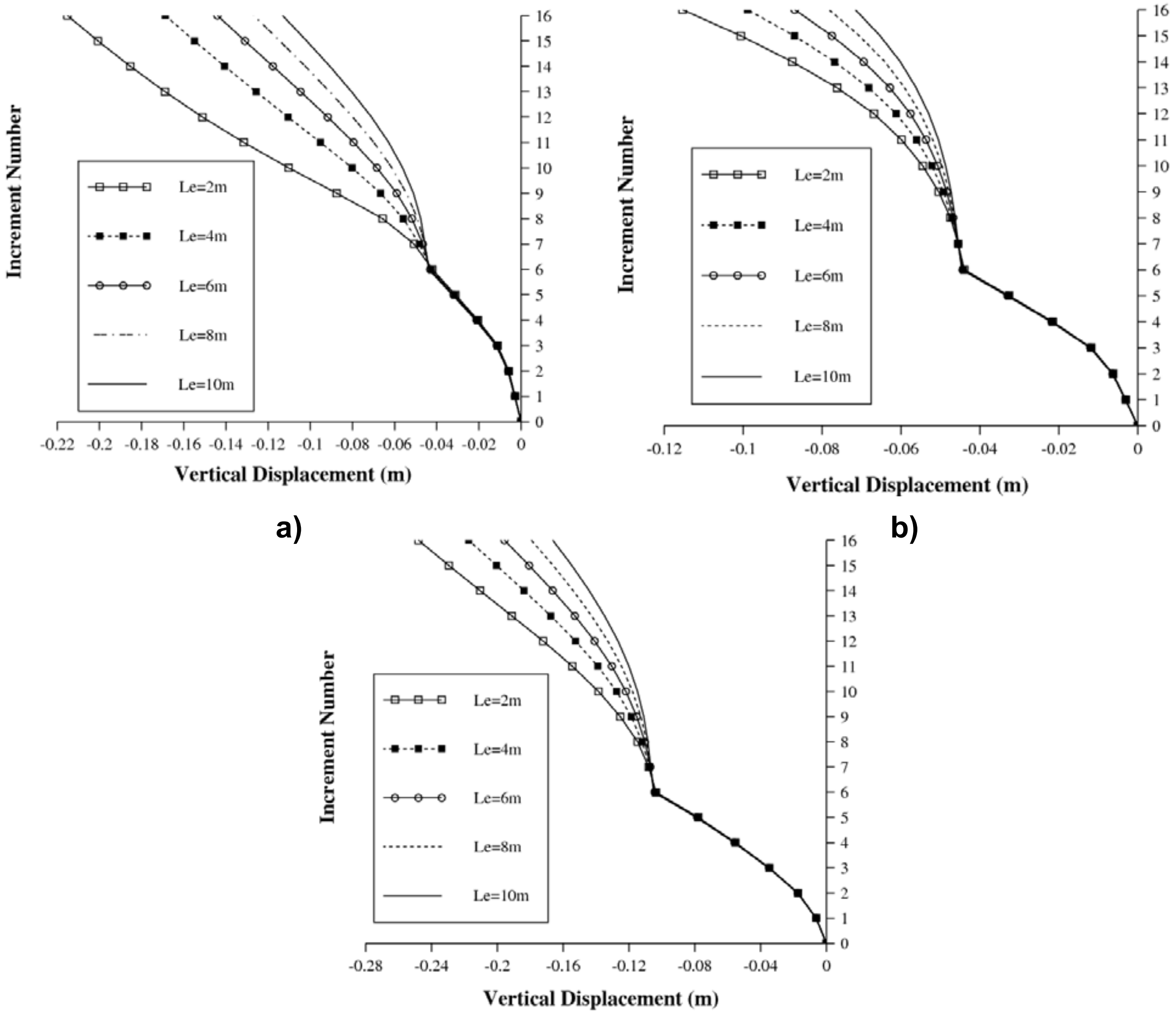


Figure 7: Vertical settlement of a) the left footing, b) middle footing and c) the right footing for different Le (Case 6)

The benefits of the Fully Coupled FEM analysis practical assessment of nonlinear soil-structure interaction problems is further demonstrated by considering the results obtained for Case 6. In this regard, vector plots of displacements in the soil sub-domain in the vicinity of the structure and excavation for increment number 6 (before excavation) and increment 12 (after excavation He=6m) are shown in Figures 8 and 9, respectively.

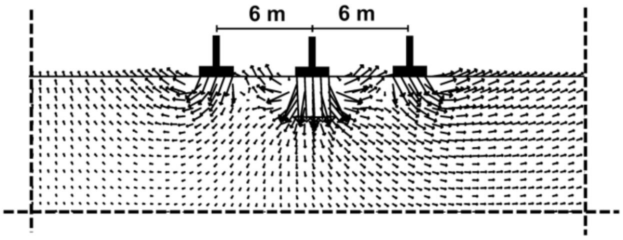


Figure 8: Vectors of displacement in soil sub-domain in increment 6 (Case 6)

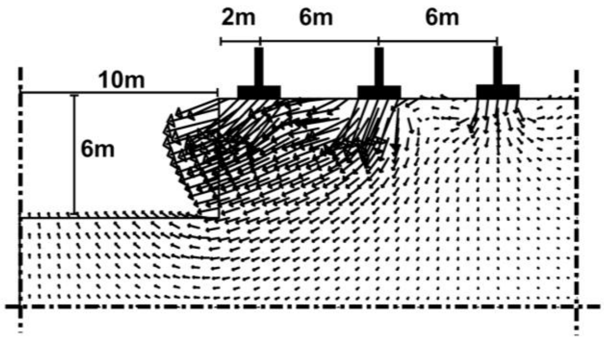


Figure 9: Vectors of displacement in soil sub-domain in increment 12 (Case 6)

7. Associated Damage

The corresponding deformed shape and bending moment variation in the structure sub-domain for different increments are also shown in Figure 10a and 10b respectively. It can be clearly observed that the maximum bending moments of the structural elements after the excavation are significantly higher than before the excavation as shown for four selected regions A, B, C and D, as shown in Figure 10b, It is evident from the deformed shape of the structure after excavation and also from the vectors underneath each of the three footings that after 6m of excavation the footings experience rigid tilting and significant vertical settlements. However, the footing nearest to the excavation has the smallest tilting, as its deformation is also dominated by the horizontal movement towards the unsupported excavation. It is worth mentioning that the structure may be damaged when the excavation-induced differential settlement is larger than the tolerable value, which is merely equal to 25-30 mm2 (Tung-Chin, 2012).

As mentioned before, the evaluation of the associated damage to the nearby structure is well connected to the excavation-induced deformation state in the adjacent structure. Indeed, in practice, the excavation-induced deformation state in the structure would normally be the controlling factor in the design stage referred to as serviceability-based design. As stated by Son and Cording (2005) the generalised damage criterion of structural elements could be based on the state of strain at a point as shown in Fig. 11.

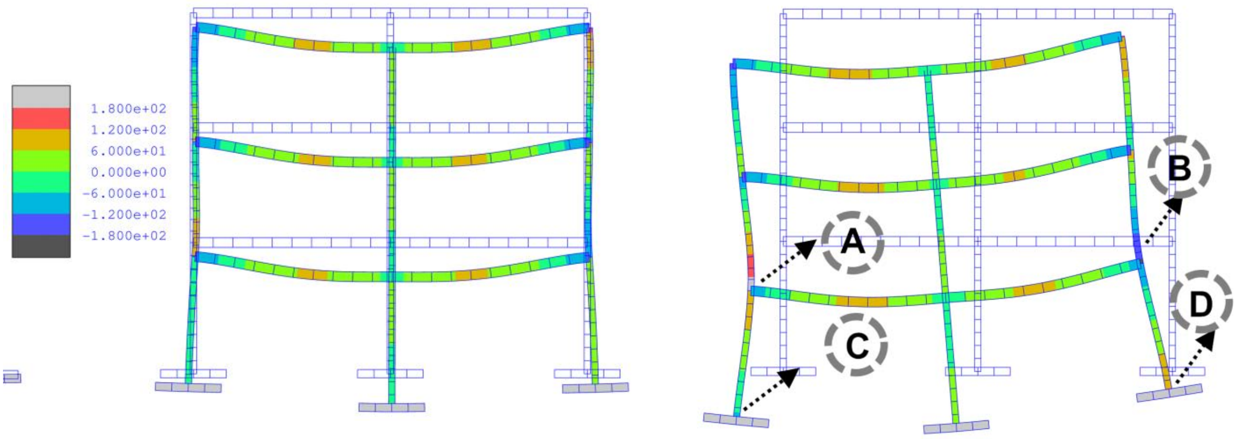


Figure 10: Deformed shape (scale=5) and bending moment (kN-m) of structure (a) before excavation, (b) after excavation

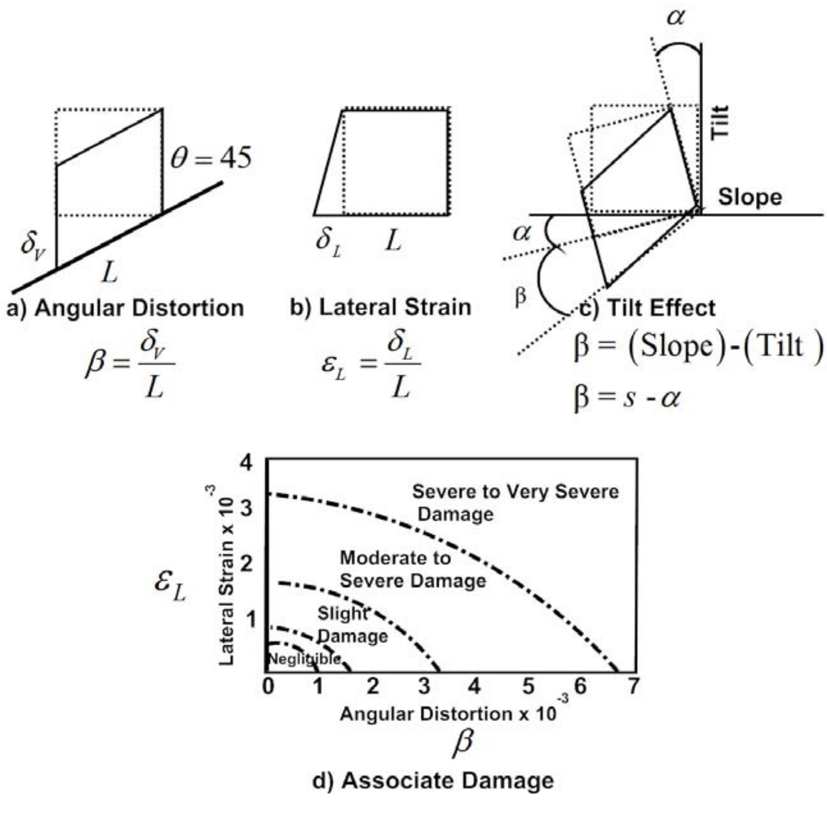


Figure 11: Associate damage in structural elements due to ground movement from Son and Cording (2005)

8. Conclusions

This paper discusses the behaviour of excavation and the response of a neighbouring structure by utilizing a fully coupled FEM in nonlinear modelling of the corresponding soil-structure interaction problem. Findings from this study offer valuable insights regarding the utilized partitioned FEM simulation technique. Moreover, the results highlight the nonlinear response sensitivity of the fully coupled SSI problem to various scenarios with respect to the applied loading to the structure, the excavation depth (He) and the distance of the structure from the excavation wall (Le). The study, further illustrates the high importance of considering the nonlinearity of both soil and structure sub-domains in SSI analyses, where nonlinear elasto-plastic constitutive behaviour of the soil, as well as both geometric and material nonlinearity of the structure, has been taken into account. Furthermore, the results highlight the high potential of using a fully coupled soil-structure model in such SSI problems, where proper assessment of building behaviour necessitate capturing the accurate behaviour of not only the ground movement patterns but also the building's structural elements.

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