Earthquake Geotechnical Engineering

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Lecture 25

Soil-Structure Interaction

I welcome you for this course on earthquake geotechnical engineering. And we are discussing the module 3 of this course which is on ground response analysis, soil structure interaction and local site effects. So, within the GRA and local site effect today we are going to talk about soil structure interaction which is one of the important area which falls under the geotechnical engineering as well as structural engineering. So, we are basically under module 3 which is on GRA and local site effect. In the first chapter we already covered ground response analysis using 1D GRA and 2D GRA where we have 4 lectures. Today in the second chapter of this module we are going to talk about soil structure interaction, and we will have 2 lectures on this SSI about this and finally we will cover local site effects.

So today let us do for SSI soil structure interaction that is the part 2 and what is going to be covered in this chapters are listed here. And that first 5 points we will be discussing this lecture and the next 2 points we will discuss in the next lecture. So today we are going to talk about objective of soil structure interaction SSI, effects of SSI that is kinematic and inertial interaction. Then we are also going to talk about overall effects of dynamic SSI or seismic SSI, major issues and methods of analysis and directions of structure methods.

So, these will be today we are going to talk. Now let us have here what is the basic objective of the SSI, soil structure interaction. The basic principle of dynamic soil structure interaction can be explained which is like there is a book first book on SSI by John P. Wolf published in 1985 with the title dynamic soil structure interaction and which is in frequency domain and the in time domain version came in 1988 of the same authors. So accordingly, and otherwise also basically you know that the problem with the soil, soil is not a finite medium, it is a semi-infinite medium as we discussed during the wave propagation.

And major problem in dynamic SSI or let us say seismic SSI is the modelling of unbounded soil domain. For any analysis you cannot consider the infinite domain particularly when you are dealing with the finite element methods. So you need to model this unbounded soil domain. So that is the first and fundamental objective of the SSI or how we model the unbounded domain. For dynamic loading a structure which could be a foundation or superstructure it will always interacts with the surrounding soil, and it is not adequate to analyse the structure independently.

If seismic loading is applied to the soil region around the structure, then one has to model this region along with the structure. So in the case of static loading what we can do we can consider a fictitious boundary which can be included at a sufficient distance from the structure where one can expect that the response will diminish from a practical point of view. However, for dynamic loading this process cannot be used. Why it can be explained in this slide you have a structure which may be a structure and foundation are taken together. It may be subjected to external dynamic loading which may be due to wind load, or it may be due to subjected to seismic loading or a combination of these.

So basically, when it is subjected to some dynamic load the structure then it will create some waves which will pass through the soil and these waves will go to infinity and will not come back. But if you put a fictitious boundary as the case here in that case the waves will reflect back to the structure this dotted line shown here that is showing that this is the reflection occurring which is not actual in the actual scenario and in that case because this is fictitious boundary which is in fact there is no boundary, but you are putting for analysis. So as a result, this is we need to deal with this fictitious boundary. So, what the fictitious boundary would reflect waves originating from the vibrating structure back onto the region and so this is not permissible. So, what is required in soil-structure interaction we need to model this fictitious boundary and this modeling is the primary objective of the SSI.

So, what is done here when we model this fictitious boundary what is the requirement that this fictitious boundary should absorbs all incoming waves, and it should not reflect back which the waves which strike this boundary back to the structure. So that is the basic fundamental concept. So, as we discussed it should be model in such a way that it satisfy what we call the radiation conditions. So the condition where we say is that all incoming waves will be absorbed by this boundary that is basically radiation condition. So, this boundary should represent what we call an energy sink where only outgoing waves can occur, and this boundary should be modeled adequately.

So, the modeling of this boundary is very important in any soil-structure interaction analysis, and this is one of the major challenge that how to model this boundary. So as a result the fundamental objective of the analysis of SSI and dynamic response of the structure as well of soil is to be calculated taking into account the radiation of energy of the waves propagating into the soil region which is not included in the model what happens like when you put the fixes boundary actually as a result you cut down the remaining parts because for the soil stratum it is going to infinity in the horizontal direction as well as in the vertically downward direction. But once you put the fictitious boundary then you are cutting the region so first of all this boundary which you are putting should satisfy the radiation condition and it should simulate the missed part of the soil. So analysis of dynamic response of the structure as well as soil is to be calculated taking into account the radiation of energy of the waves which propagating into the soil region which is not included in the model so that is the fundamental objective and there are different types of boundaries which we will discuss in the next lecture on the SSI how to deal with the boundary. Now before that what are the effect of SSI what is the case when I consider soil structure interaction and I do not consider and where it is required, it can be explained by comparing the dynamic response of a structure which is founded on rock or an identical structure which is embedded in the soil.

So, you have two structures both structures are identical one is founded on rock, and another is embedded inside the soil. So, figure in the next shows two identical structures which are with a rigid base one sitting on rock while other embedded in soft soil. So you have here two identical structures are there structures are identical but at the base one is lying on the rock the first one the second one there is a soil column between bedrock and the base of the structure. Let us say that both the structures are subjected to same seismic excitation. So, you will see that response of these two structures even if the structures are identical will be very different in the second case.

So, in the first case when the structure is situated on the rock then the waves coming from the seismic source there will be not much change. This is similar to what we have discussed in ground response analysis. That is why this the first step of any SSI analysis is basically ground response analysis. So, the ground response analysis we have discussed that when the waves travel through the rock there is not much change in their amplitude or their characteristics but when these waves passes through the soil particularly through the loose soil then there is a change in their characteristics and most of the time these waves get amplified at most of the frequencies. So this is the case here two cases. Now what is the effect here? So, like here both are identical these things we already discussed a horizontal motion is considered here vertically propagating horizontal motion is considered with control point at the free surface.

First the seismic input motion acting on the structure will change so it is here let me explain with this slide. So, what is done here you have A, B, C, D, E cases are there. C is the case where you it is rock outcropping motion, bedrock outcropping motion. At the C you do not have any soil column on the top of it so whatever the motion coming at the point C will be your control motion or it is the motion which is given by the seismologist. And when you have at C then next when you have this at this motion if I put a soil column on the top of it which is the case in case of figure C what happens because there is no foundation there is no structure no building.

So, the input motion will convert into what we call the free field response or free field motion. The wave will start, input will be given at point C and then the waves after travelling they will reach at point D and E. So the amplitude of the motion which is denoted here in the case size of the arrow which you could see. So once like this was your input which is given here. First of all, due to the presence of the soil column even at the point C the motion will change which is normally less than whatever you have at the point C.

Then point D and E it will get amplified. So, the size of the arrow you see that at point D and E are different than the size of the arrow at the base which is at point C. So, this is what we call the free field response or free field motion, that is the second case. Now what I do in the case D we put structure on the location where the foundation is supposed to come that is the dotted line shown here. But we do not consider the mass of the structure or initial force, only stiffness is considered elastic properties.

So again, when the structure is present then the motion at the same point which you recorded at D and E earlier will further change and for the same input motion now you get in the output both translation and rotation. Translation component will keep varying over the height of the structure. It is not constant it is here and here and at the base of the structure that is the point O you get a rocking component. So, your input was only translation, but your output is translation as well as rotation you get. So this was the case. Now in the last case this is called kinematic interaction.

The case D where you are not considering the mass of the structure, but you are considering the stiffness properties will be treated as a kinematic interaction. Now in the case of E where you have considered the mass of the structure also in addition to what we have considered the elastic properties. In that case further the motion at the same points which have been recorded earlier will change and that is called the effect of inertial interaction.

These are the effects which we have discussed. So, effect of SSI can be discussed control motion plus effect of SSI then you get modified free field motion. When you means modified free field motion on the top of it you have effect of base then what is you called kinematic interaction and if you add the mass of the structure then you get inertial interaction. So, this is about that how we go from control motion to this free field motion then free field motion to kinematic interaction ki and ki to inertial interaction.

So, continue with this now let us talk about what is the effect how this soil which was present in this case in the second case how it influence your results, how it influence the response. So, each frequency component of the motion is affected differently because basically as you see during the ground response analysis that the amplifying factor they depends very much on frequency of excitation and in real earthquake you have a consists of a number of frequencies as a result the response which you get will be different for each frequency component. For example, in an acceleration times 3 which is quite different from the control motion. This amplifying of the seismic motion which we are discussing GRA that is indicates the structures which are founded on a deep soil soft soil side have been damaged more severely in actual earthquake that have neighboring structure founded on rock.

When the earthquake comes it has been seen during the damage in scenario those buildings those structures which are founded on rock rocky side damage is not so much but those founded on deep like soft soil sides the damage was more. So that shows that the effect of amplification. So, this was the first effect of GRA. So the effect of ground response analysis that is the effect of soil. The second the presence of the soil in the dynamic model will make the system more flexible and if your system is more flexible then there will be change there will be decrease in the fundamental frequency and after decreasing in fundamental frequency which may be significant below the applicable for the fixed base structure.

First effect is amplification. The first effect will try to increase the response of the system because due to amplification effect. In the second case omega n due to the presence of soil omega n is expected to decrease because when you consider the soil inside the system the value of k will decrease which is with the rock. So in case of rock k will be higher in case of soil k will be low and mass will more or less same. So, what here because k decreases as a result natural frequency omega n will decrease and once omega n decrease then it may go away from the frequency of excitation.

As a result, your response may decrease. Many times, it has been observed when you considered SSI the response may decrease due to this effect. The first effect ground response analysis may increase this effect may decrease the response. The implication of this reduction will depend on the frequency content of the seismic input motion because this also will depends also like because how far omega n is whether after change in the frequency where your natural frequency is going close to the frequency of excitation, or it is going away. If it is getting close to excitation, you will get amplification. If you are going away, then it will reduce the amplification.

In certain cases, the fundamental frequency will be moved below the range of so this is we already like will be moved below the range of high seismic excitation resulting in a significantly smaller system input felt by the structure.

The third effect which is related to damping. The radiation of energy of the propagating waves away from the structure will result in an increase of the damping of the final dynamic system. When you consider the in the soil in the system instead of rock because the damping material, damping of the soil is greater than that of rock.

So as a result, because the damping in the system have increased this may help you to reduce the response of the system. So, for a soil site which approach elastic half space this increase will be significant leading to a strongly reduced response. So here you have suppose if you have the material damping only then in that case you may not get any beneficial effect on the seismic response to be expected. So, you have three factors here now. One is the amplification due to ground response analysis. Second is the change in the natural frequency and third is the factor which is coming the effect of damping.

As a result, we have the effect of SSI will be due to all these three factors which we will discuss there. But before that it has been observed that the SSI increases when you have the more flexible the soil and the stiffer the structure. The issue basically the effect of SSI will be large when there is a difference in the stiffness of the structure and your soil. If this difference is large, then effect of SSI is more.

If difference is less the effect of SSI will be less. If you have very stiff structure which is on very flexible soil the effect of SSI will increase. If you have very flexible structure which is sitting on a rock, then effect of SSI will be negligible. The effect will be negligible for a flexible structure founded on a firm soil. So, this we already discussed the different components.

Now overall effects we have discussed three effects of SSI, and these three effects are some of them are contrary to each other. There are opposite effect that is in general because until you have the data for example what data is required for soil-structure analysis. You require the properties the stiffness and like mass of the structure then same stiffness and mass of the soil and then you calculate what we say the natural frequency of the system. And the next is your frequency of excitation your input motion. So all these input motion, material properties, geometrical properties are available then only you can carry it out the analysis and you may see whether due to consideration of SSI the response will increase or decrease because there are three factors and out of these three factors one ground response analysis is due to ground response analysis the response is expected to increase but other factors may increase or decrease your response.

So, but if we neglect the first one that is the effect of amplification then normally the response which you get considering the soil-structure interaction is the less compared to when you do not consider. So as a result, it is called the beneficial effect of SSI. So, this is economic consideration, let us see that what is the beneficial effect of SSI. For the approximate interaction analysis the control motion is directly used as input motion in the final dynamic system and the fixed base analysis leads to larger values of the global response as for example the total overturning moment and the total transfer shear and thus to be on a conservative design.

So that is there. Now economic considerations normally dictate that when designing the structures, the reduction in seismic force which result from considering the approximate soil-structure analysis be used. So, like we use approximate SSI for this from the economic consideration because like carrying out like exact soil-structure interaction analysis may require little more complication and more involving it is rigorous. There are some exceptional cases where the simplified interaction effects will govern the design. Thus, approximate method of calculating the interaction that neglects the free field site analysis and the geometrical averaging effect is inconsistent that may not be the exact one. For special structures, for example nuclear power plants SSIs always analyze consistent considering all effects for all effects means including ground response analysis then the effect on the natural frequency and the third one is the effect of the damping.

Taking the flexibility of underlying soil into account when calculating the seismic response so it complicate the analysis considerably and in general the presence of soil makes the system flexible and thus decreasing natural frequency or increasing natural period. So normally as we said when we consider the soil which is flexible compared to structure then the natural frequency of the system decreases, and it will increase the natural period. Normally acceleration for the structures which are founded on soft soil is smaller than that for the structures which are founded on rock. So, this slide says what are the beneficial effects of SSI. So, what you have here you have type first, type second, type third, three types of soil spectral acceleration coefficient.

The type first is rock or hard soil, type second is medium soil and type third is soft soil. So this is response spectrum which is given IS 1893 of course it is little bit change it is in IS 1893 like in 2002 version in 2016 it is little bit. So, what you have here in this case like when you increase the natural frequency may decrease when you consider the soil inside the system as a result period which is 1 over f and f is nothing but omega over 2 pi. So, 2 pi over omega n. So, when you have this time, the natural frequency decreases your period will increase and when your time period this increases so you will move most of the time from this plateau which is 2.5 you move in this side.

As a result, your spectral acceleration coefficient value of Sa by g decreases. So, because the value of Sa by g is decreasing so it is expected that in the design you require there will be less demand of forces. So, the design is going to be economical. So basically, effect of SSI in this case is considered to be beneficial and it is beneficial in the sense it will help to reduce your response. So, most of the time we observe this is the effect, but it is not always again.

In general SSI lead to smaller acceleration and stresses and thereby smaller forces in the structure. So as a result, your design is going to be economical. So whatever you are investing in analysis of considering soil structure interaction then you can save that money in the design. However there are numerous document case histories where the perceived beneficial effect of SSI have led over simplification in the design leading to unsafe design in foundations and superstructure. One of the authors like Mylonakis and Gazetas, 2000 in this case the authors have said that one need to do it is not always the case that there will be the effect of SSI will be beneficial rather than it may be contrary, or you may have other effect.

Now what are the major issues for when we carried out soil structure interaction analysis they are listed here. The first and foremost which is primary issue which we already discussed in soil structure interaction is the modeling of unbounded domain to satisfy the radiation condition. So this is the first important issue whether you are considering the other factors or not but this need to be must need to be considered. Now we need to do the modeling of soil in such a way that that constitutive model of the soil should be that it captures frequency dependent characteristics.

The properties of the soil for the dynamic load they are not constant rather than dynamic stiffness or impedance functions they are functions of frequency. So, when the frequency changes dynamic stiffness will change so that is the second point here in the modeling of soil. Once you have model for the linear case another issue comes modeling of nonlinearity of soil and which is nothing but strain dependent properties, strain dependent characteristics that the property of the soil is changing they are different at different strength and how they change with the different strength we have already seen during the last module which is on dynamic soil properties. If your soil conditions are saturated and loose then there could be liquefaction and need to carried out the modeling for soil liquefaction also. Though you have so many problems here but still what we do we consider for the simplicity the simple models which is the linear model's elastic model in that case the point number 3 and 4 will not be fulfilled that means we are doing only the modeling for the linear case where unbounded domain is modeled and soil frequency dependence characteristics is captured.

So, in SSI soil is mostly assumed as a linear though nonlinear analysis is also possible which we said. Total solutions sum of the response of the free field and the interaction part therefore nonlinearity cannot be considered until direct methods are used. So here what you do you find the total response in two steps. First is free field and the interaction part as a result because you are doing the sum of while to find the total response you need to have the sum of two components. So, you already assume some nonlinearity in the system and once you are carrying out the superposition then linear analysis possible.

And what we have components interaction effects are in two part one is Ki is kinematic interaction and Ii is inertial interaction both of these things we have already discussed, and free field motion is represented by ground response analysis or in short what we call the GRE. Now there are different methods of analysis for soil structure interaction and there are different approaches. So approaches which are used to solve SSI can be classified. First is continuous model which are based on theory of elasticity. Second is discrete models based on the lumped masses and third is finite element techniques.

So, in this case there are three methods continuous and then discrete and the finite element. Each one have its advantage and limitations. In case of discrete method like you have in the case of continuous model you have in continuous model which is based on theory of elasticity you can consider the damping of the system, but nonlinearity is not possible to consider. In the second case discrete model with lumped masses, you can consider the nonlinearity, but it is difficult to deal with the material nonlinearity as well as it is like inertial effects are difficult to consider. The third case finite element techniques it overcome the limitation of the first and second, but it comes at the cost of higher computation.

So, I will stop it here and we will discuss these two slides in the next lecture. Thank you very much. Thank you.