Applied Seismology for Engineers

Dr. Abhishek Kumar

Department of Civil Engineering

Indian Institute of Technology Guwahati

Week – 06 Lecture - 01

Lecture – 11

Hello everyone, welcome to lecture 11 of the course Applied Seismology for Engineers. In earlier lectures, we have discussed primarily about what are the different layers of the earth in terms of physical properties as well as in terms of mechanical properties. As a result, because of the development of convection current primarily driven by variation in temperature across the depth, there will be movement of different plates across the globe. As a result of this, primarily at the boundaries where the two plates are coming in contact with each other, there will be development of shear strain; there will be accumulation of shear strain. Subsequently, over the period of time, when the stresses which are getting accumulated is more than the in-situ shear strength of the material, the material will undergo failure. As I mentioned that across the globe, there are different kinds of plate boundaries: some are transform plate boundaries, some are convergent plate boundaries, some are divergent plate boundaries. So, depending upon the type of movement which are dominating at a particular plate boundary, the two plates might be moving towards each other, they might be moving away from each other, or there is slight pass movement with respect to each other. As a result of this movement and the energy which is getting released when the in-situ stresses are more than the shear strength of the soil of the material involved, there will be release of energy in form of earthquakes. This is the general understanding about earthquake.

Later on, wherever the earthquake is happening, there might be release of seismic energy from the source along the propagation medium like between the source where the earthquake has actually happened, and if you take into account the building damages or the casualties or induced effect, these two locations might be at certain kilometer distance, maybe 200-kilometer, 500-kilometer radial distance away from each other. As a result, whatever seismic waves are getting produced at the focus of the earthquake will be interacting along the propagation medium. Again, the propagation medium is also consisting of rocks. There will be heterogeneity present in the medium. There might be gaps also present. Unconformity might be present in the medium. As a result, whatever was the characteristics of ground motion at the source means how much is the frequency content, how much is the amplitude of motion generated at the source that will continuously undergo modification along the propagation path. Subsequently, once it reaches to a particular site, there will be other phenomena which we will be discussing in today's class.

So, collectively whatever was generated at the source will subsequently undergo modifications whether it is because at the source, whether it is because along the propagation path, or whether at a particular site of interest where one is interested to find out how much is the earthquake loading, how much is the forces applicable to trigger any induced effect such as landslides, such as liquefaction. So, in today's class, we will be discussing about what is ground motion, what is primarily the simulation because many a times what we have seen that earthquake occurrence in particular region if you take into account the Himalayas, the seismicity has been building up. There are earthquakes for centuries and more than centuries. But if we take into account the ground motions which are available, regional ground motion records, hardly for last 45-50 years in which ground motion records are available. Again, if we take into account the ground motion which might have been generated during deadly earthquake such as 1897 Shillong earthquake, 1905 Kangra earthquake, 1833 Bihar Nepal earthquake, 1934 Bihar Nepal earthquake. So, these are first thing when I say 1833 is the year in which the earthquake has happened, and Bihar Nepal is the region in which primarily the epicenter was located. Similarly, with respect to Kangra earthquake, so 1905 there was an earthquake in Kangra. Now if we take into account the damages, the casualties, loss of lives, again failure of utilities whatever were available during that particular earthquake time, those are well documented.

But in order to understand what will happen if similar kind of earthquakes which happened during 1905, which happened during 1950 Assam earthquake, which happened during 2005 Kashmir earthquake, or any other earthquake which had happened before actually earthquake recording had started. So, in order to understand those damage characteristics and to see what will be the damage scenario if similar earthquakes are going to get repeated during the present time or if you are going to construct an infrastructure at present which might be lasting for next 25-35 years, what is the potential ground motion one should take into account such that whatever has been experienced in the past in terms of building damages, in terms of casualties can be minimized to significant extent. It will only be possible if there is a way we can find out what is the level of ground motion, what is the characteristics of ground motion which might have been triggered during 1905 Kangra earthquake, 1897 Shillong earthquake, or any other earthquake for which actual ground motion is not available. So, as the name suggests in today's class, we will be discussing about what is ground motion simulation. Simulation means there is no recorded ground motion but what we are trying to do we are trying to synthesize taken into account significant parameters, significant number of parameters which are representing the phenomena happened during a particular earthquake.

So, we take that into account so that we should be able to synthesize, we should be able to simulate, we should be artificially able to create ground motions. Ground motions again if we take into typical ground motion which are available at present in terms of records that is acceleration time history, displacement time history or velocity time history. Similar thing we are trying to simulate artificially rather waiting for major earthquake or great earthquake to get to be witnessed in the near future and then we take that record to analyze the safety of existing infrastructure or to go with design of new infrastructure. So, primarily when we discuss about ground motion simulation, we are trying to understand what will be the characteristics of ground motions for which actual ground motion record firstly either it is not available or if we are interested to generate the second part, if we are interested to generate ground motion prediction equations or some empirical correlation which will give an understanding based on empirical correlation that what will be my spectral acceleration at different periods. So, again we will go with ground motion prediction equations.

These are regional empirical correlations which are primarily based on the larger set of ground motion record but as we mentioned many a times what will happen that regional ground motion records are not available. As a result, you are interested to develop ground motion prediction equation, or these are also called as attenuation relation. So, what will happen we are interested to develop some empirical correlation for regional earthquakes but whatever database is required to develop these empirical correlations are not available. Primary reason is number of ground motion recording instruments are not uniformly distributed in a particular region. Secondly, even if there are records since last 35, 40, 45 years not all the earthquake magnitudes have been covered in such ground motion records. Primarily we might be witnessing different earthquakes all along the Himalayan boundary but if we take into account those are in the range of maybe 3.5 to as high as maybe 6.5, 6.8, 7-magnitude. But on the contrary, if we take into account last 100, 150 years there have been incidences of great earthquakes also.

So, that means whenever we are taking into account the existing database and try to develop ground motion prediction equation, there are gaps in terms where there is no recorded ground motion to develop these empirical correlations. When do not have any recorded ground motion and we are developing an empirical correlation using available database, that means that database will not be applicable to predict ground motions because of maybe the magnitude of the earthquake for which the database is not accounting. So, if the database is not having above 7 magnitude earthquake record and you are developing ground motion prediction equation, then certainly that ground motion prediction equation cannot be used to predict ground motion properties for any earthquake having magnitude above 7. So, the ground motion prediction equation also requires many a times the simulation to be done on significant scale such that all magnitude earthquakes, all hypo central distance as we know that whenever earthquake is happening very close to the site the ground motion will be significantly higher as the epicenter is far from your site of interest, there will be significant reduction in the amplitude of ground motion. So, again when we are going with ground motion prediction equation development, we have to take into account very much similar to larger set of different magnitude ground motion, we also have to have ground motion which are covering larger distance of hypo central distance such that if I am having a site located at one particular coordinate corresponding to this particular site, there might be a number of seismic sources, this is my site of interest.

So, any of these seismic sources, whether you are calling it as 1, you are calling it as 2, 3, 4, so depending upon the orientation of this particular fault with respect to the site and the seismicity with which each of these faults are able to produce earthquakes, the ground motion because of fault 4, because of fault 3, because of fault 2, and fault 1 will be different, significantly different. So, how much significantly different depends primarily upon what is the magnitude of the earthquake which has been triggered on fault number 1, on 2, on 3, and 4. Depending upon the relative position of each of these faults with respect to your site of interest, we can say site 1 is closer. That means any earthquake happening on site 1 will have significantly higher amplitude of ground motion in comparison to site 4, and these kinds of understandings we can make.

So, when we are going with the development of ground motion prediction equations, one is we have to have a larger dataset because that dataset will give us an understanding of what is the property of ground motion and how it is correlated with respect to earthquake parameters such as magnitude, epicentral distance. Subsequently, we can also bring into account many more parameters, which resemble propagation path, source properties, and site properties. So, we will discuss in the coming slide what are source, propagation path, and site properties, which can also be taken into account while developing ground motion prediction equations such that, in the end, one is able to develop an empirical correlation. The sole purpose of empirical correlation is to predict how accurately the future ground motion will be. Taking that prediction into account, one can go either with respect to the design of earthquake-resistant buildings, retrofitting of buildings, or quantification of induced effects. Subsequently, the findings in terms of seismic hazard analysis can also be applicable with respect to city planning, city development, and all that.

So, how this will be used in seismic hazard analysis, we will discuss in lecture 12 and lecture 13. So, when we are discussing ground motion prediction, our understanding starts with seismic waves released during a particular earthquake. If you put a recording station, what it will sense is basically how much vibration is happening at a particular site of interest, wherever we have put our recording station, and how this variation in the amplitude of ground motion is happening with respect to time. This is basically the signature of ground vibration or ground motion. Whenever we say any ground motion record is available, that means we know how, with respect to time, the ground acceleration, the ground velocity, or the ground displacement was changing when the earthquake-generated seismic wave passed through your recording station.

Earlier also, we have told and later on also we will tell that whenever seismic waves are produced, it is not only one type of seismic wave. There will be different types of seismic waves. As each of these seismic waves passes through your recording station, it will leave some signature on your sensor of your recording station. That will be indicated in terms of how the acceleration, how the velocity, and how the displacement value of the ground is changing with respect to time because of the passage of different seismic waves from your recording station.

Now, the recording station can be installed at the ground surface, it can be installed at the soil top, it can be installed under outcrop conditions, or it can be installed even within the ground. So, all kinds of recording stations are available across the globe. Even there are recording stations that use downhole arrays, that means recording how the ground motion is changing with respect to depth or at different soil layers beneath the ground surface. Such ground motion records are also available for understanding the local site effect. So, these vibrations, if you are putting a recording station, that will sense the vibration. Other than the recording station, if there is a building, definitely the building is going to respond to that particular vibration. So, take into account how much is the frequency content of vibration and how much is the natural frequency, fundamental frequency, higher mode corresponding frequency, how many natural frequencies are there, and the input ground motion frequencies. Comparing these two, one can come up with the response of that particular building with respect to ground motion.

So, when a sensor is there, it will give you quantified ground motion. When a building is there, it is going to tell how the particular infrastructure is responding to that particular ground motion. Such types of ground motions which are sensed by the ground, if it is not weak because usually some recording stations have a threshold beyond which the ground vibration will not be sensed by the recording station, primarily it will not be of use as far as its engineering application is concerned. So, depending upon what is the sole purpose of those recording stations, the threshold for the ground motion amplitude can be set, and different sets of recording instruments are also available to sense the vibrations. All these ground vibrations can be detected and recorded by sophisticated instruments. Ground vibrations, if recorded, provide useful information about the earthquake. What useful information? When a particular magnitude earthquake of, suppose, 7.8 occurred during the 2015 Nepal earthquake, what was the ground vibration at maybe Kathmandu, maybe Pokhara, maybe Patna, or any other region if ground motion records are available for that particular region.

So, that means even though there was an earthquake in Pokhara, how much vibration because of that particular fault mechanism during that particular earthquake has been transferred to different recording stations or different locations? If we collectively get information from a larger dataset of such records, definitely taking that into account and doing regression analysis, we will be able to develop some empirical correlation. Stating that again in the next 50 years, 20 years, if another earthquake has the possibility to reoccur, then what is the expected level of ground motion for my building which I am going to design, retrofit, or assess for vulnerability and risk? All those things can be done using ground motion records. These types of ground motion records are very useful to understand the damage characteristics. Damage in terms of building damage, in terms of induced effects, if you are talking about hilly terrain, then definitely the landslide. If you are talking about level areas, cohesionless soil, and water table is very high, you can talk about liquefaction. So, all these things will require some understanding of ground motion, which is likely to occur, or which has occurred during an earthquake, for which you are trying to understand what triggered so much failure as happened during the 2023 Turkey earthquake.

These kinds of ground motion will give real helpful information about the assessment of damage during a particular earthquake. Such information is primarily required for earthquake-resistant design, for estimation of ground motion attenuation, how the ground vibration is reducing, primarily in terms of the amplitude of different frequency waves, how it is happening as the vibration is covering a particular physical medium. It can happen along the propagation path, it can also happen between the bedrock and the ground surface. So, how the attenuation is coming into the picture, how the vibration characteristics are primarily reducing over distances, then subsequently it can be used for seismic hazard analysis, which will also give you an understanding of what is the potential ground motion at my site of interest. As I mentioned, the site of interest means at the bedrock level also it can be there. It can be corresponding to different site classes. It can also be at corresponding outcrop motion.

So, further, the output of seismic hazard assessment, taking building classification into account, one can continue for vulnerability and subsequently for risk studies taking into account the potential intended use of that particular infrastructure. Subsequently, if ground motions are there, you can also quantify induced effects like liquefaction. So, how much is the in-situ strength of the soil, and how much is the stress going to be induced in the particular soil medium by the ground vibration? That collectively will give us information about whether a particular site is prone to liquefaction occurrence, is prone to landslides, or is prone to any other induced effects. Similarly, in order to find out damage characteristics, one can go with fragility analysis. So, taking into account potential ground motions and correlating with respect to the damage characteristics, one can also develop the fragility curve for a particular structure of interest for a particular site of interest. So, there also you have to have a larger set of ground motion for performance-based design also, in order to find out, corresponding to a given system, how the system is going to respond to a larger set of ground motion, which are potential ground motions expected at a particular site of interest.

So, we will not rely on one particular ground motion to find out whether the building will undergo damage or not because there are lot many parameters which can control ground motion, and depending upon those parameters, the performance of the building may change; performance of the infrastructure may change. So, we have to take a larger set of ground motion records, a larger dataset of ground motion records. If you do not have recorded ground motion, definitely, we have to go with simulated ground motion.

Additionally, such ground motion can be used to understand the damage potential even for future earthquakes, or if we are interested to find out how the damage during the 1905 Kangra earthquake, how damage during the 1950 Assam earthquake, or the 1934 Bihar-Nepal earthquake had triggered. Again, if we have those recorded ground motions, we can use it because we do not have. So, we can take into account the simulated ground motion to understand the damage characteristics: what actually went wrong—whether the building was not properly designed, whether the ground improvement was not done, or anything else which led to, finally, the failure of the infrastructure. It can be building, it can be soil stratification. So, all those things require an assessment about ground vibration. Not only one vibration will be possible at the site of interest—you have to have a larger set of ground vibrations which are likely to occur, and which are a function of what is happening at the source, how it is modified between the source and the site, and subsequently, how it is further modified at the site of interest.

Now, as I mentioned many a times, or majority of the times, the regional ground motion records have gaps in terms of non-availability of ground motion records for maybe intermediate magnitude, maybe for higher magnitude also, maybe for great earthquakes also. In such a case, if we solely depend upon the ground motion record and the region is likely to witness or has a history of witnessing great earthquakes also, certainly with this limited information which is having no database related to great earthquakes, you cannot predict the ground vibration which is likely to occur during potential future great earthquakes.

So, we have to have an understanding about it, and that brings us to ground motion simulation or synthesis of ground motion. So, the requirement of ground motion cannot be fulfilled only by recorded ground motion, primarily because ground shaking due to earthquakes originated distance are required. So, you need not be only taking the ground motion which is from regional earthquakes, but even at larger distances. For performance-based design also, you have to have a larger set of ground motion and significant variation, which are possible at your site of interest. You have to take those potential variations into account while developing a larger dataset of ground motions for performance-based analysis. Similarly, in order to find out non-linear dynamic analysis, which will take into account significant variation in terms of strain energy, we have to have significantly larger variation in terms of ground motion properties which cannot be accompanied, which cannot be taken into consideration with limited set of ground motion data. So, actual ground motion dataset, though the dataset is large, but if you take in terms of magnitude, whether you take in terms of distance range it is covering, that might be having some limitation in order to use solely that particular dataset for performance-based design, for non-linear analysis, or even for fragility analysis for damage characteristics assessment.

So, to further understand about damage scenario, many a times we are discussing about smart cities. Damage scenario means we will also take into account what is the potential region which are expected to undergo more damages primarily because of ground vibration, primarily because of building, primarily because of induced effects. So, what I mean, all these regions are potentially controlling the damage.

However, if you are going to smart city planning, we can take this thing into account well in advance before actual execution is starting. This will help in identifying potential regions which are lesser prone to earthquake and its induced damages, and the region which are more prone to earthquakes and its induced damages. Accordingly, we can find out what should be the site which are relatively safe to be used for hospital construction, to be used for rehabilitation, to be used for maybe relief camps, or where medical supplies, essential item supplies can be stocked during any particular kind of earthquake or other seismic event. So, for these things also, one has to have very accurate information about what are the locations which should be used for important supplies, for relief camps, for hospitals, and what are the areas which can be marked as relatively safer, but moderately safer also can be marked over there because not every kind of infrastructure you can only develop in extremely safe regions. So, there are other regions also, where also some kind of construction will be happening. So, there, what we can do, we can take into account what is the potential ground motion likely to occur. Accordingly, whether ground improvement is required, you go with ground improvement. If that has to be strengthened in terms of infrastructure, then superstructure should be strengthened accordingly.

Again, to quantify induced effects, as we witnessed during the 1934 Bihar-Nepal earthquake, a larger area witnessed slump, or there was liquefaction which was witnessed during 1934 earthquake. Even some of the areas witnessed liquefaction during 2015 Nepal earthquake. So, again, we need not wait for liquefaction to occur. But, if you have larger set of ground motion, that will give us, like actually, how much is the amplitude of ground motion which will be loading your in-situ soil medium.

Thirdly, in terms of developing design response spectra for major projects, we can go with site-specific design response spectra, which will be taken into account how much is the regional faults, what are the seismic activity of those faults, what are the past seismicity of those faults. Taken collectively, those in rational manner, what is the design response spectra or response spectra at your site of interest, which is only dedicatedly developed for that particular site. So, it can be used for seismic design of the particular building and subsequently, it can be continued for vulnerability studies as well. To find out, how the local site effect is playing the role, many a times, whenever vibrations are transferred from source to your site of interest at the bedrock medium, the vibration will be relatively small, but because of local soil which is available between bedrock and the surface, the vibration many a times undergo amplification, and this amplification can be maybe 1.1 times also, it can be as high as maybe 3 to 4 times also, 5 times also, which has been witnessed during past earthquakes.

More about this amplification because of local soil, we will discuss in later lectures. We will be discussing about ground response analysis. So, in order to find out, again, how the amplification during different earthquake or different vibrations are happening at particular local soil, we have to have an understanding about what is the ground motion. If exposed to the local soil, then there will be change in the amplification. If you take one or two input motions, then certainly we will not be touching upon the entire range of amplification which the soil can undergo at different amplitude of ground vibration. So, for this also, we have to have larger dataset. Say, larger dataset is not available, we can go with ground motion simulation. Similarly, in order to perform risk and vulnerability studies also, one has to have larger dataset of ground motion records.

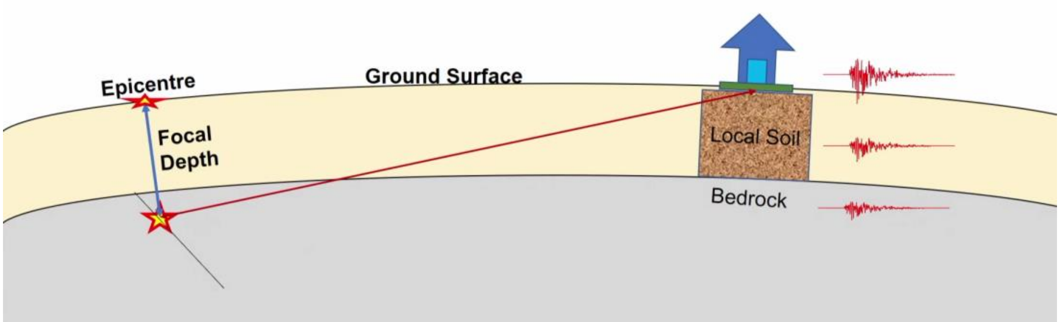


Fig.1 Origin of ground motions

Now, this is in a nutshell the entire problem. That means, we are talking about something which has happened at the source. That means, there was building up of strain energy when the corresponding stresses exceed the in-situ shear strength of the medium available in this particular region or on both sides, or how much is the strain energy could be accumulated after up to certain distance, and after that, there was release of strain energy along the fault plane. So, what will happen, there will be release of energy, and there will be propagation of seismic waves in all the directions in three-dimensional space. So, this is happening in three-dimensional space. The seismic energy was released at one particular point or in a particular area which is called as rupture area, and then it started propagating in all the three-dimensional space. It started in terms of seismic waves, which are actually propagating all the direction with respect to this rupture area. So, between this particular source and your site of interest, it is actually undergoing lot of amplification. So, it should go like this because even if it goes through local soil because of properties of local soil, the ground vibration will not be able to propagate longer distance as far as local soil is concerned. So, primarily, we will take into account this as the propagation medium or propagation path.

So, this is the propagation path. Now, this particular propagation path, if we see, there will be a lot of heterogeneity—primarily heterogeneity. Secondly, whatever started at the source is actually expanding in three-dimensional space. So, in order to conserve the energy as it is going more and more away from the epicenter, there will be attenuation in terms of wave energy. So, this is starting from the source, and then along the propagation path, once we discuss different kinds of waves, we will understand that when any kind of seismic wave is passing through a particular medium, there will be oscillation in the medium, and there will be particle displacement in the medium. Depending upon which kind of wave we are targeting, different kinds of movement will be happening. As a result of this, there will be development of heat, and there will be particle oscillation. So, that will also consume some energy. Heterogeneity will also consume some energy. As a result, whatever seismic wave or seismic energy was released at the source, a significant portion of the energy has been modified at the scattering at the source itself. Because of inelastic attenuation and because of heat, again, it is losing energy. So, every time there will be attenuation or reduction in the amplitude of vibration for different frequency content.

Finally, the vibration reaches the bedrock level or maybe engineering rock. Then we can say bedrock and engineering rock is there, and subsequently, because of dynamic soil properties which are available to the soil medium beneath the foundation and above the bedrock medium, this particular medium is also going to offer resistance to external loading depending upon how much shear strain is mobilized by this particular loading in your local soil. So again, dynamic soil properties will alter your vibrations. Collectively, if you take into account something happening at the source, there is a larger area undergoing rupture, then followed by scattering as you move away from your source and towards your site of interest. Inelastic attenuation is there, and heat is there, which is happening. Finally, once it reaches a particular site of interest, you have local soil, which is again playing a dynamic role in terms of offering resistance to external loading and subsequently transferring the motion from bedrock to the surface.

So overall, if you take into account, this is maybe your building on which you are interested to find out what the damage characteristics will be. Or, if you are going to go with the design of this particular building, you can find out, based on this process, how much is the earthquake loading. Thirdly, this is your recording station. What it is going to sense is basically whatever vibration was generated at the source, modified along the propagation path, and further modified along the local site. Collectively, all this modified ground motion is the vibration which is going to be sensed at your recording station. This further will be used in case of seismic hazard analysis and building damage. This is a vibration that is actually absent for larger magnitude earthquakes. It is basically absent for maybe higher epicentral distances, which we are trying to understand or generate using synthetic ground motion models.

So, whenever we are going with variables of synthetic ground motion models, that means we have to find out the parameters which will help us in understanding accurately what is happening at the source, what is happening along the propagation path, and what is happening at the local site level. If we are able to capture all these parameters into account accurately, that means we will be able to simulate whatever would have been the ground motions. Say, an example for the 1934 earthquake: the 1934 earthquake generated somewhere over here, but as a result, I am able to simulate the ground motion. How much will be the ground motion? Maybe at Patna, maybe at Lucknow, or any other site which is maybe in a 300-, 400-, or 500-kilometer radial distance with respect to the epicenter of the 1934 earthquake. So, I can take that into account and generate ground motion which I can use. If I am going to design an important building, I am going to construct that building. I can simulate that ground motion and maybe do performance-based analysis or, using simulations, find out, corresponding to this particular ground vibration, what the response of my building will be. I can generate design response spectra and find out how much is the earthquake loading, which has to be taken into account for the earthquake-resistant design of the structure.

So, these are the variables which basically you have to take into account, which can be called source variables, propagation path variables, and site variables. We have to take certain parameters which will be able to capture what is happening at the source, what is happening at the site, and what is happening along the propagation path. So, if we are able to simulate, if we are able to capture those effects by means of different parameters and collectively bring that, subsequently, the vibration generated at the source is getting modified as it is moving away from the source and reaching the site of interest. We will be able to simulate those ground motions as accurately as possible.

So, the synthetic ground motion model simulates ground motion at a specific site due to a target earthquake. Usually, we will be interested to find out where the earthquake is happening and how big the earthquake is. So, it is primarily related to the magnitude of the earthquake. And at some known hypocentral distance, I can say, if the 1897 earthquake is going to get repeated, whether my building will be able to sustain that earthquake, if I am going to design a new building or assess the safety of an existing building. So, what I will do, I will try to generate the 1897 earthquake and try to see the response of that particular building. Of course, I will take into account all the parameters which may come into play affecting the 1897 earthquake simulation to a particular site of interest. So, I have to take that into account. I cannot simply generate one ground motion and do the analysis in terms of safety and damage characteristic assessment. So, the accuracy of synthetic ground motion generated depends on how accurately one is able to simulate or capture source effects, propagation path effects, and site effects.

Now, source effect means what are the epicentral coordinates? That means how far is the source with respect to the site? What is the focal depth where the release of energy has actually started, or where is the focus located with respect to the ground surface? Strike: what is the orientation of your fault with respect to north? Dip: what is the orientation of your fault plane with respect to horizontal? Even fault mechanism can also be brought into account. Was it normal faulting, strike-slip faulting, or reverse faulting? Rupture length: if a fault is extending like 500 kilometers, not the entire length of the fault will undergo rupture during a particular earthquake. There will be some dimension, some finite dimension, but certainly, not the entire length of the fault will undergo rupture.

So, how much is the area, how much is the length, and how much is the width which has undergone rupture to create a particular earthquake? One can take that into account. Then, target event magnitude: how much is the magnitude of the earthquake which might have triggered or which I am expecting to trigger during the design life of the structure? Focal mechanism I have already highlighted. Directivity effect: with respect to the site, what is the orientation of the fault? Generally, the ground vibrations that are going to be recorded along the direction of fault movement and perpendicular to your fault movement will be different. So, in order to account for that, one has to also take into account the directivity effect. Then, coming over to path characteristics. Path characteristics mean what is the in-situ strength of the path. So, path properties, strength properties, and frequency content modification. Now, something has generated at the source, and it is continuously propagating. So, it is like some vibration you are left at the source, and now it is continuously propagating through a medium, which is also offering resistance because it is also having some shear strength parameter. How much is the modification in those frequency contents?

Third one is attenuation. As I mentioned, it is moving away from the source, so it is actually expanding in three-dimensional space. There will be a loss of energy, and then there will be heterogeneity present in the medium. There will be heat generated because of particle oscillation, so all these will be responsible for modification or attenuation in your ground motion characteristics and geometric spreading. As I mentioned earlier, it is moving basically in three-dimensional space.

Then, site characteristics. What is the site condition where you are interested to simulate ground motion? Whether you are interested to simulate ground motion at rock medium, outcrop medium, or whether you are interested to simulate ground motion at maybe different site classes, like site class A, site class B, site class C, D, E, so which is the site condition at which you are interested to find out the ground vibration? This can also be taken into account. The coordinates of the site will basically give you what is the relative position of your site with respect to your focus, and what is the relative position of the site with respect to fault orientation.

Then, the range of frequency content of interest. Generally, this will be important so that one can take into account at least the frequency in which your building's natural frequency may vary, or the frequencies in which your soil's natural frequency may vary. So, what is the range in which I am interested to find out how much modification from the source to your site of interest has happened in your ground vibration?

As I mentioned, whenever we are talking about the range in terms of frequency content, I am interested in a particular frequency content—whether between the bedrock and the surface—whether it has undergone amplification, and how much is that particular amplification. So, that can be taken into account, and then, whether we are simulating with respect to weathered rock, whether we are talking with respect to engineering rock, or whether we are talking in terms of soil medium. So, all these pieces of information will give more accuracy about what the site characteristics are.

So, methodology. Generally, we have two models or two ways in which models work. One is a point-source model where the entire process of rupture is happening just at the one source, which is considered as a point. So, Brune in 1970 proposed this point-source model to generate synthetic ground motion. So, that means the entire phenomenon of earthquake occurrence was limited to a single point. So, Brune's point-source model of 1970 was the first point-source model. After that, in 1983, this model was modified by Boore and introduced band-limited white noise so that we can actually take into account what the frequency content of interest is and also narrow down what frequencies we are interested in simulating. This was done using the white noise stochastic model, and this model was called SMSIM.

Later on, it was realized that rupture is happening in a finite dimension, which is also controlling the duration of vibration. It is also controlling the duration because it is not at one particular moment that the rupture started and then ended. So, rupture has started at some particular point, and because now a particular rupture length and width is concerned, the rupture will propagate from the point of origin of rupture or point of initiation of the rupture to the entire rupture length and width. That will define what will be the duration for which the ground vibration has been generated at the source. So, that can be done only in the case of the finite-source model. Two models are primarily available: one is called EXSIM, and the second one is called the FINSIM model, which is a finite-source model. EXSIM was proposed by Motazedian and Atkinson in 2005 based on the finite-source model.

So, as per Boore, the ground vibration characteristics or ground motion characteristics, because of seismic moment M_0 generated at R corresponding to some frequency content of interest, can be correlated as a combined effect of the source, which is given over here, path, and site effects.

Source

Site

$$Y(M_0, R, f) = E(M_0, f)P(R, f)G(f)$$

Path

Where,

M_0=seismic moment related to Mw

R =distance

f =frequency content

So, M_0 is a seismic moment related to the event for which you are interested to simulate ground vibration. R is a distance. You can say maybe hypocentral distance, epicentral distance, or any specific definition of distance you are interested in. F defines the frequency content—what specific frequency you are interested in simulating vibrations—so that is taken into consideration. Again, when we are talking about the source, primarily we will be interested to find out how much is the scalar moment, which is defined as the measure of the size of seismic disturbance. It can be correlated with respect to how much area undergone rupture, how much was the slip involved there, and how much is the institutional strength of that particular medium.

Corner frequency: it is the frequency below which the source spectrum decays, so that helps in identifying how much is the corner frequency of that particular medium, which can also be related with respect to the seismic moment. Then, seismic energy means how much energy was involved in a medium—an infinite medium without taking any kind of energy loss. So, that is going to give you how much the seismic energy has been involved in a particular earthquake event. Then, another parameter that will come into the picture is stress drop. Before and after an earthquake, how much is the stress condition? So, that difference is indicated by the stress drop. Both the shape and amplitude of the source spectrum must be specified as a function of earthquake size.

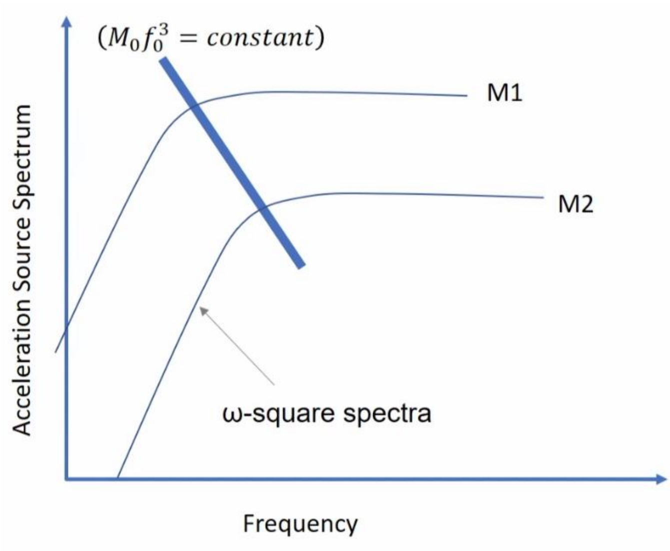


Fig.2 ω-square model

So, two source spectra, corresponding to magnitude M_1 and magnitude M_2, both have unique characteristics. That is, M_0 (seismic moment) times the corner frequency, cube of the corner frequency. This is maintained constant in terms of source spectra corresponding to M_1 or with respect to M_2. In terms of the point-source model, which is the omega-squared model, primarily it was targeted.

$$E(M_0, f) = CM_0S(M_0, f)$$

$$C = R^{\theta}FV/(4\pi\rho{\beta_s}^3R_0) \quad \text{(a Constant)}$$

$$S(M_0, f) = S_a(M_0, f) \times S_b(M_0, f)$$

Displacement source spectrum determines the shape of the source spectra

$$S_a(M_0, f) = \frac{1}{1+\left(\frac{f}{f_0}\right)^2}$$

$$S_b(M_0, f) = 1$$

ω-square model

R^{θ} =radiation pattern (average 0.55 for shear waves)

F =free surface amplification (2.0)

V =partition onto two horizontal components (0.71)

ρ =density in the vicinity of source

β_s =shear wave velocity in the vicinity of source

R_0 =reference distance (usually set to 1km)

Then, coming over to further this parameter, so E (M_0, f), which is an indication of the source parameter, can be correlated with respect to other parameters where C is there, M_0 is there, and then S times M_0 f.

So, these other parameters C further can be defined as R^{θ} F V / 4πρ β_s^3 r_0. So, R^{θ} is considered a radiation pattern. The average value of generally 0.55 is considered for shear waves. F_0 (capital F) is free surface amplification, which is given over here. Then, V is partitioning, whenever energy is released in two perpendicular directions. So, then, generally, it is that particular partitioning of horizontal components (east-west and north-south components). Many times, it is taken as 0.71. ρ is the mass density of the medium. β_s is the shear velocity in the rupture medium, and R_0 is the reference station, within which we can find out the source spectra is not significantly changing—it is usually referred to as 1 kilometer. So, corresponding to this, the displacement source spectra can be determined as S_a (M_0, f), which is also given in this particular equation as equals to 1 over 1 plus f, which is any frequency of interest, divided by f_0, which is defined as the corner frequency. Similarly, corresponding to the reference station, the value of M_0 f, which is equal to 1, this is the condition of the reference station corresponding to the omega-squared model, which is primarily the point-source model. Later on, it was modified for the finite-source model.

Propagation path: as I mentioned earlier, when the waves are propagating away from the source, there will be different mediums which will be encountered, primarily rocky mediums. So, you can see over here that whenever, with respect to this particular point, when waves are propagating, it is actually moving in a spherical wavefront.

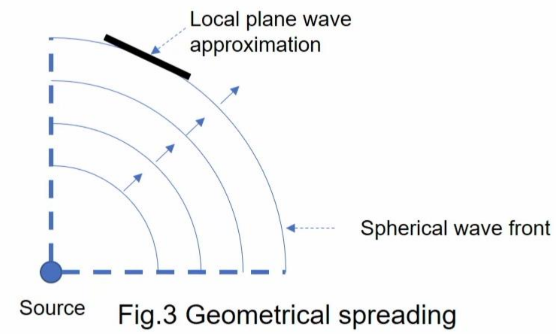
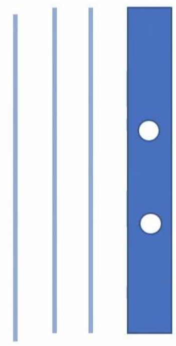


Fig.3 Geometrical spreading



mar, IIT Fig.4 Scattering

So, geometric spreading: seismic waves travel outward from the source in terms of spherical wavefronts. In order to conserve the energy, the energy per unit area, in terms of growing spheres, is actually increasing the area of the sphere. So, that means the volume of the sphere is increasing; that means the energy per unit area will also be reducing, which will lead to attenuation in the wave characteristics.

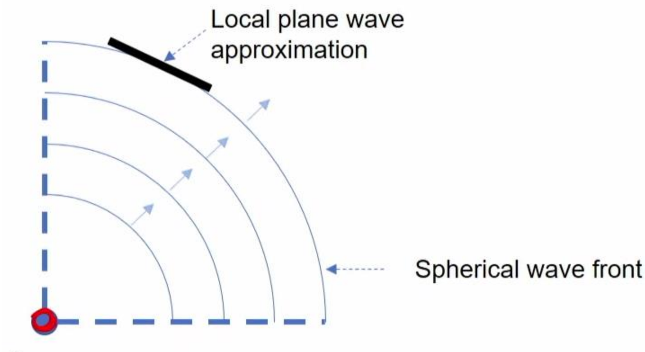


Fig.3 Geometrical spreading

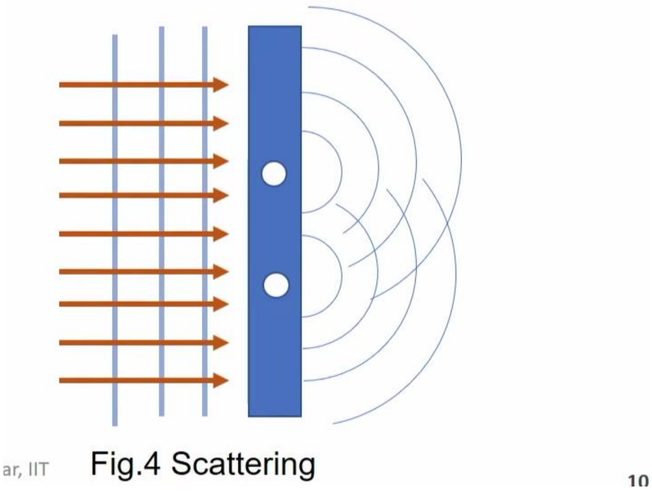


Fig.4 Scattering

In addition, scattering is there. So, seismic waves scatter primarily because there are heterogeneities present along the propagation path, between the source and the bedrock medium available beneath the site.

Anelastic attenuation: loss of seismic energy due to conservation of seismic energy, primarily because of heat. So, because of heat, also, some seismic energy will be attenuated or lost, and that will come into the picture.

So, usually, all these collectively—whether you are talking about scattering, anelastic attenuation—can be determined by means of the quality factor, which will give an indication of how much attenuation at different distances is happening in different frequency content or different frequency waves. If I am talking about one particular frequency band, how much this particular frequency band is reducing its amplitude traveling maybe 15 kilometers, 20 kilometers, like that. So, accordingly, one can determine the quality factor for a particular region of the propagation path, and accordingly, one can also compare what are the regions which are high in terms of attenuation or which are low in terms of attenuation with respect to the site.

So, this one: anelastic attenuation, because of the heterogeneity present in the medium. Though the incident wave was like this, because of heterogeneities, there will be redistribution of energy. So again, we will say this was the incident wave, and once it leaves, it is like randomly oriented and further propagating. So, as a result of which, some content of energy will be propagating towards your site of entrance, and some proportion of energy will be again redistributed, traveling in a different manner.

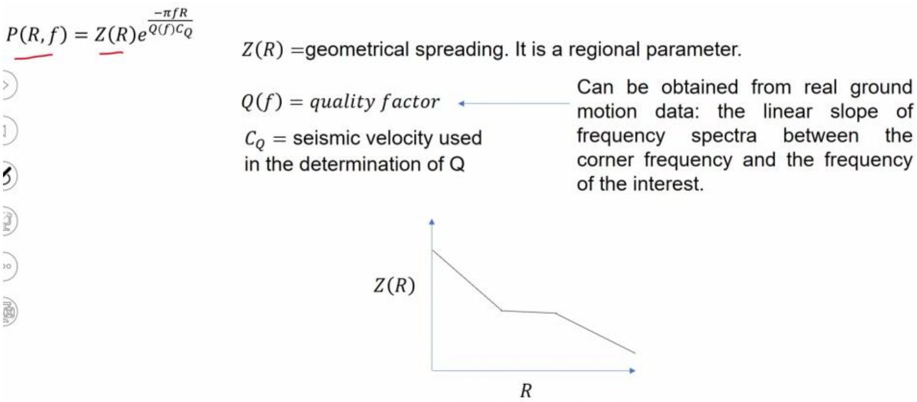
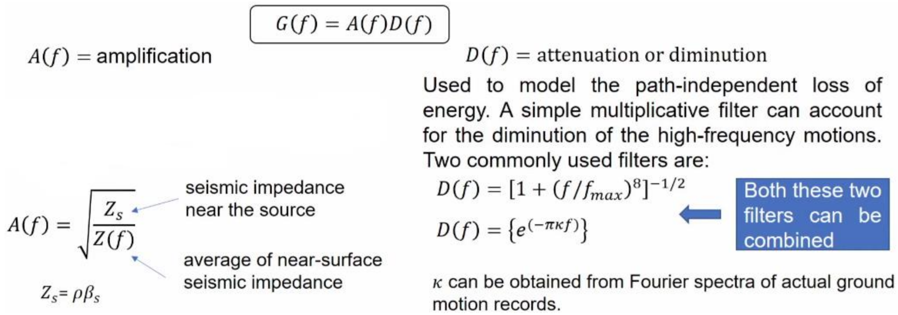


Fig.5: Z(R) depends on R

So, the quality factor can be determined using this particular equation P with respect to distance at different frequency content, given as Z, which is geometric spreading, and it is usually the regional factor. Then, exponential minus π f R, representing the distance as well as the frequency content, and then in the denominator, you have the quality factor, which is given over here.



Local site effect: primarily two things will come into the picture. One is amplification, which can be estimated like here, corresponding to different frequency contents, where Z_s is specific seismic impedance near the source, and Z(f) is near the surface, how much is the average impedance. Taking those into account, where you can find out Z_s with respect to ρ (mass density of the medium) and β_s (shear wave propagation velocity) in the propagation medium through which the medium which we are targeting here.

D(f) is attenuation. It is used to model the path-independent loss of energy. So, that can be correlated with respect to how much is the maximum frequency content in your simulation and any frequency content of interest. It can also be simulated with respect to exponential minus π κ f. So, κ value can be correlated with respect to the actual ground motion record Fourier spectra. So, based on the linear slope of that particular record Fourier spectra, one can determine the value of κ and use it in order to find out the denomination factor.

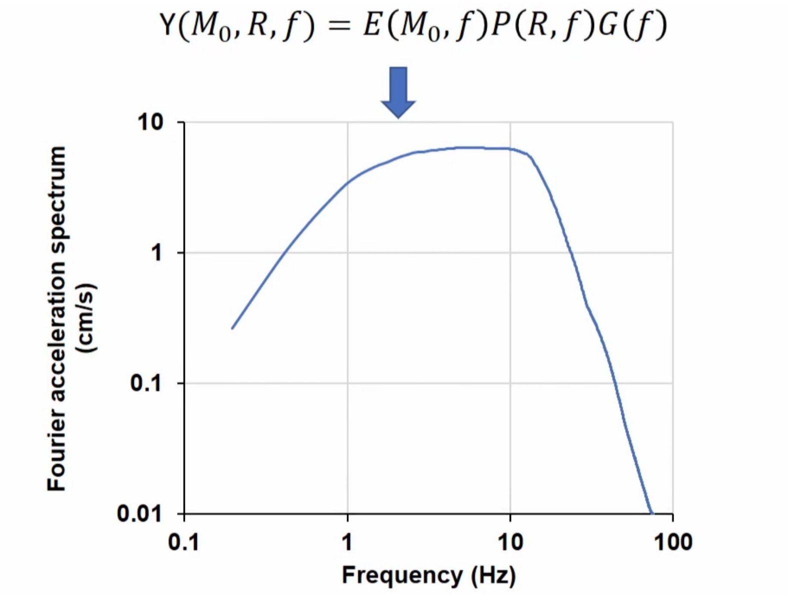
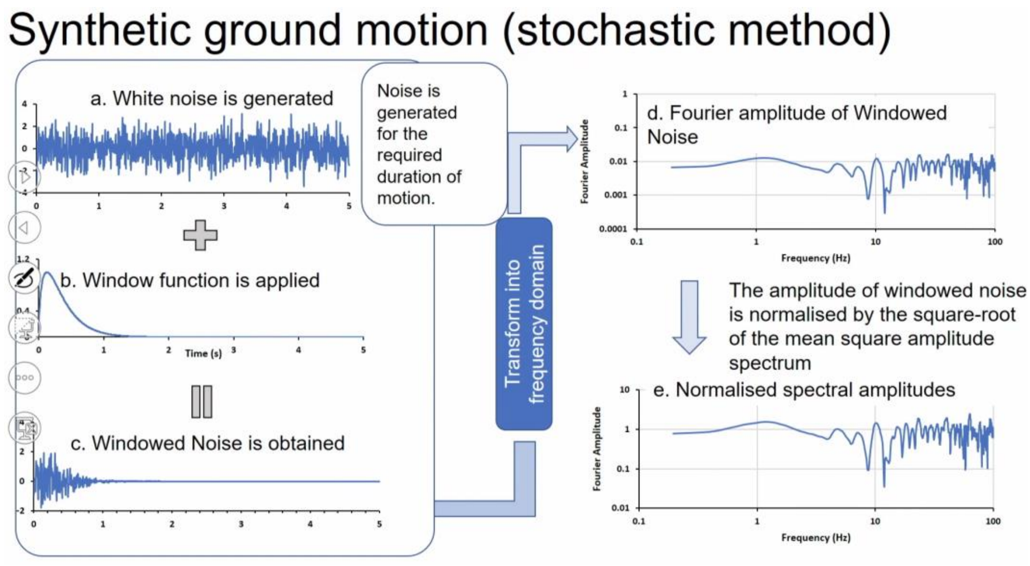
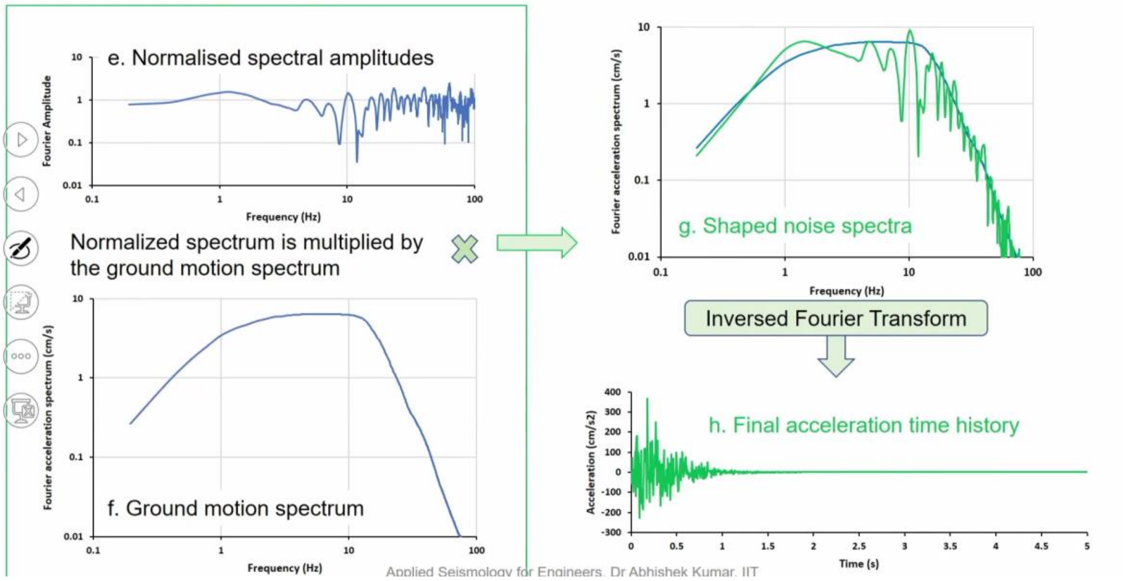


Fig.6 Ground motion acceleration spectra obtained by considering source, path and site information

So, overall, the simulated ground motion will be like Fourier spectra or acceleration spectra with respect to frequency content. This is the overall, we can say, like spectrum available here. The spectrum is used for simulating the ground motion. It is primarily inversely proportional with respect to the corner frequency.



How can it be used to simulate? So, we can say initially, in the ground motion simulation model, there will be white noise. This particular white noise will be clubbed with respect to a windowed function (stochastic simulating function), which will give you how much the frequency content of interest is. Then, based on this, we will be getting the windowed noise over here. This particular windowed noise, once you transfer in terms of the frequency domain, will give you the frequency content or Fourier spectra of windowed noise. Then, normalize it with respect to the mean square amplitude, and you will get the normalized spectrum in the frequency domain. This is a step-by-step process of how the ground motion simulation model works.



Then, normalize the spectrum, multiply it with the ground motion spectrum or source spectrum, which represents what the seismic energy source spectrum is. So, how much is the seismic energy that has been released at a particular source. This particular source spectrum will be there. Normalize the spectrum, and you can multiply it with this. Then, you will be getting the shape noise spectra, which is basically indicating that initially, this was a noise, which was curtailed by means of some windowed function. Now, you are having a more accurate representation of the site-recorded ground motion. So, using the normalized spectra, multiply it with respect to the source spectrum, and you are now getting the shape noise spectra. Do the inverse fast Fourier transformation, and then you will get the final acceleration time history.

So, when we are going with the FINSIM model, again, in the finite source model, whatever governing equations we have used, we will use those to model the source propagation path and site effects. But many times, whenever we are doing the simulation, we are not taking into account what area has undergone rupture in the point source model. So, that is why, in 1997, the finite source model or FINSIM was proposed, where the actual area that is supposed to undergo rupture has been divided into a number of subfaults. The triggering of the earthquake will start from one subfault, and then, as the rupture propagates to different subfaults, again, those subfaults will act as point sources, and the governing equation, which we discussed in the previous slide, will be applicable with sufficient delay. So, such delay is an indication of how much time the rupture took to propagate from the main subfault to the adjacent subfault. Once the rupture has started, it will take some time to reach the adjacent subfault, then to the next one, and so on. It is basically propagating from the point of origin of the rupture to another point, which is also part of the rupture area, but as a subfault, it is located some distance away from the main point of initiation of the rupture.

So, this particular time delay, if you take into account in terms of adding up the contribution of the source, that is, one point source which was available at the point of initiation of the rupture and another point source where the rupture has just started with some time delay. You can combine all those things, and then we will be able to find out how much the targeted ground vibration actually started from the source. Similarly, the propagation path and site effects will follow the same method.

Now, in the FINSIM model, what was found is that if you change the subfault size, it basically controls your ground vibrations. Later on, taking into account the dynamic corner frequency, in 2005, the EXSIM model was proposed. This was because the simulations were directly related to the dynamic corner frequency, so the correlation or dependency of simulation on subfault size was terminated or removed. So, it is a major advantage that it is insensitive to fault size, which was not the case in the FINSIM model. Conservation of energy radiated during the rupture process was also present in the EXSIM model, but it was not there in the FINSIM model. Only a portion of the subfault will be activated at any particular part.

$$a(t) = \sum_{i=1}^{nl} \sum_{j=1}^{nw} H_{ij} a_{ij}(t - \Delta t_{ij} - T_{ij})$$

This is the way it is given, so we have to find out the simulated acceleration spectra. You can see here the number of subfaults along the length and width of your rupture area, which is given over here, and we will try to find out the simulated ground motion, maybe at the point of initiation, followed by the negative sign indicating when the point of initiation of the rupture started. Since that particular time, how much delay has happened since the rupture reached any particular ith and jth subfault? So, this negative sign is basically indicating, with respect to the initiation, how much delay has happened since the rupture started.

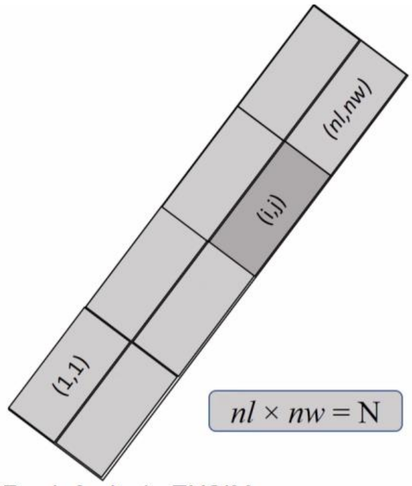


Fig.7 sub faults in EXSIM

a_{ij}=acceleration obtained considering ijth sub-fault as a point source

H_{ij}= normalisation factor for ijth sub-fault

If the rupture started here, it would then start rupturing here, then it will reach here, and at the same time, in the background, time is also counting. So, how much delay has happened in this particular process of rupture propagation is indicated by this negative sign.

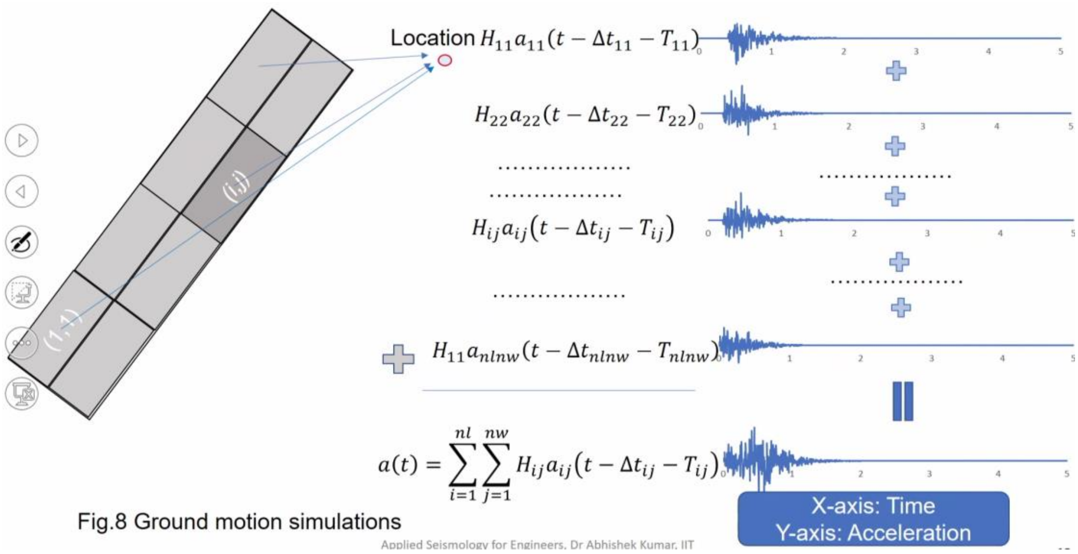


Fig.8 Ground motion simulations

That is how you combine all the contributions from these subfaults, and we will be able to find out the overall simulated ground motion following the steps we discussed when we normalized the windowed noise. Then, white noise was there, then multiplied with respect to the source spectra, and then we got the Fourier spectra, and subsequently, the acceleration time history. So, this process will remain the same; we are not getting just one point source, but we are getting contributions from a number of point sources. Adding up those contributions and subsequent time delays, we get the final result.

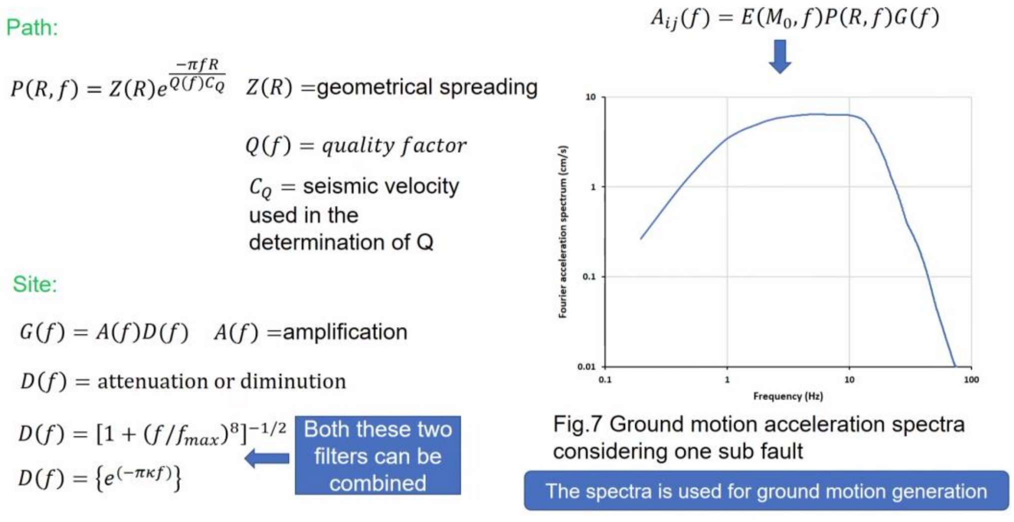
$$M_{0ij} = \frac{M_0 S_{ij}}{\sum_{l=1}^{nl}\sum_{k=1}^{nw} S_{kl}}$$

So, this is what we have already discussed. This particular equation will basically conserve the target seismic moment. Suppose we are targeting a magnitude 7 earthquake. This particular magnitude of the target event will remain conserved if you take up the seismic moment released from each of these subfaults. So, if you combine all the contributions from all subfaults, the simulation or seismic moment of the target moment should be reached; it should not be more or less than that.

$$f_{0ij}(t) = N_R(t)^{-1/3} \times 4.9 \times 10^6 \beta \left(\frac{\Delta\sigma}{M_{0ave}}\right)^{1/3} \qquad N_R(t) = number\ of\ rupture\ sub-faults$$

$\Delta\sigma$=stress drop

Then, the corner frequency is the governing equation where the corner frequency of each of the subfaults can be related to the average seismic moment corresponding to all those subfaults.



The path effect, as I mentioned earlier. So, the path effect can be correlated with all this information, which we have already discussed in the previous slide. So, the ground motion simulated acceleration spectra, considering one subfault, and subsequently, more subfaults.

So, synthetic ground motion model has certain advantages. The first one is that it can be useful when an adequate number of ground motion records are not available. Similarly, in cases where larger magnitude earthquakes or higher hypocentral distance related ground motions are not there, you can use it for performance-based design, where a larger set of ground motions is required, but we do not have so many recorded ground motions. Similarly, for seismic hazard analysis, liquefaction, or scenario-based studies, one can go with ground motion simulation. In terms of limitations, whether you are going with the finite source model or the point source model, one has to have an understanding of different parameters that can model your source propagation path and site effects. Many times, because ground motion records are not available in regions that are relatively less active, in such cases, you have to assume similar models from other regions that have these models available and are having comparable seismic settings.

Whenever we are coming to the ground motion prediction equation, so we just did ground motion parameter simulation. We simulated some ground motion model, which was a function of magnitude, hypocentral distance, path attenuation, local side effects, and frequency content changes. Taking all these independent parameters into account, which finally affect your ground motion parameters, we can have a database where ground motion parameters are related to how these parameters change with respect to magnitude, hypocentral distance, path attenuation, failure mechanism, fault mechanism, and then we can do regression analysis to find out how each of these parameters contributes to your ground motion model.

$$\ln(PGA) = f_1(M) + f_2(R) + f_3(M,R) + f_4(S) + \varepsilon$$

This is one typical ground motion prediction equation where the natural log of peak ground acceleration, is a function of a formula that will be determined based on regression analysis with respect to magnitude, hypocentral distance, and then a combined effect of magnitude, hypocentral distance, and many more parameters, which are basically controlling your simulated ground motions.

Now, depending upon how much information related to source, site, and propagation path are available, the functional form of the ground motion prediction equation can be very simple to very complex. It depends on how many parameters are available for doing the regression analysis.

$$\ln\left(\frac{S_a}{g}\right) = C_1 + C_2M + C_3M^2 + C_4R + C_5\ln\left(R + C_6e^{C_7M}\right) + C_8\log(R)\,f_R + \ln(\varepsilon)$$

- where, $f_R = \max(\ln(R/100), 0)$,

This is one example we have taken from the NDMA report, 2010. The governing equation is given here. Sa is spectral acceleration, normalized with respect to g. C1, C2 up to C8 are the regression coefficients. M is the magnitude, and R is the hypocentral distance.

Determine the mean PGA for the EQ of Magnitude 6Mw for a site which is located 100km far from the location of the epicenter having a depth of 30km. Used NDMA's GMPE, and the following coefficients.

C1	C2	C3	C4	C5	C6	C7	C8	σ(ln(Sa/g))
-4.2427	1.31	-0.0097	-0.0031	-1.3159	0.0172	1.0279	0.1083	0.4424

This is numerical based on the ground motion prediction equation. So, one has to determine the mean peak ground acceleration for an earthquake of magnitude 6 or moment magnitude scale, which is possible because of a source located 100 kilometers away from the location. Again, the focal depth of the earthquake is also given as 30 kilometers.

Solution:

$$\ln\left(\frac{S_a}{g}\right) = C_1 + C_2M + C_3M^2 + C_4R + C_5\ln\left(R + C_6e^{C_7M}\right) + C_8\log(R)\,f_R + \ln(\varepsilon)$$

$R = \sqrt{100^2 + 30^2}$

R=104.4km

$f_R = \max(\ln(R/100), 0)$

$= \max(\ln(104.4/100), 0)$

=0.043

So, using focal depth and the epicentral distance, we can determine the hypocentral distance. Once the hypocentral distance is given here, 100 kilometers is the epicentral distance, and 30 kilometers is the focal depth. So, using this as your site and focus, this is the focal depth, and this is the epicentral distance. Using this, we have determined the value of the hypocentral depth, which is given here. This is the definition of distance to be used in your ground motion prediction equation, indicated by R. These are the values of the coefficients corresponding to different periods. Your ground motion is changing with respect to different periods. If you take into account maybe the response factor, also, the spectral acceleration value changes with each period, which is marked on the x-axis. Similarly, with respect to the ground motion prediction equation, the coefficient values are also changing because the ground motion parameter is changing with respect to their period of interest. So, typically, I have taken here is some value of the coefficients C1, C2 up to C8, and then the standard error value is also included. All these equations and coefficients in this particular equation, corresponding to a magnitude of 6, which is given in the equation, and a hypocentral distance of 104.4 kilometers, I will be able to determine how much the peak ground acceleration, normalized with respect to g value, will be. So, you can follow this particular equation and the solution.

C1	C2	C3	C4	C5	C6	C7	C8	σ(ln(Sa/g))
-4.2427	1.31	-0.0097	-0.0031	-1.3159	0.0172	1.0279	0.1083	0.4424

$$\ln\left(\frac{S_a}{g}\right) = C_1 + C_2 M + C_3 M^2 + C_4 R + C_5 \ln\left(R + C_6 e^{C_7 M}\right) + C_8 \log(R)\, f_R + \ln(\varepsilon)$$

$$\ln\left(\frac{S_a}{g}\right) = -4.2427 + 1.31 \times 6 - 0.0097 \times 6^2 - 0.0031 \times 104.4 - 1.3159$$

$$\times \ln(104.4 + 0.0172 \times e^{1.0279 \times 6}) + 0.1083 \times \log(104.4) \times 0.043$$

$$\ln\left(\frac{S_a}{g}\right) = -3.26$$

S_a=0.038g

The spectral acceleration, given in this particular equation, C1, C2, C3, with respect to this particular chart, will be given for the selected ground motion prediction equation, and then this is the value of spectral acceleration. So, one can practice by taking different values of the coefficients. You can perhaps download this report or maybe other published literature related to ground motion prediction equations, and you can practice it. For example, this is going to give me, if a magnitude 6 earthquake is going to happen 100 kilometers from my site of interest, 0.038 g is the spectral acceleration, which is going to be experienced at my site of interest.

So, I am not waiting for the earthquake to happen, but still, I have information about how much the magnitude of this particular earthquake is. If that is the target event, I can take this for earthquake-resistant design, even for induced effect quantification, and then find out what measures should be taken in order to safeguard the building and the ground.

One can practice more on these numericals. The overall objective was not to discuss in detail about the ground motion model parameters, but just to give you an overview of what model parameters are available, what widely followed model parameters for ground motion simulation are, what the different components are, how the synthetic ground motion model works, what the objective of generating so much synthetic ground motion is, and how a particular ground motion prediction equation can be used for a particular region.

One thing to be mentioned here is, whenever we are going for a ground motion prediction equation, these are regional equations, so we cannot randomly select some ground motion prediction equation and start calculating the spectral acceleration or even for seismic hazard analysis. One has to be very careful in selecting a particular ground motion prediction equation because these are generated or supposed to be generated based on regional ground motion records. These records give an indication of the tectonic setting and seismic activity of the region, and that’s how these should be adopted also for that particular region. If any simulated GMPE is not available for a particular region, then we can adopt similar GMPEs from other regions where these are available, and there is significant comparison or similarity in terms of tectonic setting and seismic activity between the region of your interest and the region from where you are adopting the ground motion prediction equation.

So, with that, I have come to the end of this particular lecture. Thank you, everyone.