Soil-Structure Interaction: Its Importance in the Modelling & Design of Structures

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What is Soil-Structure Interaction (SSI)?

Most civil structures, especially bridges (piles, pile caps, abutments and retaining structures) are built on or inside the ground (Fig. 1). When analyzing such a structure, there is a great difference in the result values when the analysis is performed considering ground conditions. The ground conditions must be taken into consideration to obtain analytical results, such as the behavior of the actual structure.

Figure 1. Bridge structure with close relation to the ground

Soil Structure Interaction (SSI) is a physical phenomenon in which the structure fails to behave independently and behaves in connection with the soil when an external load is applied to the structure as shown in the figure below(Fig.2). In particular, the ground and the structures are greatly influenced by earthquakes, so this phenomenon is required as an essential consideration for seismic design.

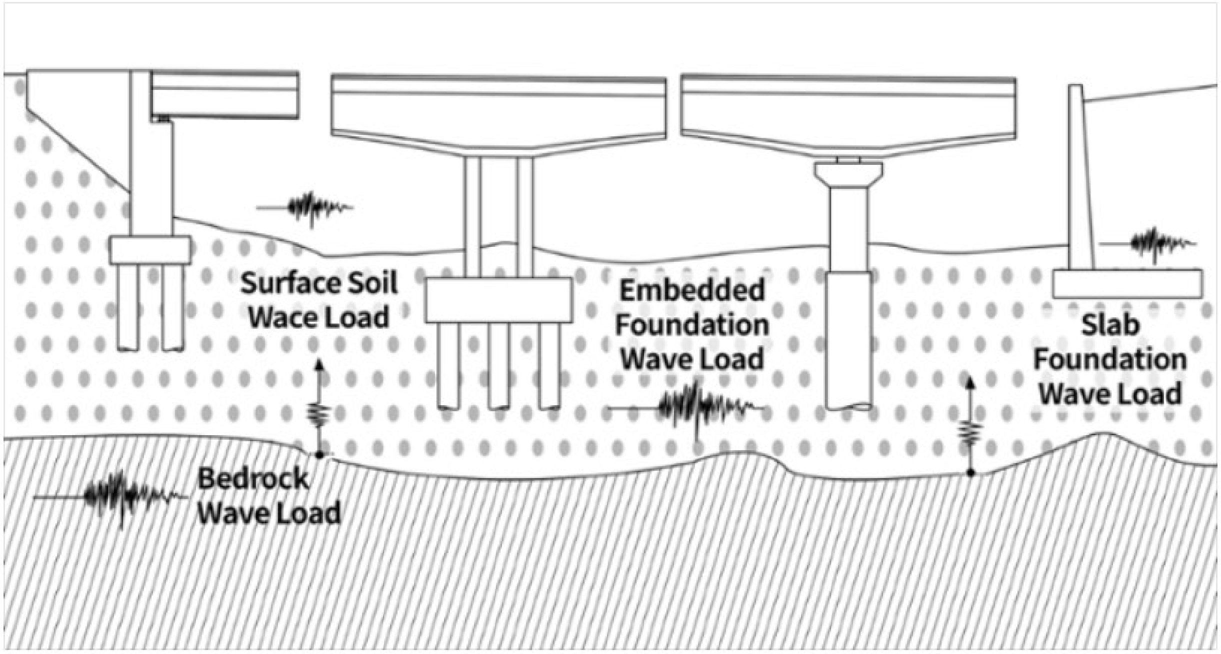


Figure 2. Interaction between the ground and the bridge structure

The study of soil-structure interaction (SSI) is related to the field of earthquake engineering. It is very important to note that the structural response is mainly due to the soil-structure interaction forces that brings an impact on the structure. This is a form of seismic excitation. A committee of engineering research deals with the study of soil-structure interaction only when these forces brings an appreciable effect on the basement motion when we are comparing it with the free-field ground motion. The free-field ground motion can be defined as the motion recorded on the surface of the soil, without the involvement of the structure. The structural response to an earthquake is highly dependent on the interactions between three linked systems, namely:

1. The structure
2. The Foundation
3. The underlying soil

The soil-structure interaction analysis is the method of evaluating the collective response of the three linked systems mentioned above for a specified ground motion. The soil-structure interaction can be defined as the process in which the response from the soil influences the motion of the structure and the motion of the given structure affects the response from the soil. This is a phenomenon in which the structural displacements and the ground displacements are independent to each other. Soil-structure force are mainly interaction forces that can occur for every structure. But these are not able to change the soil motion in all conditions.

Effect of (Soil-Structure Interaction) SSI and SSI Provisions of Seismic Design Codes on Structural Responses

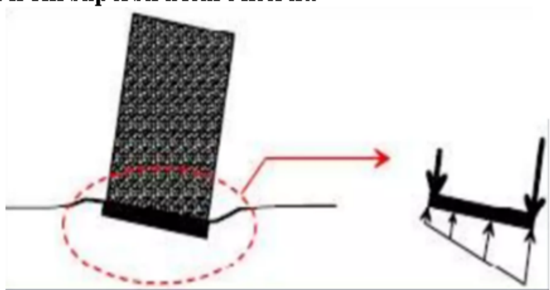
It is conventionally believed that SSI is a purely beneficial effect, and it can conveniently be neglected for conservative design. SSI provisions of seismic design codes are optional and allow designers to reduce the design base shear of buildings by considering soil-structure interaction (SSI) as a beneficial effect. The main idea behind the provisions is that the soil-structure system can be replaced with an equivalent fixed-base model with a longer period and usually a larger damping ratio. Most of the design codes use oversimplified design spectra, which attain constant acceleration up to a certain period, and thereafter decreases monotonically with period. Considering soil-structure interaction makes a structure more flexible and thus, increasing the natural period of the structure compared to the corresponding rigidly supported structure. Moreover, considering the SSI effect increases the effective damping ratio of the system. The smooth idealization of design spectrum suggests smaller seismic response with the increased natural periods and effective damping ratio due to SSI, which is the main justification of the seismic design codes to reduce the design base shear when the SSI effect is considered. The same idea also forms the basis of the current common seismic design codes such as ASCE 7-10 and ASCE 7-16.

Conventional structural design methods neglect the SSI effects. Neglecting SSI is reasonable for light structures in relatively stiff soil such as low rise buildings and simple rigid retaining walls. The effect of SSI, however, becomes prominent for heavy structures resting on relatively soft soils for example nuclear power plants, high-rise buildings and elevated-highways on soft soil.

Foundation Deformations

To understand the importance of SSI in the global analysis of the structure, it is important to understand and focus on the foundation deformations , the following Fig. 3 summarized the deformations under 2 cases.

1- Loads from superstructure inertia



2- Deformations applied by soil

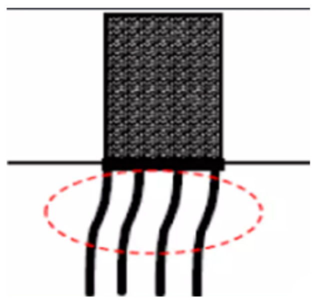


Figure 3. Foundation Deformations

Considerations in Soil-Structure Interaction Effects

A structure, when analyzed by considering its foundation to be rigid, is said to have no soil-structure interaction effects. Now, this case is considered even if the interaction force impacts the foundation. The influence on the soil motion by the interaction forces will depend upon:

- The magnitude of the force
- The flexibility of the soil foundation

The base mat acceleration and the inertia of the structure can be used to estimate the value of interaction forces. The heavier the structure the more is the soil-structure interaction effects for a particular soil site and for a given free-field seismic excitation. Most of the civil structure, whether it is lying on the hard or medium soil does not show any sign of SSI effects. As mentioned above, the SSI effects are more dealt with heavy structures that includes hydraulic structures like dams, nuclear power plants (NPP) reactor buildings. We can conclude that the soil interaction in earthquake engineering study was mainly developed and applied for these fields of construction industry. Another condition considered the soil-structure interaction effects are the soil flexibility. Softer is the soil, more is the chances for the occurrence of SSI effects. This is for a given structure and a site that have a free -field seismic excitation.

Note: *The product of mass density of the soil and the square of shear wave velocity will give the* ***soil shear module.*** *In practice, the mass density of the soil will vary around 2,0 t/m3. Hence the main characteristic of soil stiffness can be considered to be the shear wave velocity Vs.*

- If Vs< 300m/s then the soil is considered to be soft
- If Vs> 800m/s then the soil is considered to be hard.
- If Vs > 1100m/s the soil is considered to be rigid.

Application of Soil Structure Interaction

1. It is used in Heavy structures like hydraulic structures and nuclear structures
2. For those structure where the P delta effects are prominent, the analysis based on soil structure interaction is helpful.
3. The study of SSI has a significant role in the deep - seated foundations, structures supported over soft soil, tall or slender structures which have an average shear velocity of 100m/sec.

Soil-Structure Interaction and Structural Response

Based on conventional theories it has been said that the soil structure interaction has effects that are beneficial for the structural response. Most of the design codes for structures recommends neglecting the effect of SSI in the seismic analysis of the structure. This recommendation is because of the false myth that the SSI brings good response of the structure and hence have chances to increase the safety margins. More flexible structural design can be obtained if we consider the effects of soil structure interaction. This helps in increasing the natural period of the structure. This provides an improved structure when compared to a corresponding rigid structure. Incorporation of SSI effects on the structural design helps in increasing the damping ratio of the structure. This study is limited or neglected for conservative design procedures. The SSI analysis is very complicated in nature. The neglecting will reduce the complexity in the analysis of the structures. This means that the myth put forward that the SSI effects are good for structures is not true. In fact, SSI can bring detrimental effects to structures. Neglecting SSI effect can bring unsafe design of the superstructure and the substructure.

Mechanical Classification of Soil Structure Interaction

The effects of SSI can be classified into Kinematic Interaction and Inertia Interaction. Kinematic Interaction is due to the stiffness difference between the soil and the structure, and Inertia Interaction is due to the inertia force of the structure.

1. **Kinematic Interaction**

When a seismic force is applied, a difference occurs between the 'Free Field Ground Motion' (absence of any structure) and the 'Foundation Input Motion' (absence of mass in the upper structure). This difference is referred to as Kinematic interaction and includes a combination of geometry of structures, rigidity difference between foundations and soils, embedment effects and base-Slab averaging effect. Furthermore, this action can be quantified by the Transfer function as the ratio between the 'Free Field Ground Motion' and the 'Foundation Input Motion'.

Since the incident wave with a high order frequency component retains a short wavelength, the stiffness of the foundation absorbs and reflects the wave. However, an incident wave with a low order frequency component retains a long wavelength, which passes through the structure and generates motion in the structure. In case of a vertically incident shear wave, rocking motion is generated in the structure. The ground motion generated by kinematic interaction is also referred to as scattering motion. Kinematic interaction is generally affected by the type of incident wave and the shape of the foundation. If the structure is on the ground surface, the foundation is embedded into the ground at a shallow depth. On the other hand, if the surface wave is not considered, the effect of kinematic interaction is not so significant that it may be ignored during seismic analysis.

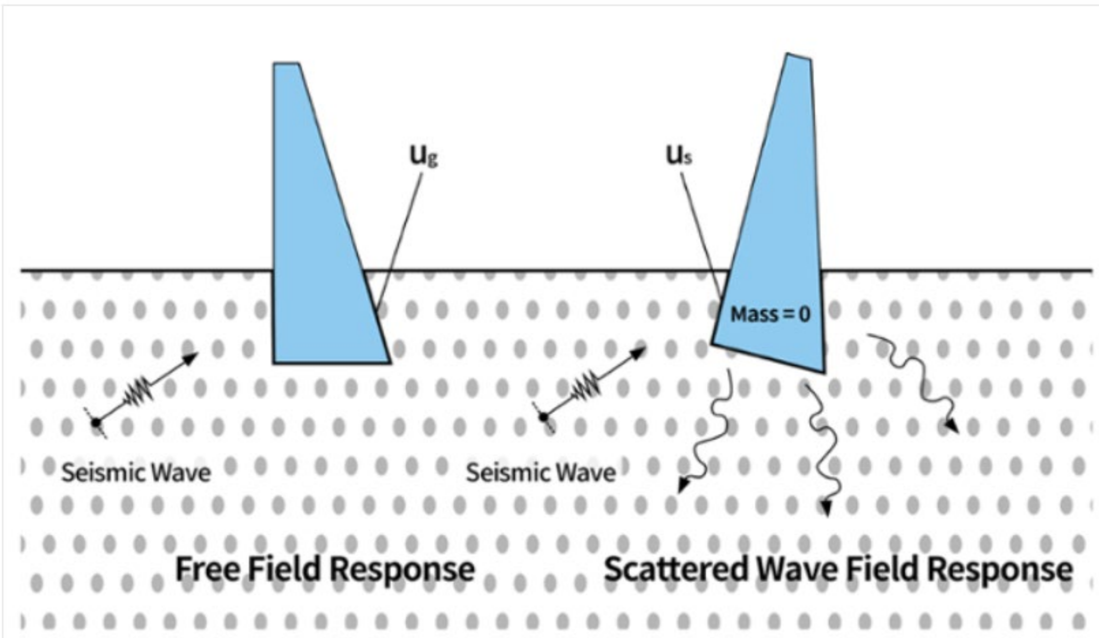


Figure 4. Free-Field response and scattered wave field response

Free Field Motion

Free-Field is referred to as the location where the structure is absent, and the design ground motion is defined as ground motion in the free-field. The point where the design ground motion is defined is called the control point, and the ground motion at that location is called the control motion. ASCE 4, Design ground motions are defined as the free-field response (acceleration, velocity, displacement) that is the site response in the absence of structure (Fig. 4).

Base-Slab Averaging Effect

Effect of free-field response across contact surfaces at the foundation of the structure being constrained by the stiffness of the base slab(Fig. 5).

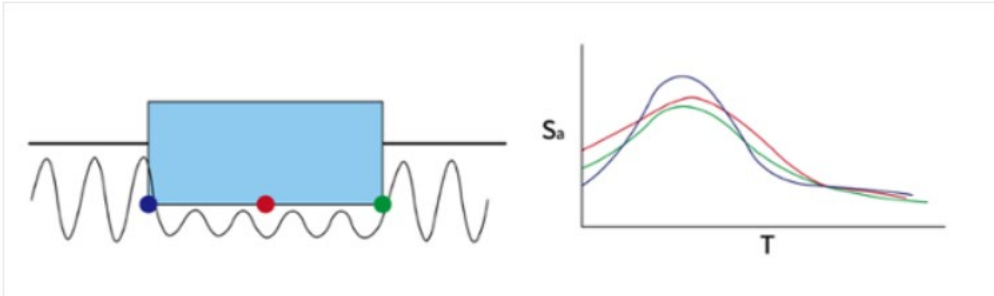


Figure 5. Base slab averaging effect

Embedment Effect
The effect of decreasing response along the depth of the structure (Fig. 6).

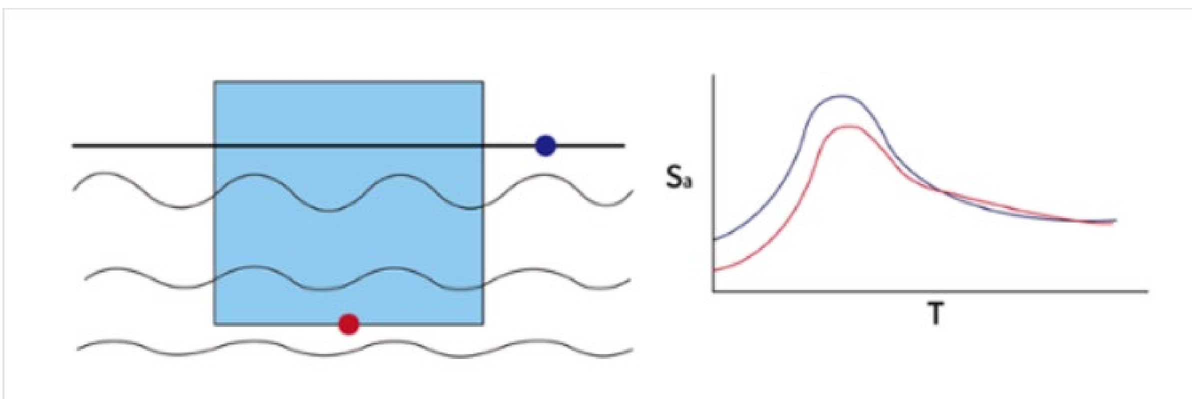


Figure 6. Embedment effect

2. Inertia Interaction

Inertia Interaction refers to a phenomenon in which the inertial force of a structure caused by seismic forces causes relative displacement between the ground and the structure, resulting in Hysteretic Soil Damping and Radiation Damping (Fig. 7).

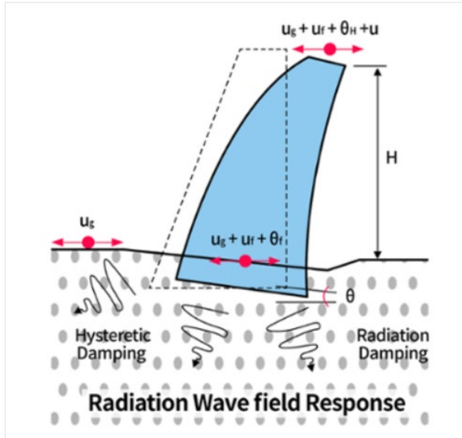


Figure 7. Response dictated by interaction between soil structure

When a horizontal seismic force is applied to the base, the final displacement generated on the structure includes sliding due to the horizontal movement and rocking due to rotation. This displacement occurs from the shear force and moment created on the foundation base by seismic forces. These displacements, which cause deformation on the ground, are referred to as inertia interaction and quantified by the Impedance function.

When the structure is excited by seismic waves, the inertia force is generated by the structure's mass. The inertia force in turn generates kinematic energy, which is then radiated to the far field soil, resulting in radiation motion of the ground. Inertial interaction increases as the stiffness difference between the structure and the nearby ground increases. Therefore, when a very stiff structure is situated in soft soils, the influence of inertia interaction is much greater.

Hysteretic Damping

A phenomenon caused by material properties, in which kinetic energy and deformation energy are converted into heat due to friction between soil particles resulting in loss of energy

Radiation Damping

A phenomenon in which the energy of a structure is dissipated by releasing wave energy into the semi-infinite soil medium.

Soil-Structure Interaction Analysis Methods

The above-mentioned interactions can be measured by two methods of analysis. They are the:

1. Direct Analysis
2. Substructure Approach

1. Direct Analysis in Soil Structure Interaction

In this type of analysis, the soil and the structure is used in the same model for analysis. They are analyzed as a complete system. As shown in Fig. 8 below, the soil system is represented as a continuum. One such example is by the representation of finite elements. The foundation, structural elements, the load transmitting boundaries, the elements at the interface located on the edges of foundation are also included.

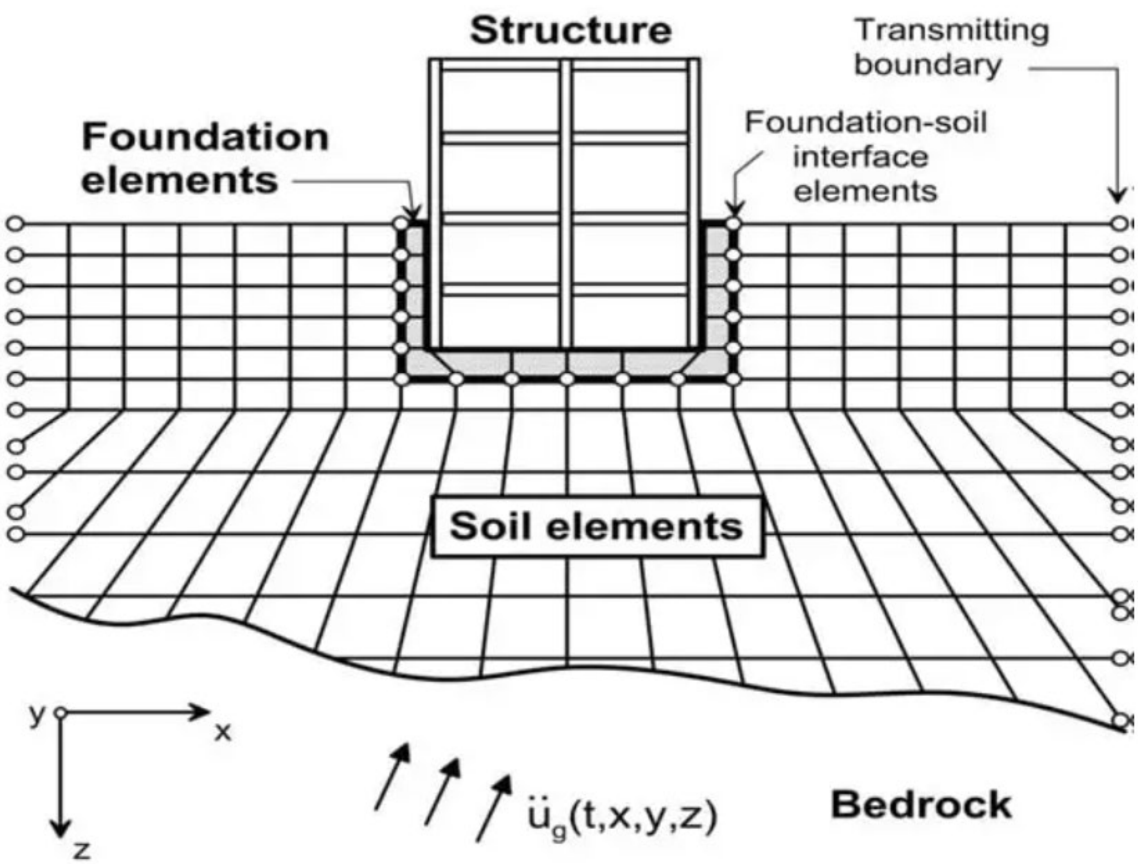


Figure 8. Illustration of Direct Analysis of Soil Structure Interaction with the help of Finite elements

This method is rarely used in practice as it involves large computation and is very complex to analyze.

2. Substructure Approach in Soil Structure Interaction

The soil structure interaction activity is divided into two parts. These are later combined to form a complete solution for the problem. In this approach, a model is generated with certain requirements:

- Free -field motions and the corresponding soil properties is evaluated
- The transfer functions are evaluated to convert the free -field motion to the foundation input motion
- Springs and the dashpots are incorporated. The springs represent the stiffness and the dashpots represent damping at the soil and foundation interface
- Response analysis of the combined structure

The Fig. 9 below shows the how a general problem A is evaluated. It is divided into two problems A1 and A2 such a way that A= A1 + A2. This is done based on the principle of superposition. Each problem is evaluated separately and the combination of the results will give the final solution.

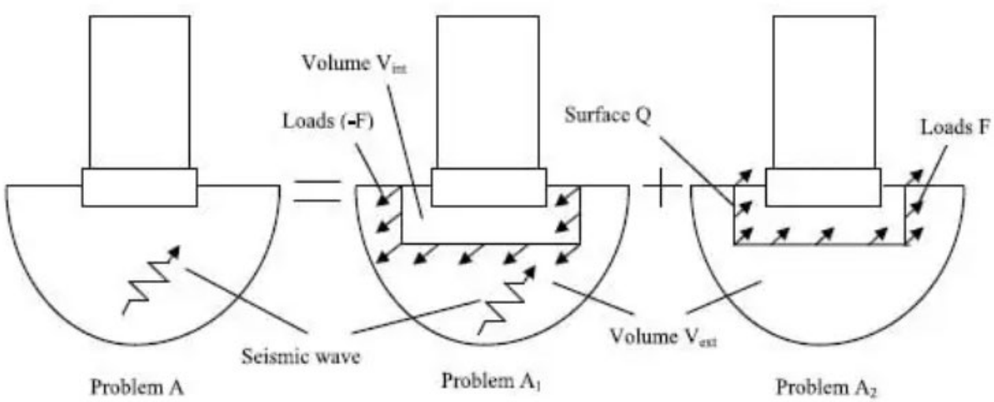


Figure 9. Splitting of a Problem A by Superposition - Substructure Approach

The Methods Used to Mitigate the Problem of the Soil-Structure Interaction

The methods most used to mitigate the problem of the soil-structure interaction on the low-quality ones (categories D and E). The most diffused techniques are the jet grouting technique and the pile work technique. The jet-grouting technique (Fig. 10) consists of injecting in the subsoil some liquid concrete by means of a drill. When this concrete hardens it forms a sort of column that consolidates the surrounding soil. This process is repeated on all areas of the structure. The pile work technique consists of using piles, which, once inserted in the ground, support the foundation and the building above, by moving the loads or the weights towards soil layers that are deeper and therefore more compact and movement-resistant.

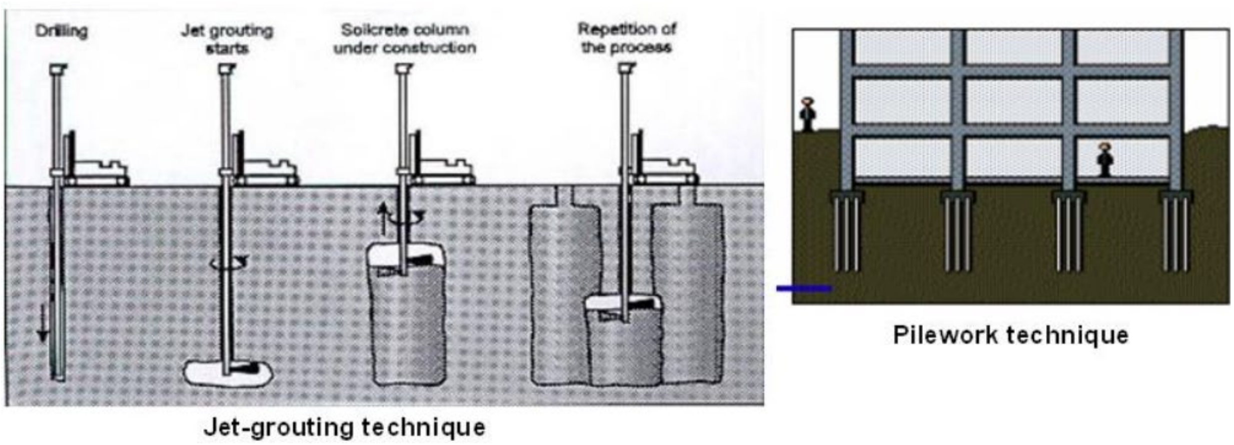


Figure 10. Jet-grouting technique

Summary of Expert Experience in the Field of Soil Structure Interaction

The following conclusions may be drawn by ***Tabatabaiefar & Massumi*** from the analytical investigation reported in this paper on ductile reinforced concrete frame structures designed based on the Iranian Codes and modelled with and without soil:

i. It is not necessary to consider the effect of soil–structure interaction for seismic design of RC- moment resisting building frames buildings (RC-MRF) founded on soil type II (375<Vs<750 m/s).

ii. It is essential to consider the effect of soil–structure interaction for seismic design of RC-MRF buildings higher than 7 stories founded on soil type III (175<Vs<375 m/s)

iii. It is essential to consider the effect of soil–structure interactions for seismic design of RC-MRF buildings higher than 3 stories founded on soil type IV (Vs<175 m/s)

iv. On the whole, it is essential to consider the effect of soil– structure interaction for seismic design of RC-MRF buildings when the following criterion exists: $Vs/fh<10$

Where, Vs=soil shear velocity; f=natural frequency of fixed-base structure; h=total height of structure.

Julio A. García concluded that, the inclusion of the soil in the structural analysis provides results, stresses and deformations, closest to the actual behavior of the structure, in comparison with those provided by the analysis of a fixed-base structure. Besides, more economic designs are obtained by including the soil in the structural analysis and design, due to the reduction in seismic loads.

Mylonakis and Gazetas have shown that increase in natural period of structure due to SSI is not always beneficial as suggested by the simplified design spectrums. Soft soil sediments can significantly elongate the period of seismic waves and the increase in natural period of structure may lead to the resonance with the long period ground vibration. Additionally, the study showed that ductility demand can significantly increase with the increase in the natural period of the structure due to SSI effect. The permanent deformation and failure of soil may further aggravate the seismic response of the structure.

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