Applied Seismology for Engineers

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Week – 08 Lecture - 01

Lecture – 17

Hello everyone, myself Dr. Abhishek Kumar. Welcome to lecture 17 of the course Applied Seismology for Engineers. In lecture 16, we had discussed about the solution when a shear wave is passing through a particular medium. So, we tried to develop what will be the equation which will govern the motion, primarily in terms of displacement, which will be a function of space as well as time. Going to discuss about how the position of or how the displacement will change with respect to space, with respect to time, because of propagation of shear wave through a particular medium. Prior to lecture 16, in lecture 14 and 15, we discussed about the governing equation through which the primary and secondary wave will pass through the medium. In lecture 17, we tried to develop the solution of that particular equation. So, the equation remains a one-dimensional equation of motion for shear wave and subsequently the solution of it, which was given in terms of u, and u is the motion or the displacement component.

In today's lecture, lecture 17, we will be discussing about a new term which is called as local site effect, abbreviated as LSE, and the methodology based on which local site effect can be quantified numerically, which is also known as ground response analysis. So, basically, lecture 17, 18, 19, and 20, four lectures collectively, will give you information about what is ground response analysis, why it is important, particularly in terms of seismic aspects, and how one can determine or quantify local site effect using available methodologies. Primarily, we will be focusing on numerical methods, more specifically about linear method, equivalent linear method, and non-linear methods, which are mainly focusing on one-dimensional ground response analysis.

So, introduction, we know whenever there is an earthquake, in case there is a recording station, one can get to know what will be the shaking characteristics of the ground with respect to time. It can be quantified in terms of displacement values, variation with respect to time. It can be quantified in terms of velocity values at the point of observation or the recording station, how that particular point is sensing ground vibration in terms of acceleration, velocity, or displacement values, which are primarily because of different kinds of waves passing through your observation point, and whether it is a rotating drum coil or it is kind of piezoelectric sensor, it will sense the vibration and record it in terms of whether it is in terms of signature on rotating drum or in terms of the corresponding coordinates.

This is about the recording part of ground motion, which is very selective. So, depending upon if the recording station is there, you can record, and you can access the ground motion properties from the recording station. But we know recording stations are not spread all across; those will be specific to some location, may be individual or a part of some seismic array.

Again, some recording stations will give you recordings corresponding to local earthquakes; some will give you recordings corresponding to global earthquakes as well. What primarily will be witnessed in terms of an earthquake occurrence is there will be damage to the buildings. It can be in terms of minor shaking, it can be in terms of cracks, it can be in terms of major cracks, it can be in terms of partial damage, or complete collapse. So, the majority of the time, as a user of the society, what we witness during and after an earthquake is building damage and depending upon the response of the building to the ground shaking, often, we also experience injuries to the user, and the worst scenario is casualties also. So, that means one part is recording of the ground motion characteristics at your observation point. Second part is the actual scenario, which is going to be created because of the earthquake and its interaction with the system. It can be ground, it can be building, it can be any other kind of superstructure. Most often, we witness, we mean the user or who is living in a society or an expert, witness in terms of damages to the building and in terms of casualties. So, some of the damages you can say in terms of building damages, sometimes you can say in terms of excessive ground shaking, sometimes we can say in terms of landslides. If you go to hilly terrain, there will be landslide; if you go to the ocean, there can be tsunamis because of earthquakes. Secondly, at times, you can even have ground subsidence, minor to major, and depending upon the amount of ground subsidence, which is witnessed at the site of interest, you can say if it is within tolerable limit or not.

So, earthquake-generated seismic waves transfer. If you try understanding the overall geometry of the problem, there is a source or the focus at which, because of movement, possible movement along the two parts of the fault block, there was building up of strain energy. When the strain corresponding built-up of stresses exceeds the in-situ strength of the material, the material will undergo failure. That we are talking about the material which is available at the fault plane, which is actually coming into the picture when the two parts of the fault blocks are in contact with each other and experiencing shear. This is happening at the source. So, the motion will continue as far as the material is able to withstand or able to store the strain energy generated. Once the material undergoes failure, there will be development of seismic waves in all the directions with respect to the material. So, in three-dimensional space, waves have been generated from the focus and start propagating between the focus and the site. Because generally, when we report damages, it is not only confined to the epicentral distance, but even at times these damages will be reported at 100 kilometers, 200 kilometers, 300 kilometers away from the epicenter or more precisely the earthquake focus. So, that means we are witnessing the damages at 200, 100, 300 kilometers distance from your focus. We have just discussed about the waves which are generated at the focus. Once these waves start propagating through the crystal medium, primarily, these waves will undergo change in motion characteristics or in its frequency content as the waves interact with the heterogeneity present in the medium. There will be scattering between the source and the site, which will be happening again in three-dimensional space. Some energy will be lost in terms of particle motion heat, as a result of which, what is observed as you are moving away from your source of an earthquake and going away in every possible direction, there will be change in the motion characteristics at each and every observation point, primarily because of heterogeneity, particle motion, heat dissipation, and scattering.

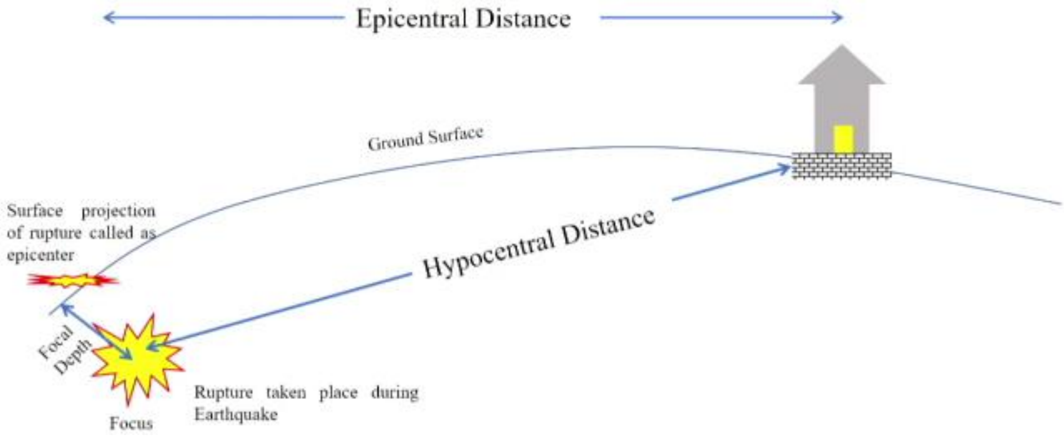
So, this change, first one, is generated at the source. So, you are having some motion characteristic at the source. When this motion interacted with the propagation path between the source and the site, it kept on changing its characteristics. Finally, the motion reaches the site. So, the second point tells about the orthogonality of seismic waves, which are actually propagating through a propagation path and reaching the bedrock. So, if I am having a building located over here and this is your ground level. So, directly, the seismic wave will not hit this particular building because this is primarily located on soil, but below this particular soil, there will be rock medium. Depending upon the characteristics of that rock, we can even identify it as bedrock medium. So, primarily, the incident wave which were propagating from the focus through the propagation path will be reaching the bedrock medium. Again, depending upon the medium characteristic, that means layer 1, layer 2, layer 3. These are also, if you remember, the derivation for shear wave propagating through a particular medium. The medium will experience particle motion. If it is shear wave, the medium will undergo shearing in a perpendicular direction. So, such a thing will happen in medium 3, medium 2, medium 1, or if there are 10, 15 kinds of layers. In each of these layers, this shearing will happen again. So, there was some incident motion which was modified already by propagation path. Again, this motion will subsequently be modified by layer 3, depending upon its impedance; layer 2, depending upon its impedance; layer 1, depending upon its impedance, which we have already discussed in one-dimensional equation of motion for shear wave and its subsequent solution. So, again, if you see motion characteristics at this particular section, motion characteristics at this particular section, motion characteristics at this particular section, and finally, at the ground surface. At each of these levels, the characteristics of the same ground motion, same ground motion means the motion which was generated from the source and reached the bedrock. The characteristics of that particular motion, that means the frequency content, amplitude, and the duration, keep on changing as the motion is interacting with different layers having different values of shear modulus, damping characteristics, Poisson's ratio, and mass density. Finally, what will be the motion which will be subjected to a building is not the motion which was actually reached to your site of interest through propagation path; rather, it will be now the modified motion, modified by n number of layers.

This particular modified motion, which is now available at the ground surface, is actually responsible for controlling the response of this particular building. So, if I am interested in finding out how much the expected level of seismic shaking is for this particular building, I have to take into account not the motion at the bedrock, but the motion which has been modified by n number of layers and is reaching your ground surface. It is primarily because of this reason that we are taking into account this, called the local soil, that means the soil which is available beneath the ground surface at your site of interest. If this is your site of interest, this particular soil, corresponding change in the motion characteristics, will be assigned by local site effect. If this is not your site, and the site is again 10 km, 15 km away from this particular building, then, corresponding to that particular site, whatever the soil properties are, that will govern how much change in the bedrock characteristics of motion will happen as the motion reaches the ground surface. So, corresponding to that particular site, how much amplification or de-amplification in the motion characteristics will happen will decide, corresponding to the 5 km distant site from this particular site, what will be the motion which will actually be induced by a particular earthquake generated at the source on that particular building. So, at times we see the motion will be amplified; that means there will be an increase in the amplitude of motion corresponding to the bedrock at the surface, and at times there will be de-amplification also, depending upon the relative characteristics of each of these layers. If there is a change in the stiffness, you can expect amplification or de-amplification. Why is it important? Because it is finally the amplified or de-amplified ground motion at the surface which is going to define how much this particular building will be subjected to seismic shaking or corresponding induced load because of a particular earthquake which has happened 100 km, 150 km, or 200 km away from your site of interest. Similarly, if the building is not there, but rather it is a soil medium, like sandy soil with a very high groundwater table, we know that sandy soil with a high groundwater table, if it is subjected to seismic shaking, can also experience loss in its shear strength, also known as liquefaction.

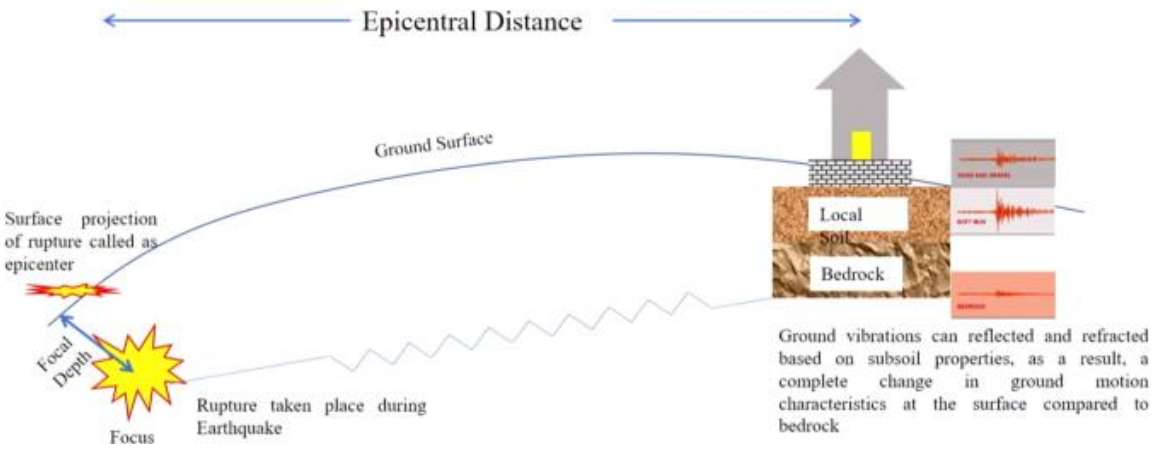
So, again, when we say it is losing the strength or subsequently there is building up of pore water pressure, it will not happen because of bedrock motion, but because of motion experienced at the surface, because the soil is available at the surface. So, even the loss of strength in the soil, which is experienced during liquefaction, will be because of modified ground motion. The same way, if you talk about excessive ground shaking, where is it happening? It is happening at the ground surface, again modified ground motion. Ground subsidence, where is it happening? At the surface, near the surface, again modified ground motion. Landslide, again, at that particular site, what are the characteristics of the slope? What are the characteristics of different layers available at the slope? That will define how much the change in the medium characteristics will happen because of local soil or the local material available at the site of interest.

So, we have understood that motion reaches the site at the bedrock level, subsequently undergoes amplification or de-amplification such that there will be a change in the medium characteristics as it reaches from bedrock to the surface. And finally, this surface motion is going to control the response of your building available at the ground surface. If you are talking about an underground structure, you have to correspondingly take into account the depth of that particular structure with respect to the ground surface, and then accordingly one can identify what motion, whether it will be surface motion, bedrock motion, or some other motion, one has to take into account in order to consider how much the loading is in terms of any underground structure. So, understanding this change in the ground motion characteristics because of local soil is called local site effect. As I mentioned here, local site effect means the effect in ground motion, which is primarily happening because of the soil medium available near the ground surface at your site of interest. So, there are different ways one can quantify the local site effect. One is by numerically taking into account the solutions of the equation which we have done in lecture 16 and quantifying how much change in the characteristics of the motion will be able to take place, taking into account the natural frequency of the medium and the frequency content of external loading conditions. We will discuss these in the coming slides and in lectures 18, 19, and 20 also.

So, whatever I have been discussing so far in a nutshell, we can understand through this particular slide. So, we are talking about ground motion primarily as far as the building damage, minimization of the building damage, casualty minimization, and ground subsidence minimization, each of these things which are directly the function of modified ground motion at the surface. So, we have to correlate this with respect to what is happening at the source.



So, if you consider this at the ground surface and this is your site of interest. Suppose here there was an earthquake, as a result of the rupture which has taken place during that particular earthquake. So, this is the focus. As a result of this, there will be the generation of seismic waves all around in the three-dimensional space, and this is a surface projection that is called the epicenter. So, this we have already discussed in earlier slides. Epicentral distance, hypo central distance, of course, we are not taking the curvature into account over here.



Now, if you go to a particular site, there will be local soil available beneath the ground surface, followed by bedrock medium. Sometimes, there will be weathered rock also. So, you can take that accordingly into account. So, seismic waves generated at the focus will propagate through the propagation medium, finally reaching the bedrock medium, and when these motions are undergoing, these will undergo reflection and refraction, as a result of which there will be a change in the characteristics of the motion generated at the focus and at any point along the propagation path. Remember, the focus and the site can be 100, 200, or 300 kilometers away from each other. Again, if you see at the particular site, the characteristics of the motion at three locations: one is at bedrock, second between the bedrock and local soil interface, and the third one is finally at the ground surface. So, you can see all these three motions, there is a significant change in the ground motion characteristics.

So, that means you cannot take bedrock into account and design a building because there will be a change in the frequency content as well as amplitude. So, you will end up underestimating the actual earthquake loading expected at your site of interest if you do not take into account local site effect properly. So, finally, the ground motion remains ground motion but is subsequently modified because of many characteristics. So, at the source, depending upon the epicenter coordinate, focal depths, fault plane solution, rupture length, rupture width, directivity effect, all these will define how much modification will happen at the source itself and finally, what will be the ground motion generated at the source. Propagation path, that means between the source and the site, depending upon the strength characteristics, depending upon the frequency content and its modification depending upon the attenuation characteristics of the motion along the propagation path. The last part is site characteristics: whether rock is there, soil is there, rock is outcrop or exposed to the surface, then the frequency content of bedrock motion. All this will define how much amplification will occur in the bedrock characteristics of the motion as it reaches any particular depth of the soil and subsequently to the ground surface.

Table 1 Summary of local site effects witnessed during various global EQs

Sr. no.	EQ	Moment magnitude (M_w)	Site effect evidenced	References
1	1985 Michoacan EQ	8.0	5 times amplification in bedrock motion in clay deposits in Mexico located at about 600 km epicentral distance	Finn (1994)
2	1989 Loma Prieta EQ	7.0	2–4 times amplification at soft soil sites in San Francisco bay area located at 120 km epicentral distance	Housner (1990)
3	1999 Chamoli EQ	6.5	Ground shaking felt up to Nepal, Pune. Considerable damage to buildings in Delhi and Dehradun located at epicentral distance of 200 km	Jain et al. (1999), Mahajan and Virdi (2001)
4	2001 Bhuj EQ	7.7	Ground failures, liquefaction in Umedpur located at 50 km epicentral distance. Considerable ground motion amplification and building damages in Ahmedabad located beyond 350 km epicentral distance	Rajendran et al. (2001)
5	2011 Japan EQ	9.0	Large area undergone liquefaction and uneven settlement in the city of Maihama and Tokai Mura located beyond 150 km epicentral distance	Nihon (2011)
6	2011 Sikkim EQ	6.8	Landslides in areas of Mangan, Jorethang, Lachung, Chungthang, etc. located away from the	Evidenced by the corresponding author during field visit to affected areas post-2011

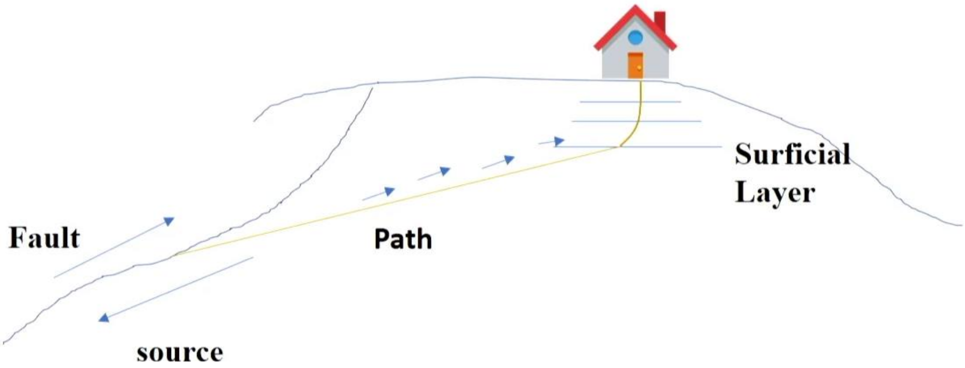
Now, we discussed local site effect, we discussed what local site effect is, why it is called local site effect, why it is important, and can be understood from this particular slide, which has been taken from Kumar et al, 2017, discussing non-linear ground response analysis for Nepal. So, further details of this paper can be found on my website. Now, here one important part why ground response analysis quantification is important has been highlighted by means of what has been reported by different authors in terms of whether ground motion amplification, whether in terms of significant building damages which were not only restricted to epicentral distance. Starting with the 1985 Michoacán earthquake, you can see the earthquake was of magnitude 8, correspondingly there was a 5 times amplification even at 600-kilometer radial distance from your site of interest. That means whatever ground motion after amplification and de-amplification would have reached at the bedrock, that motion had experienced 5 times amplification. So, that means if you take bedrock motion and design your building, you will be subjecting your building to one-fifth of expected motion; certainly, the building will not remain safe. Secondly, in the 1989 Loma Prieta earthquake, again, 2 to 4 times amplification in the San Francisco Bay area, which was located almost 120 kilometers away from your epicentral distance. In 1999, there was an earthquake in Chamoli of magnitude 6.5 in the Uttarakhand region of India. Again, you can see the vibration because of that earthquake were felt up to Nepal, Pune, and there were considerable damages to the buildings in Delhi and Dehradun. So, again, this example is just to highlight that because of the local site effect phenomena, the damages will not be confined only to the epicentral region but even at larger distances. Again, on 26 January 2001, there was an earthquake in Bhuj, which triggered liquefaction on a large scale. You can see over here it caused liquefaction in Udaipur located 50 kilometers, then a lot of building damages in Ahmedabad, which was located almost 350 kilometers away from your focus. Again, in 2011, there was an earthquake in Japan; that earthquake, of course, caused a lot of liquefaction in the Maihama and Tokai Mura regions, which were actually located 150-kilometer epicentral distance away from your epicentre. Then, in 2011, there was an earthquake in Sikkim of magnitude 6.8, which caused a lot of landslides in Mangan, Jorethang, Lachung, Chungthan areas, which were again significantly distant away from the focus. Collectively, based on the slide which is shown over here, what I am trying to highlight is it is not that as you go away from your epicentral, there will be a reduction in the magnitude or the amplitude of the ground vibration.

So, the overall objective of showing this particular slide is to highlight the importance of local soil because it can amplify even in very low amplitude ground motion. As a result, even if you are talking about X motion, which is significantly lesser than the motion experienced in the epicentral region, this X can be amplified 4 times, 5 times between the bedrock to the surface, and based on this, we can also see this 4 times, 5 times amplification actually leads to liquefaction, leads to building damages, and many more things. So, not only should one be focusing only on the epicentral region, but even if your site of interest is located away from your epicentral distance, you have to take into account the local site effect so that you can accurately estimate how much is the amplified ground motion at the ground surface. Now, historical significance is what we have just discussed depending upon the subsoil characteristics. Now, this modification of 4 times, 5 times amplification in the ground motion because of local soil definitely will pose more load to the building and subsequently, there will be more damages if the building has not taken the local site effect-based modified ground motion in its design and construction. So, the extent of damages can vary as a result of the local site effect, not only to the epicentral distance but even to distant locations. Some of the examples had experienced damage even up to 200, 300, 600 kilometers away from your epicentral distance.

Again, large-scale damages, 1985 earthquake, 1989 earthquake, we have already discussed. So, depending upon the impedance contrast, like how much change in the stiffness of the medium, that will define how much change in the amplification, de-amplification will take place between two layers which are adjacent to each other available in the stratification. So, I have mentioned some of the earthquakes; again, you can see about many more earthquakes where the importance of local soil effect was highlighted in terms of amplified ground motion, building damages, liquefaction, landslides, and many more induced effects. Again, in the Indian scenario, we discussed the 1999 Chamoli earthquake, the 2001 Bhuj earthquake, and the Sikkim earthquake. So, those also highlighted that even at larger distances, there can be building damages primarily because of amplified ground motion.

So, why it is important to understand the local site effect because if you are not taking the local site effect or corresponding to that the amplified ground motion into account, your building will be subjected to amplified ground motion, not the motion which is available at the bedrock, and if the building is not designed for this amplified ground motion, certainly the building will undergo damages. There are intended uses also, so depending upon the collapse of the building, there can be casualties. Again, if it is a landslide-prone region because of amplified ground motion, the slope can undergo failure. So, in order to minimize such kinds of building damages and subsequently casualties, one has to take into account how much quantification or how much change or modification the bedrock motion because of local soil has happened in the past or how much it is possible in the near future because of potential earthquakes. So, the change in the ground motion characteristics due to the presence of local soil can be determined, and it will help in developing how much will be the design response spectra for that particular site of interest. Corresponding to that, one can take into account how much will the load on the building; accordingly, one can design the building and do the construction part of the building. That means you know how much the loading is expected at the site of interest because you have taken that expected loading into account in your design and construction, your building remains safe, and subsequently, the intended users will also remain safe. It will also help in minimizing the end-user effects such as liquefaction, landslides because now you have already quantified expected modified ground motion at those sites so that accordingly you can take appropriate measures before an actual earthquake is going to hit your site of interest. If it is soft ground, you can actually improvise the stiffness of the ground before going for any kind of construction or any other utility preparation. So, subsequently, you can actually reduce even casualties, not only the induced effects.

Further induced effects, such as ground settlement, liquefaction, can be controlled because now you are having the modified ground motion-based information; you can quantify those and then take suitable remedial measures. If the ground is soft, you can go for ground improvement. If the building is not designed for that, you can appropriately see if retrofitting of the building is possible, then you can do that part, and subsequently, other induced effects can be quantified well in advance, and suitable measures which otherwise will be developing because of these induced effects. So, you can actually arrest those. Again, site-specific ground motion studies will help in quantifying local site effects and subsequently developing inputs for each of these above-mentioned parameters. So, local site effect, as I mentioned over here, from the source, vibrations are propagated along the propagation path. Now, at the propagation path, once it reaches the site, there will be a number of layers, and as you move from bedrock towards the surface, in general, the stiffness value will reduce. As a result, though the wave at the bedrock is not moving, the level was incident at some angle, but we will see because of reduction in the stiffness value, the wave propagation will be almost vertical as you move from deeper layers to the shallower layers and subsequently to the ground surface.



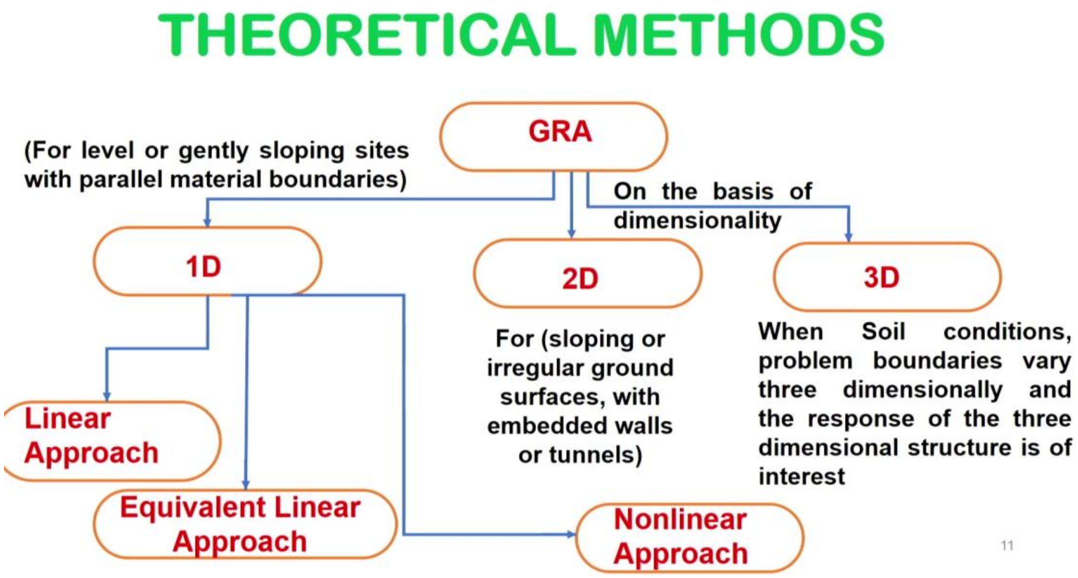
So, as mentioned in this particular figure, because of surficial layers which are available at the surface or near the surface, the wave propagation path will be almost vertical, and keeping that understanding into account, that means the propagation path is almost vertical, that will lead to shearing in the horizontal direction. So, we will take this understanding about propagation path, source effects, and more prominently, when we are discussing about local site effect, we will be taking into account the stratification characteristics and quantify the modified ground motion.

So, knowledge of rupture at the source where the waves can be generated during a particular earthquake, knowledge of the propagation path through which the wave will be modified till it reaches the bedrock at the site of interest, and then knowledge of subsurface layer medium which will be further enhancing or modifying the ground motion before it is reaching the ground surface. So, challenges here are we are interested to quantify local site effect, but we do not know what the expected level of ground is shaking during the design life of the structure. So, one has to quantify that also because that will tell how much the expected level of ground is shaking even at the bedrock level. So, there are some challenges; that means collectively we are interested to find out what is the more accurate ground motion which is actually going to be induced at the bedrock level because subsequently, once you have bedrock motion, you have subsurface layer details and their corresponding stiffness, you can quantify local site effect. Again, the properties of the propagation path one has to take into account if you are going for a completely region-specific study. Otherwise, if some site-specific recordings are there, you can take that into account and correspondingly modify them and go for local site effect quantification.

So, seismic hazard analysis, as we discussed in earlier classes, will help in quantifying the expected level of ground motion, usually at the bedrock level. In seismic hazard analysis, either we target the bedrock or we target site class A condition, depending upon the ground motion prediction equation used in the seismic hazard analysis. So this is going to give you the expected level of ground shaking at the bedrock. After that, you will get the motions at the bedrock, use those motions at the bedrock medium, and then go for local site effect and modify those motions or quantify those motions and determine the expected level of ground shaking at the surface. So, modified or modification—the bedrock motion due to layers of soil available beneath the site of interest—one has to deal with in ground response analysis. That means when we talk about local site effect, that is basically the phenomenon or the effect which is primarily coming into the picture because of the local soil available beneath the ground surface. If you go with ground response analysis, it is a measure of quantifying how much local site effect is possible at your site of interest for a corresponding motion and corresponding to local soils. I am telling in the beginning also, and I will tell again repeatedly in lectures 18, 19, and 20 also, that whenever we quantify local site effect, it significantly depends on the motion which you have used at the bedrock level. So, if you are using a very high amplitude motion, generally, it is seen that the amplification because of the local soil will be relatively low. If you are using very low motion, there will be a lot of amplification because of the local soil. This phenomenon is governed by the timing properties of the soil, which we will discuss in the coming classes.

So, there are different methods based on which one can assess or quantify local site effect. Experimental method—so this method utilizes ground vibrations in the form of ambient noise or passive sources, which are already existing in your domain of interest. Take those into account and try to understand the ground characteristics, as well as the change in those characteristics because of the vibrations, modification which are happening because of local soil characteristics. So, that is called experimental methods. Then comes empirical methods—these evaluate the ground motion characteristics, such as acceleration, velocity, and displacement values with respect to soil characteristics, and then one can determine how much the design response factor is. Again, one can refer to different codal provisions where the values of different coefficients corresponding to a particular site class have been defined. So, take those coefficients, refer to that, and you will be able to determine how much the modified displacement, velocity, or acceleration values at that particular site class will be because of a target input motion. The third one is the semi-empirical method, where you utilize ground motion from records and take site-specific observations, which you are determining from in-situ experimental methods. Clubbing these two, you will be able to determine the local site effect using the semi-empirical method. So, you have the experimental method, which is going to use completely in-situ measurements. Empirical methods mean that based on codal provisions, coefficients are known to you depending upon the site class, depending upon whether you are targeting acceleration, velocity, or displacement, you can pick up the coefficient and determine the design response spectra. In the semi-empirical method, even the site property you are going to define based on ground motion regional records and then take that into account along with other properties of the site and quantify the local site effect.

Next is theoretical methods, or sometimes these are also referred to as numerical methods, where you will take into account the soil properties at the particular site of interest and the solution of the one-dimensional equation of motion for shear waves, which we discussed in the last class, and see how the displacement changes between the base of a particular soil layer to the top of that particular soil layer, and subsequently, it follows. So, this can be quantified in terms of one-dimensional space, primarily when you are talking about local site effect, where the stratification is almost horizontal, and the surface itself does not have much change in the topography of the medium. You can go with one-dimensional ground response analysis. Subsequently, depending upon the change in the medium properties, you can also look into two-dimensional and three-dimensional ground response analyses. So, one has to take or refer to two-dimensional and three-dimensional wave propagation models. As far as this particular course is concerned, because we will be discussing ground response analysis, we will be focusing on one-dimensional ground response analysis in particular. Hybrid methods can take into account long-period vibration and correlate the characteristics of those vibrations with respect to local soil properties. So, as I mentioned, theoretical methods—we will be covering more in terms of ground response analysis.



So, in theoretical methods, we will be quantifying ground response analysis numerically, primarily based on three methods: one is the linear method, the second is the equivalent linear method, and the third one is the non-linear method. So, whenever we say linear, equivalent linear, or non-linear method, basically, we are trying to understand the response of local soil, keeping the soil property constant, keeping the soil property as a function of shear strain or corresponding to shear strain, and thirdly, how, with respect to the duration of loading, the change in the dynamic properties of the soil is taking place—that we will quantify in non-linear analysis. So, there is a significant difference between linear, equivalent linear, and non-linear analysis. It will be clearer once we start discussing each of these methods, which we will try to cover in the coming classes. Again, it will remain within one-dimensional, two-dimensional, and three-dimensional space. So, depending upon whether you are taking into account a level or gently sloping ground, quantifying local site effect based on one-dimensional ground response analysis is going to give you relatively accurate values. If there is sloping ground or irregular surfaces, you can take into account two-dimensional ground response analysis or wave propagation models. Again, in the three-dimensional space, if we are talking about some basin effect, you can take into account the three-dimensional ground response analysis.

So, some important terminologies that we will require throughout your ground response analysis—why are these important? Because we are trying to understand local site effect, which is the modification in the ground motion characteristics between the bedrock and the surface. Now, there are two ways: one is that you have the bedrock motion known to you, or if you have a sensor placed at the bedrock level at your site of interest, and you are regularly monitoring it. This generally does not happen because if you are going for recording, you are not using it at every site—like, if every site is used for construction, not every site will have a sensor recording the motion. Even if you do so, the motion will be recorded during a particular earthquake, so that motion cannot be utilized to quantify local site effect and incorporate those modifications in your design and construction. So, existing motions that are available—are mostly referred to as bedrock motion. So, one can refer to region-specific seismic hazard analysis, one can refer to regional ground motion records, and one can also refer to the damages that have happened in the past or historical earthquake-induced ground vibrations or intensity values and try to figure out what is most likely to be repeated ground motion at your site of interest. That means if regional ground motion records for an earthquake, which has been identified as the most promising or more potential earthquake to your site of interest, can trigger significant seismic hazard at your site of interest, certainly that motion you will take into account, modified at your bedrock condition to the site of interest. That means if I am targeting my site as being potential to experience a motion of, say, 0.1g, this particular 0.1g I am quantifying based on seismic hazard analysis. But 0.1g is just a quantity or a number given from seismic hazard analysis. In order to perform ground response analysis, one has to have a complete understanding of the motion corresponding to which the peak ground acceleration is 0.1g. So, you can refer to regional ground motion records that will give you an understanding of the general characteristics of ground motion in that particular region. If regional records are not available, one can refer to records at larger distances, finding similarities in terms of seismic hazard or seismic activity between the region of your interest and the other region where ground motion records are available.

The third approach can be if there are no regional records, even at your site of interest or any other site having similar seismic activity. This is possible because, many a time, ground motion recording instruments are also not available. So, in such a case, one can solely depend upon synthetic ground motion or ground motion simulation, taking into account the source, propagation path, and characteristics of the current medium in which ground response analysis has to be done or any particular region where a similar kind of propagation path, characteristics, as well as source characteristics, have been quantified in the literature. So, you can refer to such papers, and there are, again, synthetic ground motion generation models, so one can refer to those and quantify the bedrock motion.

Again, when we talk about motions, one has to be very clear. When we are talking about motion, whether this particular motion is recorded at bedrock, the motion is recorded at the ground surface, or the motion is recorded at the outcrop? Where the motion has been recorded? Because if you are taking that motion as site-specific motion and further utilizing it in ground motion ground response analysis, one has to ensure that the motion itself, which you are using as input motion, should also not be recorded at the ground surface and should not be recorded at the outcrop because outcrop motion will have different values in comparison to bedrock motion. Similarly, surface motion, even at the soil site, will have different amplitude in comparison to bedrock motion. So, if you take those motions directly as bedrock motion and do ground response analysis, again, the quantified surface motion will not be a realistic value.

Hence, one is the ground motion which has to be used as input motion while performing ground response analysis. The second is where that particular motion has been recorded. If the motion is at bedrock, then it is fine. If the motion is at the outcrop, you have to change that motion's characteristics to bedrock condition. If the motion is recorded at the ground surface, again, you have to change the characteristics such that this is a modified ground motion, which now I will be using as input motion. And once I knew the characteristics of that motion record, I have modified it. So, now the motion which I am going to use for ground response analysis is actually indicating the characteristics of motion at the bedrock itself. That is why these important terminologies come into the picture, which will help in understanding where the motion has been recorded and, subsequently, whether modification is needed or not in these motions before you start utilizing this motion in ground response analysis.

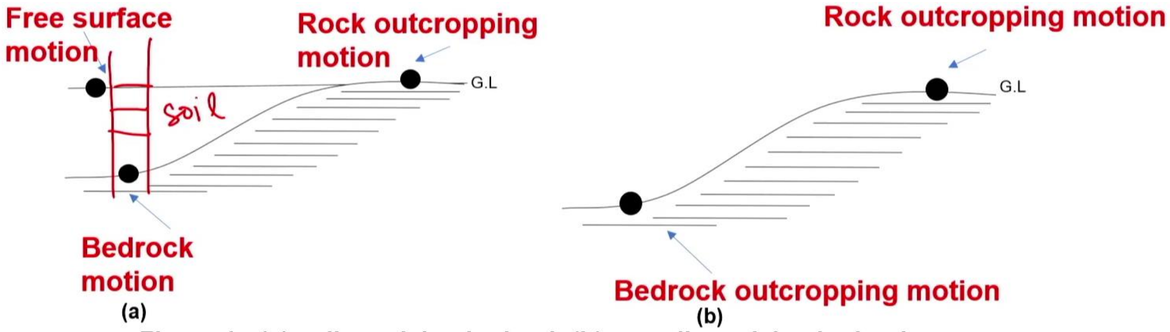


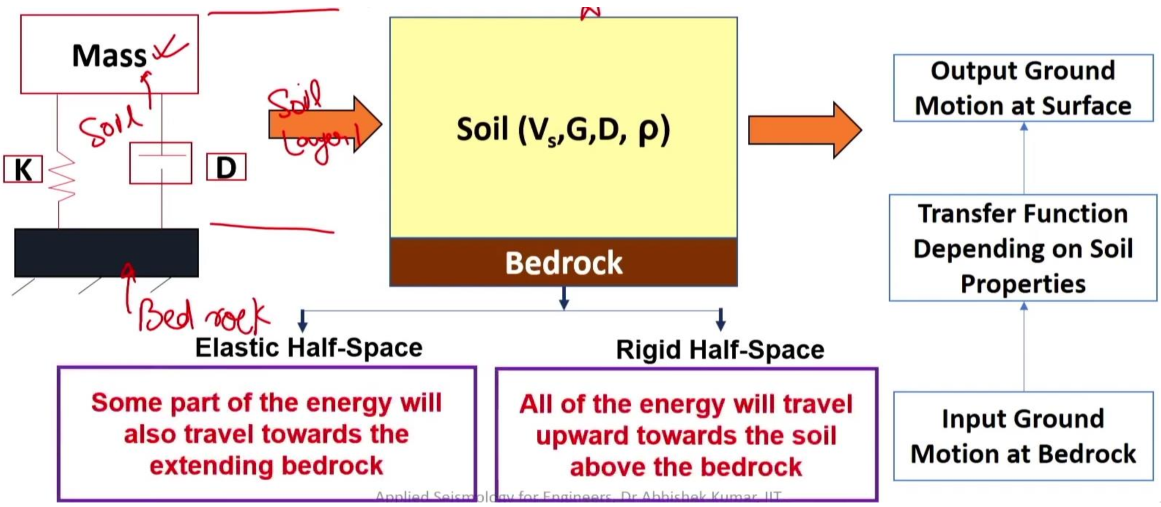
Figure 1 : (a) soil overlying bedrock;(b) no soil overlying bedrock

So, first, you can see over here, depending upon the lithology, it is quite possible that the bedrock is located at a certain depth beneath the soil medium. Then, there is a free surface on which you are going to construct a building, and then, at times, the bedrock is also, or the rock which is available at the bedrock medium, is also exposed to the surface. So, such things mean that motion is there, but in order to quantify the local site effect, one has to understand. If it is outcrop motion, certainly I cannot use it, but because this is free surface motion, due to the free surface, there will be amplification in the motion characteristics. Similarly, if it is bedrock motion, directly you can take it into account because this motion you will take into account and quantify the local site effect from each of these layers. Thirdly, if it is free surface motion, that means it is already the motion available at the ground surface. Remember, all these things I am referring to in case there is site-specific ground motion available to you. So, if motion is not available at a site-specific location, you can choose motion from a similar seismic activity region and use it over here. But one has to have an important understanding because that can affect your local site effect significantly. So, important terminologies are, again, you can see over here: bedrock outcrop motion and then rock outcrop motion. So, bedrock is also there, but there is no soil above it. And then, there is rock, which is also exposed to the ground surface. In between the two, there will be a change in the motion characteristics.

So, important terminologies: bedrock motion—the motion which has been recorded at the base of the soil column or at the top of the rock. So, it is the motion that is available beneath the soil. This is called soil. So, the base of the soil or the top of the bedrock—that particular motion is called bedrock motion. Free surface motion—that means motion which is recorded at the surface or the top of the soil. The third one is rock outcrop motion—that is, the motion recorded at the exposed rock at the ground surface. The last one is bedrock outcrop motion—that means the motion recorded at the bedrock, but there is no effect of local soil over here, and it is not the rock outcrop, but it is significantly at a different level with respect to the rock outcrop.

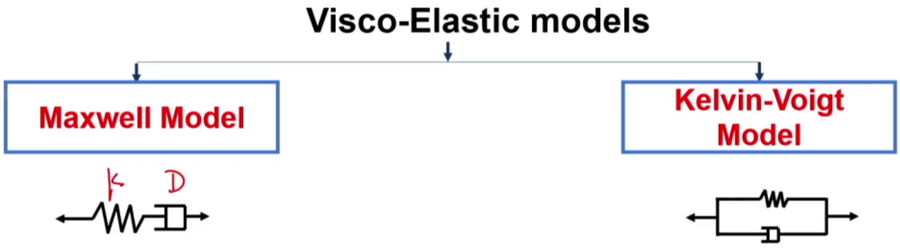
So, these possible locations mean that if you are talking about input motion, these are the possible locations in which you can find input motions. If that part is not clear to you, you can take free surface amplification or refer to seismic hazard values and quantify the motion accordingly, such that whatever you are going to get corresponding to bedrock condition, your motion should also match with the peak ground acceleration value corresponding to bedrock condition. If it is corresponding to site class A condition, at outcrop motion, it will be used over here. Then, do deconvolution, transfer the motion to bedrock condition, and then use it for ground response analysis.

So, when we go with 1D linear ground response analysis, there are some assumptions, meaning the soil layer properties are not changing. So, it is like the soil properties do not change with respect to shear strain. Whatever initial property you have taken into account, the properties are going to remain constant in terms of linear ground response analysis. So, we will not be bothered. In general, the soil properties change with respect to shear strain experienced by the soil. But in linear ground response analysis, we will be using the same properties throughout the solution.



So, consider over here: there is bedrock, and there is soil medium. Inertial forces will be generated, so the medium has some stiffness value, which in terms of soil, we also quantify in terms of shear modulus. And then, you are having damping properties. So, collectively, a soil medium through which, if you consider this as a bedrock medium or the medium in which there are incident ground motions, this motion, and this is your soil medium, which has some mass and stiffness properties as well as damping properties. Depending upon these properties, how much modification the motion will undergo for this particular mass m has to be quantified. So, you can approximate this with respect to one soil layer. This is one soil layer, and this is your bedrock motion. So, how much amplification in the soil layer at the surface will take place because of some soil which has stiffness properties of K and damping properties of D—that will be quantified in terms of local site effect. Soil again has some value of shear modulus, some value of shear velocity, damping ratio, and mass density. So, again, the objective is, you have input ground motion at the bedrock level. Using these properties of the soil layer, we will try to find out the transfer function, taking the impedance contrast of that particular soil layer with respect to the bedrock layer, determining the transfer function, and then, taking the transfer function into account, modifying the input motion. You get the output motion at the top of that particular surface of the soil. If one layer is there, you can say transfer function of the soil, which is available beneath the soil surface and the bedrock, determine the transfer function, multiply it with respect to the input motion, and you will get output motion and frequency content. Then, subsequently, you can convert it to the time domain. So again, bedrock, there are two characteristics. One is elastic half space, where you see when there is incident wave, some portion of the energy wave is carrying will propagate downward, and the rest of the energy wave it was carrying will start propagating upward and control how much will be the vibration controlling the response of the soil, and then elastic half space and rigid half space. So rigid half space, entire energy will be incident that will propagate towards the surface and controlling the response of each of the soil layers.

So, assumptions for ground response analysis, 1D ground response analysis, based on some assumptions that the soil boundaries are horizontal, stratifications are horizontal, response of the soil are primarily because of SH wave. You remember, wave is propagating like this and causing shearing in horizontal direction because of vertically propagating shear wave between the bedrock to the surface triggering SH kind of motion. Soil and bedrock are considered to be extending infinitely in horizontal direction and soil behaviour in ground response analysis, particularly the soil behaviour, is approximated by KV solids or Kelvin Voigt solid. When we talk about Kelvin Voigt solids, it is a viscoelastic model. Again, viscoelastic model, we mean viscoelastic model means there is component which is coming from elastic response and a component which is coming from the rate of loading or the viscous behaviour of the medium.



So viscoelastic model, again you can see two kinds. One in which one is called as Maxwell model, which generally attempts to use for modeling the polymers. In case of viscoelastic model which you are going to use in ground response analysis, we will be using Kelvin Voigt model. So, Maxwell model, you can see both the value of stiffness or elastic material as well as the damping, these two are connected in series. However, in case of Kelvin Voigt model, which we will be using for modeling the soil medium, the damping as well as the stiffness are connected in parallel. That means, from this particular side if there is loading, the other particular side there is response. So, if this you are considering as bedrock, the other part you will consider the top of that particular soil layer. Now, based on this particular photo which is given over here, you can see at any particular time of loading, the strain value in spring as well as in the damper will remain constant because these two are in parallel.

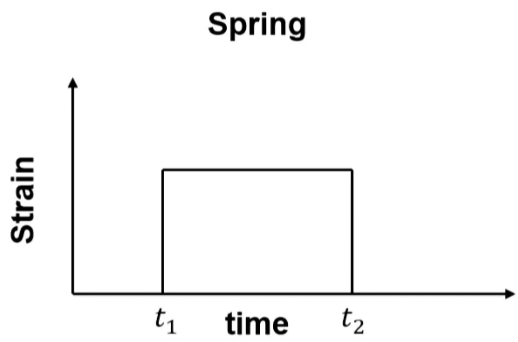
$$\epsilon_{total} = \epsilon_{spring} = \epsilon_{damper}$$

However, the total stresses will be the summation of stresses in elastic spring as well as in the damper. Remember, I am telling about elastic spring, so the loading in the spring will remain within the elastic limit. So, same thing which I mentioned here, the total strain will be equal to the strain in the spring or strain in the damper.

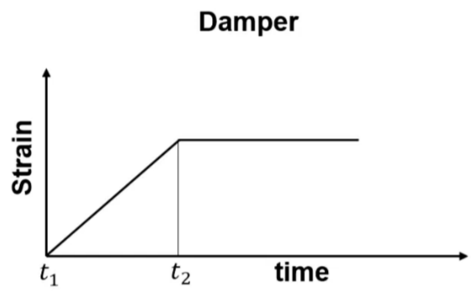
$$\sigma_{total} = \sigma_{spring} + \sigma_{damper}$$

$$\tau_{total} = \tau_{spring} + \tau_{damper}$$

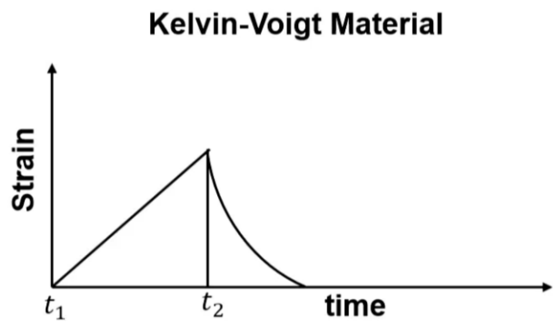
Total stresses will be summation of, we are talking about normal stress or shear stress, that will be the summation of stresses in the spring plus in the damper.



Now let us see the loading behaviour. If you say in terms of spring, because it is elastic, so depending upon the time you apply loading and you remove the loading, the spring is going to experience some strain, elastic strain, and then it will come back to its original position. So, this is the loading duration between T1 and T2.



If you go with damper, you applied some loading and after that whatever is the response or resistance damper is going to offer, that will be there. The initial part will be the rate at which you are applying the loading, that will govern how much will the strain energy or the resistance damper is going to offer to the external loading. So collectively, if you merge these two in parallel, which is the indication of KV solids, you are going to get this particular response.



This is how the, with respect to time, the strain will be mobilized in the KV solids. So initially it will be linear, but after reaching a particular point, even if you remove loading, it will not suddenly stop offering resistance, primarily because there is damper which is going to offer some resistance to loading, and that resistance will decay with respect to time. So, transfer function which will be used throughout, so transfer function is generally used to represent or to correlate the motion between the bedrock and, I mean, the motion which is incident at the bedrock and the motion which will be modified motion at the top of that particular layer. So valid only when the initial condition of strains are 0. System should be linear, time invariant and satisfy the position, superposition, and homogeneity principle. It acts as a filter media to change the input motion to the output motion. Primarily, we will be using in terms of linear ground response analysis and try finding out how much will be the modified ground motion.

So, in one ground 1D ground response analysis, this is just an overview. So, there is an input motion which is incident at the bedrock. This motion, depending upon the characteristics of the soil layer in which it is incident, it will try to find out firstly the fast Fourier transformation or the frequency content of this motion using fast Fourier transformation. Then multiply this with respect to the transfer function. How much is the transfer function? How we are going to quantify that I will discuss in the next class. So, this is a flowchart of the solution for 1D linear ground response analysis. So, input motion is there, then transfer this motion from time domain to frequency domain, multiply this motion with respect to the transfer function which is a function of impedance contrast of the medium through which the wave is passing. So, you will get from here FFT into transfer function. Again, this will be in frequency domain. Do the inverse fast Fourier transformation of this, you will get in time domain, which will be basically the output motion or the motion at the surface. So, output acceleration time is 3.

$$U(z,t) = A\cos(\omega t+kz) + B\cos(\omega t - kz)$$

Now in earlier lecture, that is lecture 16, I have derived this particular equation as the solution of one-dimensional equation of motion for shear wave propagating through a medium. That is U(z), I have mentioned over here, that is space, and t is time equals A cosine of omega t plus kz plus B cosine of omega t minus kz.

$$e^{i\theta} = \cos\theta + i\sin\theta$$

Now if you use Euler's theorem, exponential of iota theta equals cos theta plus Iota sine theta. So, using this, the above equation has been modified. How it has been modified, we will discuss in the next class.

$$U(z,t) = A\,\mathrm{Re}\{e^{i(\omega t+kz)}\} + B^{*}\,\mathrm{Re}\{e^{i(\omega t-kz)}\}$$

Finally, you will get the motion in this particular form, that is A real part of the quantity written in the bracket plus B real part of the quantity which are written in this within bracket. So, Re is the real part of the complex function.

$$U(z,t) = Ae^{i(\omega t+kz)} + Be^{i(\omega t-kz)}$$

Therefore, the solution of one-dimensional equation of motion which we will be using ground response analysis, U (z, t) equals to A exponential Iota omega t plus kz plus B exponential Iota omega t minus kz. So, this is the equation which we will modify with respect to the previous equation derived in lecture 16. Get this equation and then subsequently try to quantify the local site effect or the motion properties which are going to modify because of a particular soil layer having known value of stiffness and damping and then input motion which is again motion corresponding to different frequency content. So, with this we have come to the end of this particular lecture. Thank you everyone.