Analysing Structural Behaviour under Dynamic Loading with Soil-Structure Interaction

Yogesh N. Bafna[a], Darshankumar Patel[b]

[a,b] Assistant Professor of Civil Engineering Department, SVKM Institute of Technology Dhule

Abstract: Several studies have shown that the Soil Structure Interaction plays a major role in the extent of damage caused by the recent earthquakes. It has been discovered that the performance of the structure is greatly impacted by the interaction between the soil and the structure. This research presents the impact of soil-structure interaction on the natural period, vibration mode, damping, and dynamic response of the structure.

Keywords: Foundation, Loading, Soil-Structure Interaction.

Introduction

The majority of civil engineering constructions have some kind of ground-contact structural component. When these systems are subjected to external stresses like earthquakes, neither the ground displacements nor the structural displacements occur independently of one another. Soil-structure interaction (SSI) is the process by which the motion of the structure affects the response of the soil and the response of the soil influences the motion of the structure. Traditional structural design techniques disregard the impacts of SSI. For light structures in moderately stiff soil, such low-rise buildings and basic inflexible retaining walls, neglecting SSI makes sense. However, the impact of SSI becomes more noticeable for large, heavy structures that are supported by comparatively soft soil, such as elevated roadways, high-rise skyscrapers, and nuclear power plants.

Damage incurred during earthquakes, such the Kobe Earthquake of 1995, has also brought attention to the fact that a structure's seismic behaviour is greatly influenced by the ground's and the foundation's responses in addition to the superstructure's. Because of this, current seismic design codes, like Standard Specifications for Concrete Structures: Seismic Performance Verification (JSCE 2005), mandate that the superstructure, foundation, and ground should all be taken into account when conducting a response analysis.

An engineering structure's seismic reaction is influenced by the medium it is built upon. A "fixed-base" structural reaction happens on solid rock, and it can be assessed by letting the foundation experience the same "free field" ground motion that would happen in the absence of the structure. On a deformable soil, on the other hand, there is a feedback loop in which the soil reacts to the dynamics of the structure and the structure responds to the dynamics of the soil. The interaction of the input motion, the structure, and the properties of the soil then controls the structural reaction. The phenomena known as soil-structure interaction, or SS, has drawn attention from researchers for the past forty years.

In terms of structural response, SSI has two main consequences as compared to the equivalent fixed-base system. First off, the SSI system's dynamic characteristics have changed due to its increased number of degrees of freedom. Secondly, radiation waves that radiate back into the soil from the vibrating foundation-structure system or hysteretic material damping in the soil may dissipate a substantial portion of the vibration energy of the SSSI system. As a result, SSI systems exhibit longer natural vibration periods than their equivalents with fixed bases.

According to certain rules of practice for seismic design, the structure's seismic response will benefit from any extension of the natural vibration period. However, based primarily on the design response spectrum at the site, SSI effects may result in an increased structural reaction in specific seismic and soil environments. Furthermore, the simplification fails to take into account the fact that free-field ground motion does not affect a structure that is suffering SSI. Rather, the dynamic features of the superstructure and the characteristics of the foundation soil determine the input motion. Even though they have significantly improved due to recent developments in information technology and numerical processing, SSI analysis techniques that were created in the late 1960s and early 1970s are still in use today. The sub-structuring method is especially well-liked. advantageous for the structure's seismic reactivity.

The initial difficult problem can be solved quickly and easily by breaking down the soil, foundation, and building domain into multiple smaller domains. Though theoretical solutions have also been created that shed light on the physical phenomenon, methods utilizing sub structuring are restricted to the linear elastic or viscoelastic domain since they rely on the idea of superposition. However, before the resulting analytical solutions are implemented in engineering practice, they must be experimentally verified.

Many investigations, tests, and research projects have been conducted worldwide over an extended period of time in an effort to comprehend or assess the impact of soil structure interaction on the most recent measures and techniques used to improve the performance of the structure. A portion of these studies and their findings are covered in this paper.

The interaction between structures, their foundations, and the soil medium beneath the foundations has been the subject of research by Dutta and Roy [2002]. Research shows that the real behaviour of the structure is much different from what is obtained from the structure alone when soil-structural interaction is taken into account. To improve the design of significant structures, a model of the system that interacts with the soil, foundation, and structure is required. The Winkler model, the elastic continuum model, and the enhanced foundation models are the different models.

The numerical simulation of soil-structure interaction (SSI) phenomena in a shaking table facility has been studied by Pitilakis et al. [2007]. The goal of the shaking table test is to verify that the numerical substructure technique can accurately replicate the SSI phenomena. Inside a specially made shaking-table soil container sits a dry bed of sand that has a model foundation-structure system with strong SSI potential. The experimental system experiences a significant ground motion. Using the substructure technique, the entire soil foundation-structure system is numerically simulated in the linear viscoelastic domain. It is satisfactory that the experimental and numerical responses coincide in the frequency and temporal domains. The numerical simulation captures many significant SSI features that are visible in the experiment. Moreover, it is demonstrated that the numerical modelling is sufficient for real-world engineering design needs.

Researchers Livaoglua R. and Dogangun A.[2007] examined how a structural frame supporting a fluid-containing tank affected the fluid-elevated tank, foundation, and soil system's seismic behaviour. Consideration was given to six distinct soil types as listed in the well-known Seismic codes. The analyses covered the sloshing effects of the fluid as well as the soil-structure interaction of the divided tanks situated on these six distinct soil types. The finite element (FE) technique was used to study fluid-elevated tank foundation-soil systems. Using the Lagrangian fluid FE approximation implemented in the general purpose structural analysis computer tool, ANSYS, the fluid-structure interaction was considered. The impacts of the elevated tank foundation-soil interaction were incorporated into the FE model using a viscous boundary. For both embedded and non-embedded foundations, the models were examined. It was discovered that the embedment in soft soil had a considerable impact on the tank roof displacements; however, this effect was less pronounced for stiff soil types.

Studies of previous earthquakes show that crucial lifeline infrastructure, such as elevated water tanks, is damaged and fails to function properly, posing major risks long after the catastrophe. The dynamic properties of elevated tanks supported by cylindrical shafts (shaft staging) are thoroughly studied in the context of such dangers suggesting deficiencies in the current seismic design strategy of such structures. The same is manufactured using small-scale experiments and meticulous finite element analysis to generate and validate analytical simulations. The walls of the shaft-staging of such reinforced concrete (RC) tanks as well as the columns of frame-supported tanks (tanks with frame staging) are prone to tension, according to a subsequent analysis of the seismic reaction of representative tanks. especially with the tank empty. Ignoring the influence of soil-structure interaction (SSI) during design appears to exacerbate this potential. Recognizing the shortcomings in the existing design, a straightforward design process for these raised tanks is suggested, making use of the discovered formulas. It is also found that the torsional vulnerability of elevated water tanks supported by shafts is rather negligible, compared to that of frame-supported tanks.

Model of structure-foundation soil interacting system

According to Dutta and Roy (2002), the modelling of the foundation and superstructure is more basic and easier than the modelling of the soil media below. However, it is frequently observed that several typical structures lack a straightforward yet reasonably realistic model. Due to its heterogeneous, anisotropic, and nonlinear force displacement characteristics, the soil exhibits a great deal of complexity. Its complexity is increased by the water table's change. There are several approaches to modelling soil, each with varying degrees of rigor

Idealization of structure

Building

Structures Using two node beam elements, the superstructure of the building frames can be idealized as a three-dimensional space frame in its most generalized form. By placing the loads of the walls on the beams they rest on, the effect of the infill walls may be explained. It is possible to add plate components of the right size to replicate the behaviour of slabs. For the purpose of assessing the building frame under static gravity loading, this idealization seems to be sufficient. However, when the structure is subjected to lateral loading, the infill wall gives the structure a significant amount of lateral stiffness since it acts as a compressive strut. Therefore, as recommended by Dutta and Roy (2002), the effect of the same must be taken into account under lateral loads. It is well knowledge that the stiffness and strength of concrete members will deteriorate after a few cycles of loading that causes the tension in the building's reinforced concrete part to exceed the yield strength. The available computational resources and needed precision can be used to select an appropriate model. Yet, steel-framed buildings appear to be less susceptible to this deteriorating influence on stiffness and strength.

Aqua tank

Dutta and Roy (2002) concentrated on the task of facilitating the convenient modelling of the elevated water tank with frame or shaft-type staging for the sake of analysis under static loading using any common finite element software. However, after an earthquake, the functionality of such an elevated tank becomes vital. The remaining water in the container travels with the container under lateral ground shaking, but the top portion of the water experiences sloshing vibrations with a period that is typically significantly higher than the container and the staging. This effectively turns the system into a two-mass model.

Nearly all of the water in the tank is designed to slosh during the torsional vibration, with a period that is far longer than the torsional period of the entire system, including the staging and containers. It is possible to simulate the commonly used foundation system using appropriate circular or rectangular plate parts. The well-established theory of beams on elastic foundations can be used to represent the strip or grid foundations. Circular or annular rafts are typically utilized for cooling towers and water tanks.

Simulation soil media

In order to represent the soil-media in the soil-structure interaction problem, Dutta and Roy (2002) provide a physically near and mathematically straightforward model that demonstrates two fundamental classical approaches: The Winkler a method and the Continuum approach. The key factor at the soil-foundation interface is the distribution of contact pressure. The behaviour of the foundation (i.e., rigid or flexible: two extreme circumstances) and the type of soil deposit (clay or sand, etc.) determine how the pressure distribution varies. The goal of foundation design is to distribute the structure's weight onto the earth, hence the most ideal foundation modelling replicates the distribution of contact pressure in a way that is closer to reality.

From this vantage point, there are certain drawbacks to both basic techniques. However, the mechanical behaviour of subsurface materials seems to be incredibly complex and unpredictable, and it doesn't seem conceivable to develop any mathematical laws that would be consistent with empirical observations. A lot of research has been done recently in the field of soil-structure interaction simulating the underlying soil in a variety of intricate methods.

Interaction of soil with structure under dynamic loading

According to Dutta and Roy (2002), when analysing and designing buildings under dynamic loads, it is typically considered that the structures are fixed at their foundation. However, taking into account the actual flexibility of the support shortens the system's duration and lessens the structure's overall stiffness. The response spectrum curve shows a significant shift in spectral acceleration with natural period. Therefore, a shift in the natural period may significantly affect how a structure responds to earthquakes. Furthermore, the inherent features of soil media contribute damping. Some of the research also address the problems of lengthening the natural period and involving significant damping in soil as a result of soil-structure interaction in building structures.

Furthermore, the relationship between the structure's vibrational periods and the supporting soil's vibrational periods is crucial for understanding how the structure will respond to earthquakes. The significance of this issue was increased by the destruction of structures at the 1967 Carcas earthquake and the demolition of a portion of a plant in the 1970 Gediz, Turkey, earthquake. Therefore, a key factor in predicting the total structural response is the interaction of the soil structure under dynamic stresses.

Impact of soil structure interaction on the response of the structure

Numerous design codes have indicated that it is reasonable to overlook the SSI effect while doing a seismic study of a structure. This fallacy concerning SSI seems to have its roots in the misconception that SSI improves safety margins by lowering a structure's overall seismic response. The majority of design codes employ oversimplified design spectrums, which decline monotonically over time after reaching a fixed period of constant acceleration. When soil-structure interaction is taken into account, a structure becomes more flexible and has a longer natural period than a matching rigidly supported structure. Furthermore, taking into account the SSI effect raises the system's effective damping ratio. Smaller seismic response is suggested by the smooth idealization of the design spectrum with enhanced natural periods and an efficient damping ratio because of SSI. customarily It was thought that SSl may be conveniently disregarded for conservative design under this supposition. Furthermore, SSI greatly lessens the complexity of the structural analysis, which has enticed designers to overlook SSI's influence in the study. For some classes of structures and soil types—such as light structures in relatively stiff soil—this cautious approximation is appropriate.

Sadly, the presumption documents aren't usually accurate. As a matter of fact, SSI can negatively impact the structural response, and SSI neglect in the analysis could result in dangerous foundation and superstructure design.

Dutta et al. investigated a shaft-supported elevated water tank, taking into account the effect of soil-flexibility, in order to investigate the seismic reaction on structure. Base shear for the elevated tank is calculated in Table I at fixed base conditions and takes soil flexibility into account for both tank-full and tank-empty conditions.

Table 1-Variations in the seismic base shear of tanks supported by shafts

Type of clay	Seismic base shear (KN)					
	Full Tank			Empty Tank		
	Without SSI	With SSI	Variation	Without SSI	With SSI	Variation
Very Soft	860	1080	25.58%	435	535	22.99%
Medium		1140	32.56%		475	9.20%
Very Stiff		1134	31.86%		434	0.23%

Soil Structural Interaction – Negative Effect

Through extensive numerical simulations, Mylonakis and Gazetas have demonstrated that, contrary to what the simplified design spectrums suggest, a rise in the natural period of structure caused by SSI is not always advantageous. The period of seismic waves can be greatly extended by soft soil sediments, and an increase in the structure's natural period may cause a resonance with long-period ground vibrations.

Furthermore, the study demonstrated that the SSI effect can cause ductility requirement to rise dramatically when the structure's natural period increases. The soil's irreversible deformation and failure could make the structure's seismic response even worse.

The ground moves differently when a structure is subjected to an earthquake's excitement because of the interactions it has with the soil and foundation. In general, there are two phenomena that comprise soil-structure interaction: Inertial interaction (b) and kinematic interaction (a) Soil displacement resulting from earthquake ground motion is referred to as free-field motion. The kinematic interaction is brought about by the foundation's incapacity to match the free fall motion, as it is buried in the earth and will not follow it. Conversely, the superstructure's bulk transfers the inertial force to the soil, leading to more soil deformation; this phenomenon is known as inertial interaction.

The kinematic impact is more prominent at low ground shaking levels, prolonging the period and increasing radiation damping. However, as the shaking becomes more intense, inertial interaction predominates, causing excessive displacements and bending strains concentrated near the ground surface, which leads to pile damage close to ground level. Near-field soil modulus degradation and soil-pile gapping limit radiation damping also occur.

Recent earthquake observations have demonstrated that the soil's and foundation's reactions can have a significant impact on the overall structural response. There have been numerous instances of significant structural damage from SSI in previous earthquakes. Yashinsky (1998) notes that the Loma Prieta Earthquake in San Francisco in 1989 caused damage to a number of pile-supported bridge constructions. According to a thorough numerical analysis conducted by Milonakis and Gazetas, one of the causes of the spectacular collapse of the Hanshin Expressway during the 1995 Kobe Earthquake was the seismic activity.

Many earlier studies on the seismic behaviour of raised water tanks disregard the impact of soil-structure interaction. Indeed, there appears to be a correlation between an increase in the lateral natural period of vibration and an enhanced spectral ordinate in some of the elevated water tanks that failed in the 2001 Bhuj earthquake in Gujarat, India. Therefore, in such cases, a small miscalculation of the lateral natural period may result in a small underestimation of the structure's design forces. According to Dutta et al. (2009), these elevated water tanks are vulnerable because to the stress that may form in the shaft walls while the tank is empty, especially if the effect of soil-structure interaction is not taken into account during the design process.

It could also be interesting to look at the potential for the columns of the frame-supported raised water tanks to generate this kind of tension. Figure 1 illustrates how an elevated water tank is affected by underestimating forces and ignoring soil-structure interaction.

Fig 1: Failure of elevated Water Tank

Conclusion

The seismic performance of a structure is related to the soil beneath the footing, as supported by numerous studies. If the interaction effect is ignored, there could be significant reductions in the margin of safety or an over- or underestimation of the true structural forces in the members. For an accurate evaluation of the structure's response, interactive analysis must be performed.

References

- Dutta and Roy "A Critical Review Idealization & Modelling For interaction Among Soil-Foundation-Structure System" Computer & Structure 80, 1579-1594 (2002).
- Dutta Sekhar Chandra, Dutta Somnath and Roy Rana, "Dynamic Behavior of R/C Elevated Tanks With Soil Structure Interaction", Engincering Structures 31, 2617-2629 (2009).
- Mylonakis G. and Gazetas G., "Seismic Soil Structure Interaction: Beneficial or Detrimental?" Journal of Earthquake Engineering, 4(3), 277-301 (2000a).
- Pitilakis Dimitris, Dietz Matt, Wood David Muir, Clouteau Didier and Modaressi Arezou, "Numerical Simulation of Dynamic Soil Structure Interaction In Shaking Table Testing": Soil Dynamics and Earthquake Engineering 28,453-467 (2008).
- Livaoglu and Dogangun, "Effect of Foundation Embedment on Seismic Behaviour of Elevated Tanks Considering Fluid-Structure-Soil Interaction". Soil Dynamics and Earthquake Engincering 27, 855-863 (2007).
- Yashinsky M., The Loma Pricta, California Earthquake of October 17, 1989 – Highway Systems, Professional Paper 1552-B, USGSs, Washington", (1998).