Unfavourable seismic behaviour of reinforced concrete structures due to soil structure interaction

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Abstract. The soil-structure interaction (SSI) effects can substantially alter the behaviour of structures during earthquakes. Implementation of SSI within the seismic analysis often leads to lower stresses in the structure and therefore a more economical design. The recently introduced provisions in European and American codes allow for this type of approach. However, consideration of SSI can also lead to the observation of unfavourable effects (undetectable in a fixed-base analysis) due to the modification of the structure’s dynamic properties. Examples of unfavourable effects include higher global displacements or story drifts, increases of the base or story shear forces, higher post-elastic demands in the structural members or the collision of adjacent buildings separated by an insufficient structural joint. These unfavourable effects can be related to various parameters such as the structural system (frames or shear walls), foundation type (shallow or piles), geometry of the foundation, height of the building, soil type, seismic input, presence of adjacent buildings, etc. Under these circumstances, the integration of SSI into the current structural design becomes essential. As the mathematical formulation of the phenomenon is very complex and involves many parameters, the definition of complete numerical models is difficult. The provisions in the codes are often general and do not give the practicing engineers clear modelling solutions. An analysis of the current situation in the field of SSI is carried out, with a focus on the design of reinforced concrete structures. Based on an extensive literature review, the unfavourable seismic effects and the main parameters that determine them are identified. Conclusions are drawn regarding the situations when SSI should be mandatory and on the different possibilities of implementing SSI in the structural design.

1. Introduction

The soil-structure interaction (SSI) effects can substantially alter the seismic behaviour of structures, in particular when founded on soft soils. In current practice, for the analysis of seismic behaviour, building structures are considered with a fixed base. This assumption is generally conservative from a structural safety point of view, as in most cases the maximum stresses in the structural elements are reduced as a result of considering SSI in the analysis, compared to the fixed base situation. This is due to an increase in the fundamental period and in the damping, when considering soil contribution.

Only recently provisions regarding SSI appear in the Romanian [1-2], European [3-4] or American [5-7] design codes. Some of these provisions are aimed towards considering SSI in the design in order to obtain a more economically efficient solution, as it is allowed, in certain cases, to reduce the level
of the seismic demand by considering the positive effects of SSI. Most of the time, however, the provisions of the codes are of a general nature and do not permit implementation in the current practice of design and evaluation of structures.

At the same time, situations have been identified where SSI may cause unfavourable effects, as a result of the increase in global displacements or story drifts, the modification of the post-elastic mechanism or the collision of adjacent buildings separated by an insufficient structural joint. Some of these potentially unfavourable effects have already been highlighted 20 years ago [8], as the increase in the fundamental period does not necessarily lead to a smaller response of the building and as the ductility demand is not necessarily a decreasing function of structural period, as suggested by traditional design procedures.

Yet, even today, these unfavourable situations are not completely understood by practicing engineers. Under these circumstances, the current review aimed towards identifying the potentially unfavourable situations and the parameters that influence them is necessary.

2. Considering SSI in earthquake design

2.1. Modelling of SSI effects
The mathematical formulation of the SSI phenomenon is very complex and involves many parameters. For this reason, even in situations where all parameters are known, complete numerical modelling is difficult. If reliable numerical simulations are now eventually possible for an isolated building, in most cases the buildings are built in dense urban areas, where the seismic response is significantly influenced by the presence of neighbouring buildings.

Over the last 50 years, the dynamic Soil-Structure Interaction (SSI) has attracted an intensive interest among researchers and engineers in the fields of structural dynamics and soil dynamics. The investigations consisted of both analysis methods and experimental studies. The analysis methods are generally divided into two types: analytical method and numerical simulation methods. The analytical methods were mostly used in the past in order to solve simple problems. Nowadays, with the increase in computational power, there are three popular approaches for solving a typical SSI problem, namely the finite element method (FEM), finite difference methods (FDM) and boundary element method (BEM). A combination of these methods was also considered by various researchers. Extensive reviews of the analysis methods, as well as practical examples for their implementation, can be found in [9-17].

In our opinion, a relevant model should be based on a small strain hardening soil constitutive model for the soil. The model should include a type of quiet boundary. It should also allow considering several types of interaction properties and of course the integration of relevant (in the sense of the dynamic response) sub-models for the superstructure.

2.2. Code provisions
Despite the development of the vast array of methods mentioned above, very few codes prescribe guidelines for incorporating SSI in the design. According to [17], this might be due to the lack of consensus among researchers about the effects of SSI on the seismic response of structures.

According to the Romanian national codes [1, 2], the design stresses for the infrastructure of the building are determined based on the effective stresses at the base of the superstructure, considering, in the case of earthquake design, the post-elastic mechanism as well as additional safety factors. The recommendations for the infrastructure elements and the soil are that serious remnant deformations should be avoided. The provisions regarding SSI are extremely vague: “the computational model shall
be adequate as to also include, when necessary, the interaction with the soil”, but no other indication regarding the situations when SSI should be considered or how to account for them are given.

The European codes [3, 4] suggest that SSI effects must be considered when the second order effects play a significant role (P–δ effects), the structure is slender and tall, or the structure is resting on very soft soil. They include specification of a ground type with low shear strength and high plasticity index for which it is mandatory to perform special studies and include SSI in design practice. But the codes also lack guidelines for the actual quantification of the SSI effects.

The American codes [5-7] are more detailed regarding SSI. Three types of analysis are mentioned: lateral force procedure, linear dynamic procedure and nonlinear response history procedure. The lateral force procedure allows a reduction in the design base shear that accounts for the lengthening of the natural period and higher damping usually exhibited by the SSI system when compared to the fixed-base situation. It is important to note that only in recent editions of [5] a limit on the base shear reduction was introduced, with the modified design base shear being no less than 70% of the original value. For the systems with large response modification, the cap on the base shear reduction is a function of the response modification factor. The linear dynamic analysis can be performed either based on the modified general design response spectrum specified in the code or based on a site-specific response spectrum. The nonlinear response history procedure is to be used for the situations when kinematic interaction is expected to be predominant. The procedure is based on using acceleration histories scaled to a site-specific response spectrum for kinematic interaction.

### 3. Unfavourable seismic effects

It is important to mention that in most cases, considering the SSI effects corresponds to a decrease of earthquake demands in the superstructures of the buildings. But the focus of the paper is on the particular scenarios when SSI leads to unfavourable effects with regard to the fixed-base hypothesis.

3.1. Damping

Soil-structure interaction effects generally lead to an increase in the effective damping ratio of the fundamental period of vibration for buildings. This can correspond to lower earthquake demands for the superstructure elements. Still, as shown in [12, 18], for tall, slender structures, a decrease in damping may occur, leading to effective damping ratios that may be smaller than those of the superstructure on a fixed base.

3.2. Base shear

The value of the base shear generally decreases with SSI. Still, in [19] the situation of low-rise buildings on isolated or grid shallow foundations is analysed, and the results show an increase in the base shear compared to the fixed-base situation. An increase in base shear was also observed in [18] for buildings with large values of the slenderness ratio with piled foundations. It is difficult to know in advance if the SSI has a positive or negative effect on the structure’s behaviour, as it can lead to increases or reductions of the displacements while in return causing reductions or increases in base shear [20, 21].

3.3. Absolute displacement

Accounting for SSI often results in increasing the maximum displacements of the structure when compared to the fixed base case [21, 22]. Displacements under SSI effects cumulate the horizontal displacement of the foundation to those due to the rotation of the foundation and the displacements in the superstructure. The contributions of these components on the total displacement depend on various factors such as the soil type [14, 23, 24], the seismic input [24, 25], the height and slenderness of the building [22, 23, 26], the type and geometry of the foundations [18, 25, 27], or the presence of
adjacent buildings that lead to structure-soil-structure interaction – SSSI [28-31] that are discussed further below.

Increases in absolute displacements were observed both for moment resisting frame structures - MRF [14, 22, 25, 26] and shear wall structures - SW [22-24] and for shallow [23, 24, 26], or piled foundation [25]. The values are sometimes important. For instance, increases of up to 101% for SW structures [23] and 260% for MFRs [26] were observed under SSI effects. As the absolute displacements might lead to second order effects in the structure or to pounding between adjacent buildings, it is certain that they should not be neglected.

3.4. Pounding
Damage to buildings due to pounding has been observed in previous earthquakes when an insufficient gap was provided [32]. In the situations where absolute displacements increase, the risk of pounding between buildings also increases. The results of a study focused on this aspect for adjacent symmetric buildings ranging from 15 to 60 m height [28] led to the conclusion that some of the existing earthquake code provisions are insufficient and that pounding effects can be severe, in particular for a higher building nearing a less high one. As an example, the in-force Romanian design code [1] allows providing minimal seismic joints (dilatation joints) between similar buildings. In terms of the influence of the pounding on the damage index (DI) under earthquake loads, in [28] significant variations in storey shear forces and DIs of up to 16 and 48%, respectively, were observed at the critical story in SSSI cases.

3.5. Story drift
The inter-story drifts may also sometimes have higher values than in the fixed-base hypothesis due to SSI effects. For instance [25] obtained up to 56% increases in the recorded maximum inter story drifts. For the structural elements, the modified values of stresses and displacements demands that can shift the performance level toward near-collapse or collapse levels are discussed more in detail further below. But story drifts can also affect the performance of the non-structural elements.

3.6. Story acceleration
Very few studies focused on the modification of story accelerations due to SSI. An example is [15], where results were inconclusive, in the sense that the modifications of story accelerations depend on the chosen modelling parameters and can either be positive or negative. It is still important to note that story accelerations values may also be relevant for the safety of non-structural elements under earthquake loading.

3.7. Forces and displacement demands in structural elements
Increases in the value of forces or displacements due to SSI have been observed for all types of RC structures: MRF [22, 33], SW [22] and mixed SW+MRF [23].

An analysis of MRF structures ranging from 5 to 20 stories high [33] showed an increase of the damage indexes both for beams and columns of up to 12%. In the case of MRF and SW on soft and very soft soils [22], results showed that, in more than 50% of cases, the vulnerability (number of LS or CP hinges) has grown larger with SSI. In the same study, it was noticed that the seismic damage increased particularly in the lower stories, where more extended damages are expected even without the detrimental effect of SSI.

3.9. Residual displacement
The residual displacement has been extensively studied for bridges, but it is an often-neglected parameter for buildings [17], even if post-earthquake deformations and tilting are key-parameters in the evaluation of the safety and usability of a building. As soil nonlinear behaviour may be beneficial
to the seismic response of a structure, there is presently a trend to revise the traditional foundation
design concepts by allowing significant yielding in the soil or the foundation, in order to dissipate
energy and protect the superstructure [15]. Under such an approach, the potentially beneficial effects
of allowing soil yielding should always be compared to the detrimental effects of settlement or
residual tilt.

4. Parameters that can lead to unfavourable structural behaviour
The unfavourable behaviour of structures under SSI effects is due to a combination of factors. The
parameters discussed further below are not independent in their effects and the classification is aimed
at understanding how each one of them can contribute to an unfavourable outcome.

4.1. Soil stiffness
Significant differences in structural behaviour when considering SSI effects as compared to the fixed-
base situations occur mainly for soft soils [14, 15, 33]. This observation is valid also for the
detrimental effects. The effects also depend on the seismic input as is discussed further below.

When the soil is soft (usually when \( V_s < 150 \text{m/s} \)), a lengthening of the natural period of the system
typically occurs, accompanied by an increase in damping. When the underlying soil is moderate
(usually when \( V_s > 200 \text{m/s} \)), the alteration of the seismic response mainly depends on the frequency
content of the seismic motion [26]. When the underlying soil becomes stiffer (usually when
\( V_s > 300 \text{m/s} \)), the effects of the SSI on the structural deformations are in general insignificant in
comparison with the fixed base support.

A criterion regarding the rigidity of the soil is that the effect of soil-structure interaction should be
considered in the design when between the building height, \( h \), the building natural period, \( T \) and the
soil shear velocity, \( V_s \), the following criterion is met: \( h/(V_sT) > 0.1 \) [14]. This criterion is an
approximate relative measure, because even when \( h/(V_sT) < 0.1 \), relative distributions of moments and
shear forces in a building can be modified relative to the fixed-base condition, particularly in dual
systems, structures with significant higher-mode responses and subterranean levels of structures [15].

4.2. Ground motion (excitation)
For a given structure and soil type, the SSI effects under different seismic inputs are different. This
was observed for low-rise SW and MRF structures on shallow foundations [19], mid-rise MRFs on
basement with raft foundation [26] as well as low, mid and high-rise MRFs on pile foundation [25].
This can be attributed to the influence of the frequency content of the seismic input on the behaviour
of the system. When the dominant frequency content of the ground motion is close to the natural
frequency of the SSI system (resonance), more important increases of the dynamic response are
observed [19, 26].

The differences in the response can be significant. For instance, in [25] the increase in the lateral
deformation for a 5-story structure considering 4 different earthquakes varied from 8% to 37%. In
[26], for one of the considered earthquakes, the computed peak displacement was 2.2 (on loose soil)
and 6.8 (on firm soil) times bigger than the one computed for a different earthquake.

4.3. Ground geology and morphology
The ground geology can modify the seismic input from the rock base to the surface. Depending on the
nature of the ground motion, amplification and de-amplification of the seismic waves take place in the
soil layers and govern the unique response of the structure. This can be either beneficial or
detrimental. One of the most notable detrimental situations was that of Mexico City during the 1985
earthquake, where high amplification of the base shears for structures located on soft clay sites was
observed [20].
The ground morphology can also have a big impact on the peak ground acceleration, as superficial geological layers can amplify seismic waves. Hill-type geometric discontinuity is in terms of incident mechanical waves derived from the elastic semi-space a concave mirror, focusing them towards the interior of the soil mass where they can regenerate compatible waves and thus amplify the possibility of interferences with unfavourable effect. A valley-type discontinuity induces two main effects: on one hand the dispersing of incident waves due to the convex mirror shape of the upper surface and on the other hand the effect of mechanical isolation of the discontinuity edge opposite to the incident waves with a favourable effect.

4.4. Type and geometry of foundations
The foundation represents the component through which the structure interacts with the surrounding soil. The type and geometrical characteristics of the foundations can influence the structural response under seismic loads.

In the case of a shallow foundation, the size influences the fundamental frequency of the SSI system. Larger foundations might attract more inertial forces from seismic loads, while smaller foundations could lead to higher lateral deflections and inter-story drifts [27]. The embedment ratio can also influence the inelastic displacement demands for buildings, probably due to changes in the dynamic characteristics of the SSI system as well as the kinematic interaction effects [24].

In the case of pile foundations, the number of piles, embedment ratio and pile slenderness ratio influence the value of the effective period of the system [18]. The foundation stiffness also influences the effective damping [18]. The lateral displacements can be amplified, in particular for taller buildings, as a result of the rocking component [25].

4.5. Building height and slenderness
As discussed above, SSI effects on the building period and damping of a building are generally more important when: $h/(V_s T) > 0.1$ [14, 15]. Depending on the spectral shape, this can lead to an increase in the design base shear, the forces or deformations in the structure, relative to the fixed-base situation.

For low-rise short period structures, SSI can determine increases of the displacement demands [24] as well as increases in the base shear [14]. Similar situations can occur for high rise slender structures, where SSI can determine an amplification of the inelastic displacements [14, 24] and increases in the damage indexes [33].

4.6. Building ductility
Some studies [13, 19, 20, 24, 33] analysed the influence of the ductility considered in the design of the building on the value of SSI effects. For highly nonlinear structures, energy dissipated by the soil becomes negligible compared to that caused by plastic deformations in the superstructure [13]. Because of this, in buildings designed to undergo high post-elastic deformations, SSI can lead to higher displacements [24], increases in the ductility demands [19, 20] and increases in damage indexes, in particular for upper and lowest stories [33].

4.7. Presence of other buildings
Until recently, many of the SSI researches focused on isolated buildings. In the last 10 years, there has been a rising interest towards studying the behaviour of buildings in dense urban areas, either through numerical simulations in 2D [30] or 3D [28, 29, 31] or based on shake-table tests [29]. When large and rigid buildings are sufficiently close to one another, they may have significant effects on the ground motion and interact with each other. These SSSI effects are mainly due to the separation and size of the structures, the type of soil and building stiffness relative to that of the soil, the characteristics of the foundations, the frequency content and the angle of incidence of the incoming waves.
Highly unfavourable effects were observed when a large, tall structure is in the proximity of a smaller structure. The results obtained in [30] shown that the power of the earthquake can pass from the taller structure to the smaller one, which, for the analysed situation, led to increases in displacements up to 400%. For the groups of structures with similar dynamic characteristics analysed in [31], SSSI effects determined increases in the seismic response of individual buildings, as well as an amplification of the shear forces at the pile heads.

5. Conclusions
Soil-structure interaction (SSI) is an intricate issue, which is of high interest for the seismic design of structures. In the conventional seismic design, the structures are considered with a fixed base, without considering the infrastructure and the soil. Soil effects are only considered through the design spectrum specified in the codes. In many situations, SSI is beneficial, in the sense that the actual earthquake effects on the building are less than in the hypothesis of a fixed base. Yet, for reinforced concrete structures, SSI can sometimes lead to an unfavourable seismic behaviour.

Some of the unfavourable effects are related to an increase in absolute displacements or story drifts. These can lead to a risk of pounding between adjacent buildings, increased forces or ductility demands on some of the structural members, or a change in the post-elastic mechanism of the structure. The main factors that determine this unfavourable behaviour are the characteristics of the soil, coupled with the specific seismic excitation. But there are other parameters that should be analysed, such as the building height and slenderness, the designed ductility for the superstructure, the type of foundations and their geometry, as they can intensify the unfavourable behaviour. Also, in urban areas, a careful analysis should be conducted on the structure-soil-structure effects, as the presence of other buildings can modify the dynamic response.

The current design codes recommend considering SSI when designing structures for earthquake, but they do not offer a clear implementation method to be used by the practicing engineers. In this context, it is important that more studies are conducted in the field, with an aim at providing methodologies that can be integrated into the current structural design. Both structural and geotechnical engineers should also become more aware of the potentially unfavourable effects on the seismic response of RC building due to SSI effects and that a joint analysis is undertaken since the early design stages in order to achieve the best solution for a given project.

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