Applied Seismology for Engineers

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Week – 06 Lecture - 03

Lecture – 13

Hello everyone, welcome to lecture 13 of the course Applied Seismology for Engineers. In this particular course, we will be continuing the topic of estimating seismic hazard analysis at the site of interest. In earlier lecture, lecture 12, we discussed about deterministic seismic hazard analysis. The primary purpose of determining seismic hazard value at a site of interest is to find out what is the expected level of ground motion which is likely to occur at the site of interest. In last class, we also discussed that primarily two methods are there based on which one can determine the most likely to occur level of ground motions at the site of interest. Then there are two methods, one is deterministic seismic hazard analysis in which we will be targeting on worst scenario earthquake means if there is a site at which some construction is going to happen or the site of interest where one is interested to find out what is the ground motion which should be used in terms of quantification of induced effects or in terms of what is the level of ground motion to be used further for earthquake resistant design of the buildings.

So, in order to find out motions which is expected considering all the active faults which are there in and around of your study region or primarily within the seismotectonic map. In addition, we will also take into account on each of these seismic sources what are the earthquakes which have happened in the past. As we discussed in earlier lecture also that in order to collect information about past earthquakes number of databases are there which one can refer to starting with United States Geological Survey one can go with then IMD is also there Indian meteorological department and many more existing catalogues are there based on which one can determine what are the earthquake which have happened in the past at different coordinates. Then comparing these coordinates with respect to the fault orientation, fault strike values and the linear feature which are available on the ground surface. If we are targeting for linear faults, then we can map each of the past earthquake related to the corresponding fault. So, when we are talking about seismic hazard analysis most of the time there will not be just one seismic source which will be available in a particular region. But suppose this is a site of interest where I will be interested to find out that this is my site of interest and corresponding to this site and within 500-kilometer radial distance there can be a number of seismic sources or faults which are present. So, this is I am showing in plan. The number of seismic sources and even each of them are at different orientation with respect to the site of interest which is potential for a bigger project which is for which we one has to go for site specific hazard analysis.

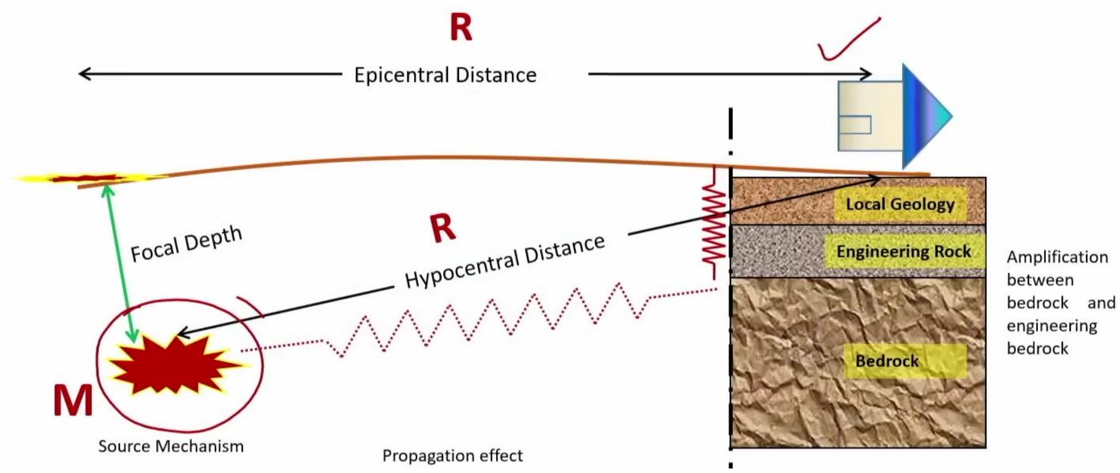
So, when we are talking about these, we will be taking all these faults into account. Similarly, 2, 3, 4, 5 and n number of faults 50, 60, 100 faults can be there which are present in and around of your study area. Then we will try to find out what is the past earthquake information on each of these faults which will help firstly in finding out the rupture characteristics of each of these faults. Similarly, it will also help in determining the seismic activity. If we refer to earlier lecture, lecture 9, lecture 10 we will be able to recollect what is the meaning of seismic activity. Basically, it will try to give us an indication about how frequently different magnitude earthquakes are possible in a particular study area that can be a linear source, that can be an aerial source, that can be entire region or seismic source zone within which you have collected the data and determine the seismic activity parameter. So, when we go for hazard analysis the first is considering all these faults which are present in the region and each of them are capable of producing earthquake from time to time. Not all the faults will be producing earthquake at the same time. Similarly, there will be some fault which are producing earthquakes very frequently but of lower magnitude. There might be some fault which are producing very rare an earthquake event but those are of maybe major to great earthquakes.

So, keeping all those uncertainty with respect to the earthquake which have happened in the past in probabilistic seismic hazard analysis we will be able to find out what is most likely to occur ground motion parameter at your site of interest. When we are discussing about spectral acceleration or peak ground acceleration then what is the most likely to occur ground motion parameter or most likely to occur spectral acceleration at a particular period of interest or most likely to occur peak ground acceleration peak horizontal acceleration depending upon the site for which you are doing the hazard analysis. If you are doing corresponding to site class A condition you will get hazard value corresponding to site class A condition. If you are doing it for outcrop motion or bedrock motion accordingly the values will be modified. So, all this depends upon where you are determining the probabilistic hazard value depends upon primarily the ground motion selection the ground motion prediction equation which one has used in order to perform seismic hazard analysis.

So, in today's class we will be discussing about probabilistic hazard analysis unlike deterministic seismic hazard analysis where we are taken into account among all these sites taking the original ground motion prediction equation into account which is the site which based on different distance and magnitude combination because each fault is capable of producing different magnitude earthquake and considering the length of the fault which is extending may be hundreds of kilometer there might be some location within the fault which is at closest distance with respect to the site depending upon the position of the site and relative orientation of the fault with respect to the site position. So, in this particular case if you are talking about this particular fault definitely this particular site will be closest distance. So in deterministic hazard analysis we were trying to find out what is the worst scenario what is the maximum ground motion which can happen at a particular site taking into account that each of these faults are producing maximum earthquake and again on each fault this particular maximum earthquake corresponding rupture is going to happen at one particular section of the fault which is located very close to your site of interest. So, if you take into account maximum magnitude and minimum hypo central distance or epicentral distance or any other definition of distance depending upon the definition of distance which is used by a particular ground motion prediction equation we will get the value of worst scenario earthquake or worst scenario ground motion at the site of interest from deterministic hazard analysis. In probabilistic hazard analysis we will deal with the uncertainties which will help us in understanding taking into account that different magnitude earthquakes are possible.

If you are talking about fault 4 or fault 3 or fault 5 it is not like every time it will be producing worst scenario earthquake sometime it will be producing 3.5, 4.5, 6, 7.5 magnitude earthquake but also very rarely it is also producing 8 magnitude earthquake. So, what is the chance that different magnitude earthquake which are less than 8 are also occurring on fault number 5, fault number 4, 3, 2 like that. Similarly with respect to fault orientation not every time the rupture during future earthquake is going to happen very close to your site of interest not every time the ground motion will be worst scenario. So, there can be ground motion which are lesser than worst scenario that means the most likely to occur ground motion at your site of interest is not the worst scenario but even the lesser value considering the design life. So probabilistic hazard analysis will give you relatively more appropriate value not keeping into account the worst scenario but most likely to occur ground motion at your site of interest considering the faults corresponding seismic activity considering the rupture characteristics all into account.

So, as we mentioned in earlier discussions also when we are talking about seismic hazard at a particular site that means we are talking about the ground motion which are expected at a particular site of interest. So, ground motion means there will be some location where site is located there is some location where your earthquake epicenter or focus is located.



So, this is your focus of the earthquake, where actually the energy has been released during a particular earthquake located at a certain focal depth beneath the ground surface. We have discussed it, but why I am insisting today on this particular part is that we will be interested to find out, like, because of this particular earthquake event which has happened at one particular focal depth or at a certain epicenter distance from my site of interest, I will be interested to find out, like, corresponding to this, we have taken into consideration the source characteristics, the propagation path characteristics, as well as site characteristics, generally up to bedrock level or outcrop level, both in terms of rocky medium, unless we are going for local site effects, which generally are not targeted in hazard analysis. So, we can go with performing corresponding analysis based on the hazard value we are getting from here. We can take into account local site effects by performing ground response analysis, and the topic of ground response analysis will be discussed in later lectures. So, what will happen over here is that at some epicenter distance from your site of interest, some earthquake has happened. As a result, vibration has been transferred from your source, considering the propagation path and at your engineering rock at the site of interest. Now, collectively, if we go into ground motion prediction equations or synthetic ground motion models, collectively, when we are talking about any attenuation relation or any ground motion prediction equation, the source characteristics, the propagation path characteristics, and site characteristics at bedrock level are generally, by default, taken into account while developing a ground motion prediction equation.

Further, we can verify and look into what is the database that has been used in developing this ground motion prediction equation. So, accordingly, we can decide whether it uses epicenter distance, hypo-central distance, or some other form of distance calculation. Similarly, whether it is using focal depth, whether it is using focal fault plane solutions or focal mechanisms. Similarly, with respect to the site, whether the selected ground motion prediction equation is only applicable to bedrock conditions, it is only applicable to site class A or site class B conditions. So, accordingly, one can get an idea about, out of this entire problem, where the source is also involved, the propagation path is also involved, and the site is also involved, what information has already gone inside while developing a ground motion prediction equation. So, whether we are going for a deterministic one or a probabilistic one, the level at which we are predicting or determining the seismic hazard value is mainly governed by the selected GMP or selected ground motion prediction equation or selected attenuation relation.

So, collectively, based on this, we can understand that the ground motion, which is responsible for the failure of the building or the collapse, is a function of the magnitude of the earthquake. Higher is the magnitude; for the same epicenter distance, you may experience significantly higher ground motion. We can also correlate this with respect to the energy released and with respect to the amplitude of vibrations, as discussed in earlier lectures. Similarly, source-to-site distance—keeping the magnitude the same—as the source-to-site distance reduces, the ground motion amplitude will increase because now, for the same energy released from the source, the propagation path will be relatively less if you are reducing the distance between the source and the site. So, definitely, this will have a direct effect on the amplitude of the ground motion generated at the site of interest. The third one is focal mechanism, as we discussed also, depending upon the dominant movement happening on a particular fault—what is the direction in which the dominant vibration has been continuing and what is happening in the perpendicular direction.

So, many a time, when we are selecting ground motion prediction equations, those equations are also specific to what coefficients one should use whenever we are talking about strike-slip faulting. Similarly, what coefficients one should use when talking about dip-slip faulting or when talking about normal reverse faulting or oblique faulting. So, corresponding to all those, one can pick up ground motion prediction equations and select appropriate coefficient values so that one can use those ground motion prediction equations. The last part, collectively, whatever we are discussing in terms of magnitude, source-to-site distance, as well as focal mechanism, will go into the database, which will be used in developing the ground motion prediction equation. That is the reason, in the beginning, I told you that the selection of the site for which you are determining the seismic hazard analysis solely depends upon the ground motion prediction equation. If you have more information about the site, as discussed in lecture 11, and that more information is related to ground motion prediction equation development, we will get a more and more complex functional form of the ground motion prediction equation, where local site effects, propagation path effects, and site and source effects can be modeled and taken into consideration while performing regression analysis and developing the ground motion prediction equation.

So, the controlling factor, if you go with this particular definition, controlling factors for seismic hazard analysis include the magnitude of the earthquake. Higher is the magnitude; more energy will be released, and definitely, this will have a direct effect on the amplitude of the ground motion. Similarly, with respect to source-to-site distance, whether you are talking in terms of ground motion or damage, again, damage will also take into account the building classification and the way the building has been constructed. So, many parameters will come into the picture. But as far as the direct correlation with respect to ground motion is concerned, as you increase the source-to-site distance, the ground motion is going to reduce. The third one is fault mechanism or focal mechanism, which will also have an effect on the vibration generated in the direction along the rupture and in the perpendicular direction. So, that will also control the ground motion and, subsequently, indicate variations in the damage characteristics. So, attenuation relations generally will also take into account the geometric spreading, as we have discussed in our lecture related to attenuation relations or ground motion prediction equations, that propagation path effects will be taken into account before and after an earthquake. How much is the stress drop? That will also be taken into account. The same thing I was mentioning a couple of minutes back, that more information about source, propagation path, and sites are there for a particular region. You can take all those parameter variations into account while developing the ground motion prediction equation. So, if there is a stress drop, similarly with respect to frequency content—what is the highest frequency content, what is the corner frequency—that will also indicate what coefficients are generated while developing a ground motion prediction equation. So, GMPs, as we mentioned in lecture 11, are empirical correlations, correlating source, propagation path, and site parameters directly with respect to the amplitude of ground motion generated at a particular site of interest.

Now, coming over to seismic hazard analysis, because we have discussed that there are different earthquakes that are generated along the faults. We have also discussed in earlier lectures that not every time you will have complete information about the fault. But whenever there is information about the fault, whether you are considering it as a point source, linear source, or aerial source, corresponding to that particular source which has produced an earthquake, and now the seismic vibration from the source has started propagating in different directions, it will reach a site of interest. In seismic hazard analysis, we will try to find out, once this motion reaches a site of interest, what motion among so many ground motions generated by different seismic sources should be taken into consideration. So, in lecture 12, we discussed deterministic seismic hazard analysis. Now, deterministic seismic hazard analysis takes into account the worst scenario. That means whatever faults are there, every fault is undergoing rupture at a distance or at the segment of the fault located closest to your site of interest. Similarly, that particular closer distance is capable of producing a large scenario earthquake or maximum earthquake.

So, we do not consider the possibility that, other than the closer segment of the fault, which is very close to your site of interest, other sections of the fault may also undergo failure. That means, if we are talking about this as the length of the fault and this section of the fault, or this sub-fault, which is capable of producing an earthquake, is located very close to a site of interest, what will happen if this undergoes rupture rather than this, or this undergoes rupture, or this undergoes rupture? I mentioned earlier that not the entire length of the fault will undergo rupture during a single earthquake, again depending upon the rupture characteristics of regional faults in a particular region, which is, again, a separate area to explore further.

So, in deterministic hazard analysis, we do not basically consider that there is a possibility of rupture or the ground motion, which we are taking into consideration based on the worst scenario earthquake. Worst scenario earthquake means what is the highest amplitude of ground motion which is possible at a site of interest? Now, certainly, there might be some highest magnitude of the earthquake, but we have to be also rational in terms of whether this highest magnitude earthquake is going to be experienced by my building, which itself has a design life of maybe 30, 35, 40, or 50 years. Because if this worst scenario does not have any possibility of getting repeated, maybe in the next 200 years, definitely whatever ground motion parameters I am taking into account resemble over-safe design. This is because the ground motion, which I am taking for my building design, has a return period that is not going to get repeated in the next 200 years, but yet I am taking it for the design of my building, which itself has a design life of 50 years.

So, one can take into consideration whether one should go for the worst scenario earthquake, or we can go with the motion which is most likely to occur at the site of interest, or the most probable ground motion at your site of interest. Deterministic hazard analysis does not take into consideration the possibility that this ground motion is going to get repeated during the design life of the structure. This event is assumed to happen very close to the site of interest. Depending upon the orientation, we can say the closest distance may be over here. If you take another fault, which is located like this, definitely the closest distance will be perpendicular to the fault from a point resembling the site, is touching the fault. That particular location resembles the closest distance. So, depending upon the orientation of the fault with respect to the site, the position of the closest distance on the fault also changes.

As again, if you go on this particular site or this particular site, that means there will be a significant increase in terms of epicentral distance or hypo-central distance. That will not be considered as the closest distance. So, closest distance means, depending upon the orientation of the fault with respect to the extreme ends of the fault and with respect to the position which is falling perpendicular to the fault, one can take a decision on which should be the closest distance with respect to the site. Again, whenever an earthquake is happening at a very close distance, we are also taking into account that, out of maybe 50 earthquakes which have happened on this particular fault, as indicated by my past earthquake history, I will be taking only the earthquake which corresponds to the highest magnitude. So, if 200 earthquakes are there, and the majority of them are in the range of 5, 6, 6.5, but even one earthquake was there, maybe 50 years back, 60 years back, of magnitude 8.5 indicated to happen on this particular fault, I will yet take into account that maximum magnitude of 8.5 to occur at a location which is very close to your site of interest.

As a result, because the magnitude is highest and the distance is lowest, if you put these minimum parameters in the ground motion prediction equation, we will get the worst scenario. Worst scenario means there will not be any scenario which is going to be more than this particular scenario. We can take, like the maximum magnitude which I just told, like based on past earthquake information. But based on earlier discussion, we have also seen that whatever past earthquake information indicates maximum magnitude, it may or may not resemble the true potential of the site. So, that means you can further increase the maximum reported magnitude from the past earthquake catalogue to find out the maximum magnitude likely to occur, or potentially the magnitude which is likely to occur at your site of interest.

So, the results are highly uneconomical because every time you are preparing for the worst scenario without taking into account whether this worst scenario is actually going to hit my site during its design life. This is like my structure is going to be at the site for the next 50 years or 60 years. I am not at all bothered whether it is going to get repeated, particularly about 8 magnitude or 8.5 magnitude earthquakes. We talk about the return period of those earthquakes being significantly higher. That means those earthquakes are not happening on the same fault every 10 years or 12 years, like that. But still, I am taking that it will get repeated during 20 years or 30 years, taking into account that the seismic activity of the fault is very low. So, all these definitely indicate that the outcomes of deterministic seismic hazard analysis are highly uneconomical. That is the reason one can take those design parameters you are getting from deterministic hazard analysis in the construction of important structures where the safety of the structure is of prime importance. Examples include nuclear power plants, dams, and bridges, where the failure of the dam, bridge, or nuclear power plant can be catastrophic in nature.

We cannot withstand, we cannot take the chance that such facilities should undergo failure, primarily related to nuclear power plants, because there will be radiation leaks and a lot of devastation. So that is why, similarly, with respect to dams and bridges, we can say when we are going with deterministic seismic hazard analysis, we generally take the outcome of deterministic seismic hazard analysis primarily for very important structures where the safety of the structure is of prime concern and not the cost involved. So, even if you end up with construction costs being maybe 2 to 3 times higher than what you should have designed based on most likely to occur ground motion, still, we do not want to take a chance with respect to the failure of such activities. So, we will go with deterministic hazard analysis, or we will go with ground motion which has a probability of not getting repeated over a very long duration. So, sometimes for these important structures, we also get input from probabilistic hazard analysis but corresponding to very long return periods.

So, one can refer to the guidelines available whenever we are using probabilistic hazard analysis, particularly for nuclear power plants based on seasonal hazard evaluation. Probabilistic hazard analysis, as I mentioned, each fault is capable of producing different magnitude earthquakes. Again, these different magnitude earthquakes will not happen only at this location, which is very close to your site. It can happen maybe very far from the site because, whenever a site is there and your fault is extending like this, rupture may happen even at this location because rupture will not happen with respect to taking the site position into account. Rupture can happen anywhere along the fault.

So, deterministic hazard analysis does not take that into account. Probabilistic hazard analysis will take uncertainty about what are the different segments in which rupture can happen in future earthquakes. It takes into account the location, which I just mentioned. Similarly, with respect to the magnitude of the earthquake, not every time an 8-magnitude earthquake is only going to get repeated. But 6 magnitude earthquakes or 5 magnitude earthquakes are also going to get repeated. And we also know that the higher the magnitude of the earthquake, the less frequently that earthquake will happen because, corresponding to that magnitude, the accumulation of strain energy will take really longer. So, if we talk about 5 magnitude earthquakes, that might be happening more frequently than on the same fault 7.5, 7.8, or 8.2 magnitude earthquakes, because 8.2 magnitude earthquakes will require a relatively large amount of energy with respect to 5 magnitude earthquakes. So, in probabilistic hazard analysis, we will also take into account that even though we are not taking into account the worst scenario, we are taking into account the scenario which is most likely to occur, or which is happening more frequently at your source of interest.

So, ground motion again useful for design of routine buildings where not every time you will take decision with respect to the safety but also you will be taking into account what is the finish involved, what is the ground motion parameter which you are getting based on your hazard analysis. So, that is the reason the results from probabilistic hazard analysis are quite useful when we are talking about the construction of routine buildings where not only the finance but also the safety of the buildings are also given equal importance. But certainly, in this particular case, finance will be given more weightage than the safety because even if the building undergoes partial cracks or it undergoes some defaults also, but still the building is able to serve the purpose, or we can go for retrofitting of the building rather than spending 2 times, 3 times, or 4 times more money in the construction itself because that will be a very huge amount. Taking into account that the ground motion, which based on probabilistic deterministic one you are taking into account for construction of the building, will not occur mostly with respect to the routine buildings.

So, certainly, we will not go for deterministic hazard value for the design and construction of routine buildings. Probabilistic hazard analysis was proposed by A. Cornell in 1969, this is the history, and then after that, there was a lot of development with respect to how the estimation of maximum magnitude at a particular fault, the minimum magnitude, or cut-off magnitude of a particular fault can be taken into consideration. Then, how accurately one can determine the seismic activity of a particular region can also be taken into account. Overall, the probabilistic hazard analysis takes into consideration not only a single magnitude earthquake corresponding to maximum magnitude; it will take all possible magnitudes into account. So, if the fault has produced magnitude 4, generally magnitude 4 and above are considered because lesser than 4-magnitude will not have a significant effect on your infrastructure as far as hazard analysis is concerned. So, what will we take? We will take all the magnitudes; if 4 magnitude is there, 4-magnitude to whatever the maximum potential earthquake is capable of happening on a particular source, we will take all those magnitudes into account and try finding out what is the frequency of different magnitude earthquakes to occur at your seismic source.

Similarly, we will not again take into account that the earthquake is going to happen only at the closest distance from the site. It can even happen at an intermediate distance; it can even happen at a farther distance. So, again, we will take into account not only a single value of distance but all the distances and all the locations that are there in a particular fault with respect to the site. So, we will take all those locations within the fault and then try finding out what if very close to the site, this is the epicentral distance; what if it is at an intermediate distance between the source and the site; what if it is at the farthest distance from the site on your seismic source. So, we will take all those distances—minimum distance to maximum distance and intermediate values also into account. Similarly, with respect to whenever we are taking all magnitudes, all distances, certainly a lot of combinations of magnitude and distance in terms of ground motions.

If we take different magnitudes, different distances from here, and put them in your ground motion prediction equation, that means you are talking about infinite or significantly high numbers of finite seismic scenarios. If we are talking about one particular fault, 20 magnitudes if you are targeting. Similarly, here also, we are talking about 20 distances. That means corresponding to each magnitude, you are considering that this magnitude earthquake can happen at all the 20 locations on the fault. So, collectively, we are talking about 400 seismic scenarios at least to take into consideration what are the potential scenarios likely to occur from just one single source, and the same procedure will be repeated for all seismic sources. So, that means if you are having a site surrounded by close to 60, 70 seismic sources, one can refer to the seismic atlas map of the region and then find out what are the active sources.

One can also explore past earthquake information into account and try developing the seismic map. So, one is going to give you 60 seismic sources are there. According to each seismic source, we have taken 20 scenarios corresponding to these 20 magnitudes, and again, all these 20 magnitudes on each source can happen at any location—any 20 locations within the fault. So, 20 times 20 times 70 is the total number of scenarios you will be taking into account rationally in order to find out the different combinations of scenarios likely to occur at your site of interest. Then, we will take into account corresponding to different magnitudes what is the uncertainty or what is the frequency to occur with respect to distance; what is the probability to occur that it may happen at minimum distance, it may happen within this particular distance range, it may happen in another particular distance range.

So, we will take that into account, and combining all those uncertainties, we will be getting the hazard curves. I will discuss what is a hazard curve here in the end. So, PSHA or probabilistic hazard analysis characterizes uncertainties with respect to location, with respect to magnitude, and with respect to frequency—how frequently with respect to magnitude and size, magnitude and location, what is the frequency of ground motion to get repeated at your site of interest, and of course, if we have local site effects also into account, that will also help in understanding the induced effect of the earthquake. So, you will get, based on probabilistic hazard analysis, not just one scenario but a significantly large set of scenarios. You can take those scenarios into account and even go for quantification of induced effects.

So, combining all those uncertainties primarily related to location, secondly with respect to magnitude, and thirdly with respect to the frequency of earthquake or amplitude of ground motion with respect to which you are interested to find out whether my scenario based on these two combinations is going to get exceeded or it will remain within the desired value of ground motion parameter. So, the steps which one has to follow for probabilistic hazard analysis are these four. Firstly, you will try to find out what are the seismic sources which have, or which are capable of producing at least a minimum magnitude of four. So, corresponding to these sources, we will try to find out what is the frequency of different magnitude earthquakes to happen on these particular sources. Taking into account the seismic activity of that particular source, or if the number of earthquakes is not significant to find out the seismic activity of a particular source, we will take into account the seismic activity of a region, and based on that, based on the principle of superposition, we will try to find out what should be the seismic activity of an individual source. Take into account that the overall seismic activity within the region should be maintained. Primarily, that can be determined using how many earthquakes in a region are there, how many earthquakes are there on a particular fault. Similarly, what is the length of the fault, and what is the summation of the length of all the faults in a particular region because primarily, based on these two parameters, one can redistribute the seismic activity from a region to individual seismic sources.

So, we have identified the seismic sources which are there which are capable of producing a magnitude of 4 and above. Based on that, we try finding out the frequency of different magnitudes to occur at the site of interest. Similarly, we also try to find out what is the distribution pattern in terms of different hypo central distances or different epicentral distances at which different scenario earthquakes can possibly happen. Based on these two, that is, magnitude frequency and distance probability distribution for each of these seismic sources is required. After that, we will try to find out, based on the Gutenberg-Richter relation, what is the frequency of different magnitudes to get repeated during the ground motion to get repeated during a given exposure period. Using different magnitudes and different distances, we will try to find out different seismic scenarios using the ground motion prediction equation. So, step 3 tells about estimating the ground motion which can be produced by different combinations of magnitude and distance from each of the steps.

So, step 1 is going to give you what is the magnitude frequency and what is the distance probability. Step 2 is going to tell you overall in a particular region or on a fault what is the frequency of ground motion to get repeated, or what is the frequency of different magnitudes to get repeated during a particular fault. Step 3 will give you what is the ground motion which is going to be produced considering the seismic scenario of magnitude in step 1 and step 2 and the distance probability in step 1. Collectively, based on this, we will try to find out the frequency of different ground motions correlating this with respect to the ground motion amplitude. We will be able to find out in step 4 the value of the hazard curve. So, the hazard curve basically is going to give you a plot or a correlation between the ground motion parameter with respect to frequency of occurrence, or we can say a return period. That means, if we know for one particular seismic source the hazard value, this hazard value is going to give me, like on that particular seismic source, how frequently this particular ground motion is capable of happening. That means, if you are talking about some seismic source F1, we have the hazard curve. Based on the hazard curve, we can say, like corresponding to 0.03g corresponding to this, and then we will try to find out, based on the y-axis, what is the frequency of 0.03g which can be produced on fault F1, based on the information which is available to us.

So, that is called a hazard curve. We can determine the hazard curve for an individual fault and then clubbing up the hazard curves of all the faults. Suppose 70 faults are there which are active in a particular region or within your seismic map. Then, you can club the seismic hazard values from all these 70 seismic sources, and then it will give you, overall, what is the hazard curve for a particular region, taking into consideration all seismic scenarios from all the 70 faults. So, we can have a hazard curve for an individual fault; also, we can have a hazard curve for all the faults and the summation of all that. Once the hazard curve is known to us, we can refer to the hazard curve, and then, considering what scenario, this is also going to give you the seismic scenario which we are targeting. If we are targeting maybe some scenario which is having, like, 2 percent probability that it is not going to exceed in the next 30 years, 40 years, or 50 years, correspondingly we can find out the frequency, the lambda value of that particular scenario. Based on the total hazard curve corresponding to that frequency, we can find out how much is the ground motion which is having this particular frequency or having this particular scenario frequency to occur.

So, that is the advantage of the total hazard curve. We can have a hazard curve for an individual fault, and we can also have a hazard curve for total faults or the summation of hazard curves for all the faults, which is going to give you the hazard curve at your site of interest, taking all the active sources within your seismotectonic province or seismotectonic map. Now, this is what we are discussing about n number of seismic scenarios. Whenever we are talking about seismic scenarios, that means we will be taking into account the ground motion prediction equation.

Based on earlier discussion, we have seen these ground motion prediction equations are based on the values of different coefficients, which are regression coefficients obtained once we had the database of whether it is recorded ground motion or synthetic ground motion. So, we had a database, and then, once from that particular database, we are developing a ground motion prediction equation, the coefficient values C1, C2, C3, and so on up to Cn. The value of these coefficients is a function of the period of interest. So, we are going with 0 period. That means whatever value of the ground motion parameter we are going to get, that will be also called spectral acceleration at 0 seconds or peak ground acceleration or peak horizontal acceleration.

Similarly, we are talking about 0.02 seconds or 0.1 seconds. Corresponding to 0.1 seconds, pick up the value of seismic coefficients, the GMP coefficients, put in the equation corresponding to different values of magnitude and distance, and again put in the equation. So, what you will get is spectral acceleration corresponding to 0.1 seconds or 0.2 seconds. Like, corresponding to what value of period we have taken, the value of the coefficients. In the end, once we are getting the ground motion parameter, that will correspond to that period alone.

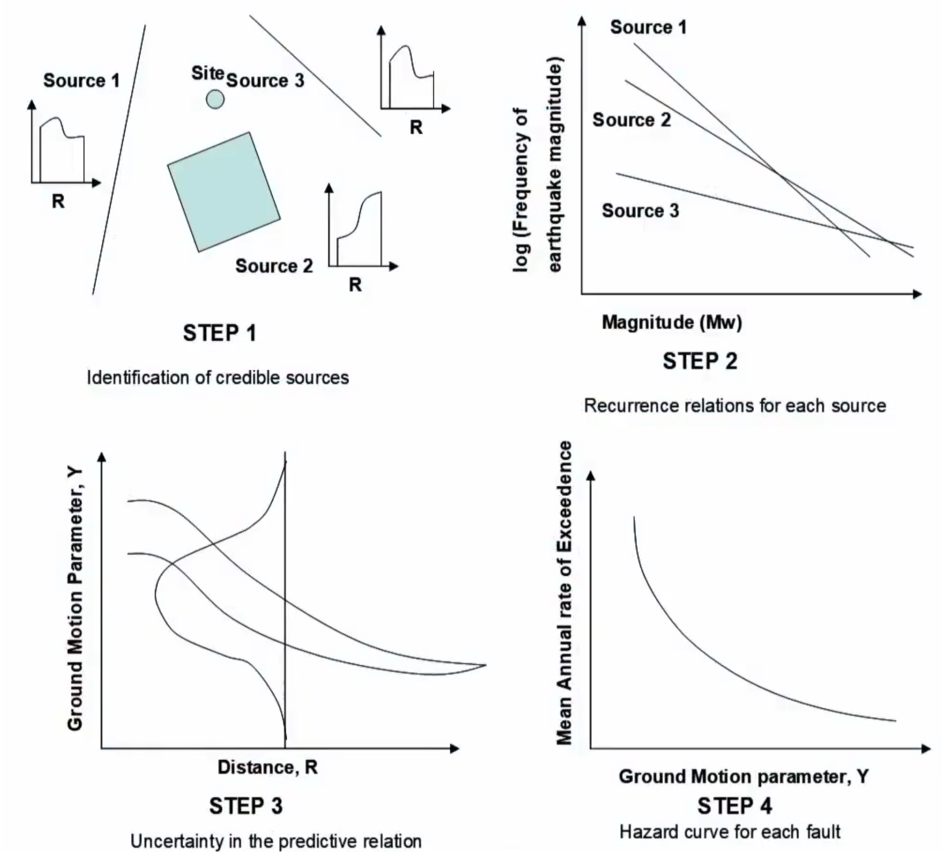
Repeating the same procedure, which we have shown over here, again, we will be getting different values of the hazard curve. So, if we are taking the coefficient values corresponding to 0 seconds and perform hazard analysis like this, in the end, we will be getting a total hazard curve for a particular site of interest. Because if you move your site of interest, the distance values will change with respect to seismic sources. So, the total hazard curve is also dependent on the site location where you have actually derived the total hazard curve. So, one is the site location. Secondly, when we are determining the ground motion parameter, our ground motion parameter is also a function of the time period of interest. So, the total hazard curve, if you are developing, considering the coefficient value corresponding to 0 seconds, definitely such a hazard curve you can use to predict ground motion for a given frequency at 0 seconds only. You cannot use a single hazard curve to determine the ground motion for any period of interest. So, there are basically two frequencies: one is the frequency of ground motion, and the second one is corresponding to this period, which is again corresponding to the period of motion. We can find out different values of the hazard curve. So, two values of frequency we will be using. One is the frequency, how frequently the ground motion is going to get repeated at the site, and secondly, corresponding to 0 seconds, 0.2 seconds, or 0.6 seconds, what is the value of the coefficients and what is the corresponding spectral acceleration?

So, one period is corresponding to spectral acceleration; the other period is corresponding to one by the frequency of the seismic scenario to get repeated during the period of interest. So, collectively, you are having four steps. One, you characterize the seismic source, then try finding out magnitude frequency. Second, distance probability, club magnitude frequency and distance probability with respect to the frequency of ground motion and determine the total hazard curve. Once the total hazard curve is there for a particular region or a particular site, then, depending upon the seismic scenario of interest, one can go and determine the value of the ground motion parameter. So, for a particular period of interest, the frequency of the seismic scenario can change, and corresponding to that, one can determine the ground motion parameter even with respect to a single total hazard curve. But if you are changing the period of interest, that spectral acceleration corresponding period, definitely you have to have, corresponding to the period of interest, the total hazard curve. Then, only you will be able to determine the value of spectral acceleration corresponding to that period.

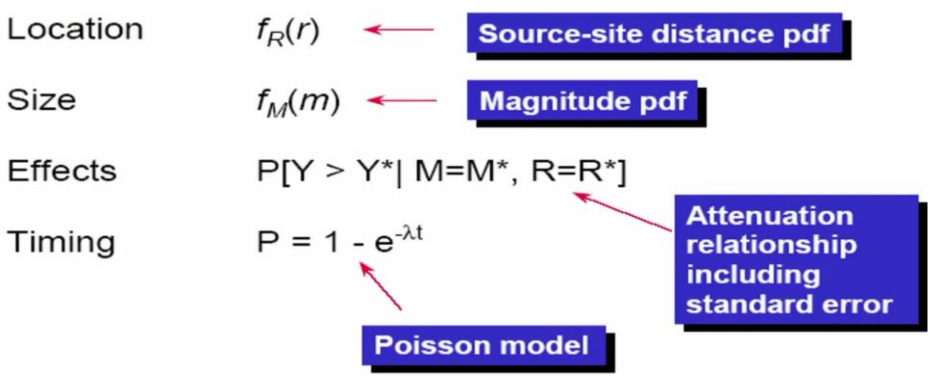
Repeat the same procedure. You will get the uniform hazard spectra. That means, corresponding to zero period, for known frequency of exceedance, we will try finding out how much is the spectral acceleration for the same frequency. Corresponding to the hazard of 0.2 seconds, again, we will repeat the same procedure. You will get again spectral acceleration corresponding to 0.2 seconds. Again, corresponding to 0.8 seconds, 1 second, 1.5 seconds, 2 seconds, repeat the same thing. Every time, based on the hazard curve, what value you are getting, it is going to give you one more point on your uniform hazard spectra.

So, the uniform hazard spectra is very much similar to the response spectra, but it is corresponding to uniform hazard. The same scenario, we are talking about some seismic scenario, which has 10 percent probability of exceedance in 50 years. Then, this 10 percent probability in 50 years will be applicable to all the points which are shown on your hazard spectra. That is why it is called a uniform hazard spectra.

So, uniform hazard spectra again will change with respect to the frequency of interest. If I am talking about uniform hazard spectra corresponding to 2 percent probability in 50 years, then all the points in your uniform hazard spectra will be indicating what is the spectral acceleration corresponding to 2 percent probability in 50 years at 0.1 seconds, 0.2 seconds, 0.6 seconds, like that. If we are talking about uniform hazard spectra corresponding to 1 second, again, the entire plot will change. So, that will give you, corresponding to 1 second, what is corresponding to a known value of frequency like 2 percent probability in 50 years. Then, all the points in uniform hazard spectra will be indicating the spectral acceleration corresponding to 0 seconds, 0.1 seconds, 0.2 seconds, 0.5 seconds. But each of these points corresponding to the seismic scenario will be having the frequency of 2 percent of not exceeding in 2 percent probability in the next 50 years. So, that is how we take the seismic scenario into account and utilize your total hazard curve in terms of determining the probabilistic seismic hazard values.

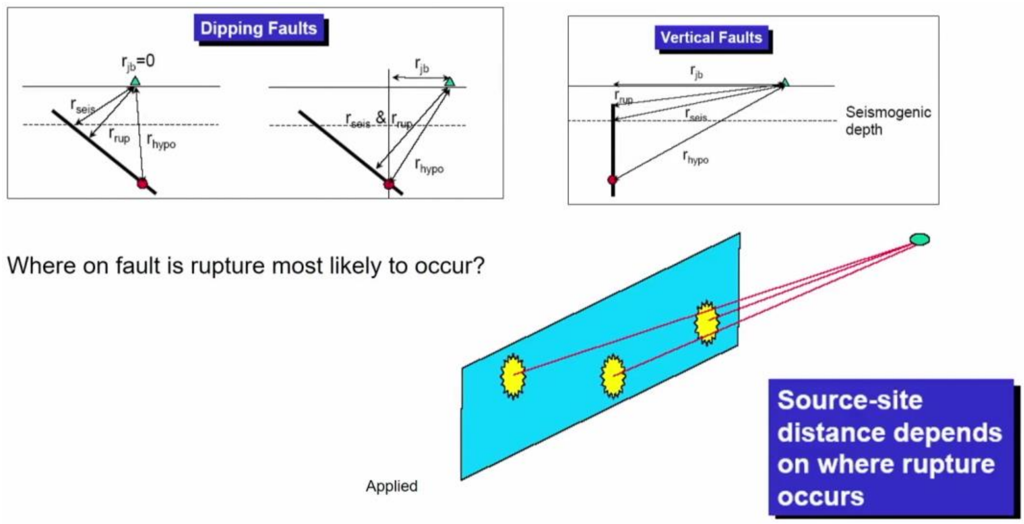


So, these are the steps which we have already discussed earlier. We have discussed this also: the seismotectonic map will take into account the geological data, geophysical information, past seismic data, and also the seismic source information. Then, accordingly, we can find out and develop the seismotectonic map of a particular region. Again, depending upon your site, we can take into consideration a radial distance within which we have to find out more information about the geological and seismological properties of a particular site or region of interest. So, one can refer to these guidelines, which are given over here, in order to find out how much detail one has to collect information in terms of geotechnical, geophysical, geological, and seismological data for a particular region of interest.

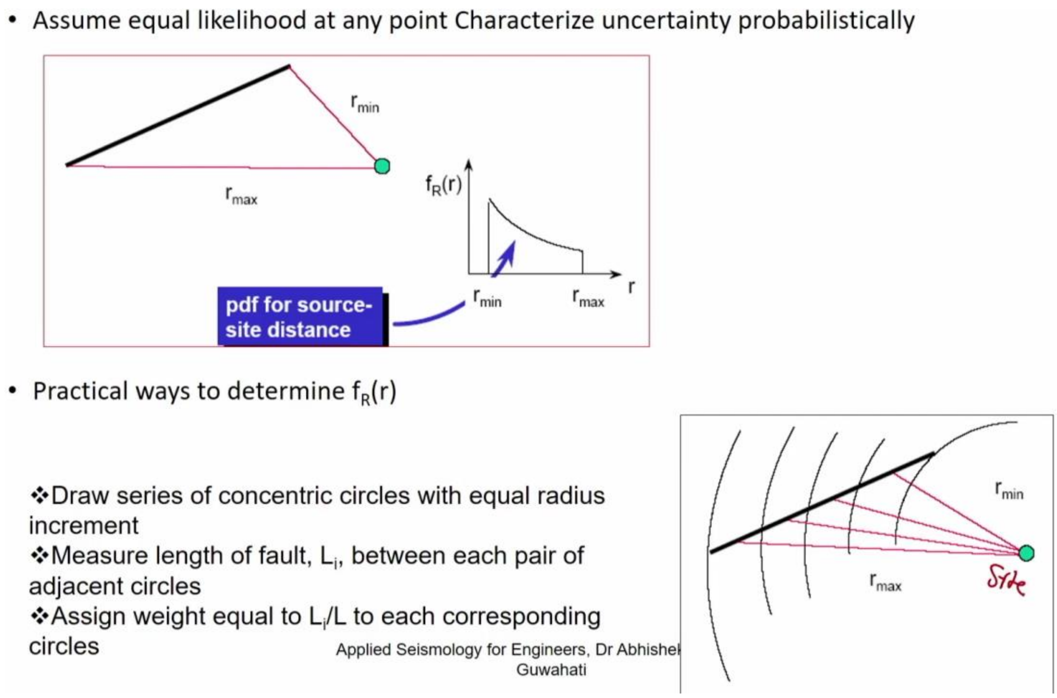


Now, as we mentioned in the summary, we will be discussing the frequency of distance probability. Then, we will discuss the frequency of magnitude, and collectively, based on this, we can say we are interested in finding out what is the probability that the ground motion at my site of interest is going to exceed another ground motion. So, if I say, "What is the probability my ground motion is going to exceed 0.5g?" Then, this 0.5g will come over here, and 0.5g should either not increase or should increase because of a seismic scenario generated corresponding to magnitude M* and distance R*. That means I have taken into consideration a number of scenarios, and then collectively, I am interested in finding out what is the probability that, corresponding to these scenarios, my ground motion is going to exceed a threshold. I am defining a threshold value of 0.01g. What is the probability that it is going to exceed 0.01g? What is the probability it is going to exceed 0.05g? Accordingly, every time I am getting how frequently 0.01g or 0.05g is capable of being repeated at my site of interest. This we will correlate with respect to the Poisson model, which will suggest that the same probability, which is given over here, is a function of 1 minus exponential minus lambda t. So, lambda is going to give me the frequency at which I am interested in targeting a particular seismic scenario.

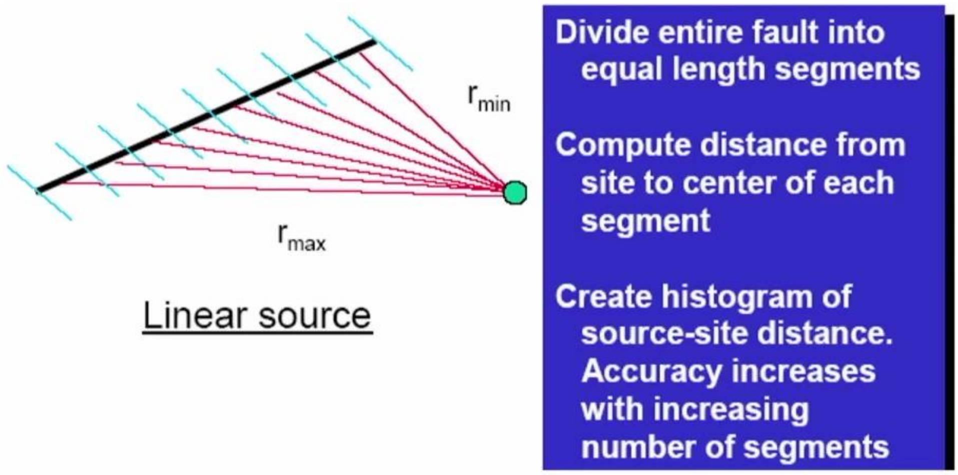
If I am interested in finding out a ground motion that has a 10 percent probability of exceedance in the next 50 years, that means whatever ground motion I am going to predict today has only a 10 percent probability of exceeding. Ninety percent of the time, this ground motion is not going to exceed in the next 50 years. Similarly, another terminology which is frequently referred to in probabilistic hazard analysis is: what is the ground motion which has a 2 percent probability in 50 years? That means I have to determine a ground motion, based on probabilistic hazard analysis, which will have only a 2 percent probability of exceeding in the next 50 years. So, if today I am going to give the ground motion from today for the next 50 years, this ground motion—which I have determined based on probabilistic hazard analysis today—has only a 2 percent chance of exceeding. Ninety-eight percent of the time, the ground motion I am predicting now will not exceed. So, this is the frequency of ground motion or seismic scenario. This seismic scenario is not going to exceed during the design life. So, t refers to the design life or period of interest. If I am saying it is not going to increase in the next 50 years, then t is 50 years. So, t is the period of interest. When I say 2 percent probability of exceedance, this means the probability is 2 percent that my ground motion in the next 50 years is not going to get exceeded. So, corresponding to this value of 2 percent and t value of 50 years, one can determine the frequency of that ground motion, which has just a 2 percent probability of exceeding in the next 50 years. Ninety-eight percent of the time, that motion will not exceed in the next 50 years. So, one is, based on this particular equation, trying to correlate the probability with respect to magnitude and distance scenarios, and based on the second, we will also correlate this with respect to the frequency of ground motion in a definite period of exposure, which is generally considered as the design life of the structure.



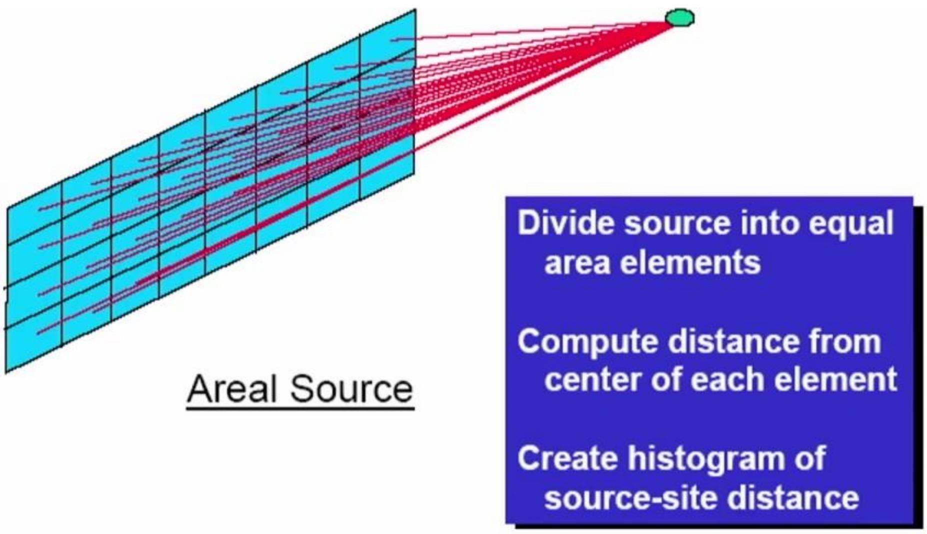
So, depending upon the position of your site with respect to the distance, we can take into account different definitions of distances when you are talking about dipping faults versus vertical faults. There are different methodologies mentioned over here. Overall, we are interested in finding out—even if you are taking into account a two-dimensional source—what is the probability that an earthquake rupture may happen here, here, or any other particular location. This is because not every time will an earthquake happen at the same location, but that particular location of rupture. So, you can say this is the location of rupture. This will be taken into consideration while determining the hypo-central distance uncertainty.



Similarly, you see this particular site. This is your site of interest, and I am interested in finding out the distance probability. So, what I will do is draw maybe a number of circles, and then, corresponding to the locations between each concentric circle, I will try to find out what is the probability that the rupture is going to happen in this particular section. What is the probability the rupture will happen over here? What is the probability the rupture will happen over here? What is the probability the rupture will happen at this particular site? Accordingly, we can find out. Remember, we are trying to find out the rupture probability here, but corresponding to this particular section, which undergoes failure, my hypo-central distance will be this distance. If the rupture is going to repeat here, this will be my hypo-central distance, which I will use in my ground motion prediction equation. So, we can go with, maybe dividing the entire fault into sub-faults, and try to determine, based on the coordinates of these sub-faults, what the distance is and corresponding to each distance, what the location undergoing rupture is.

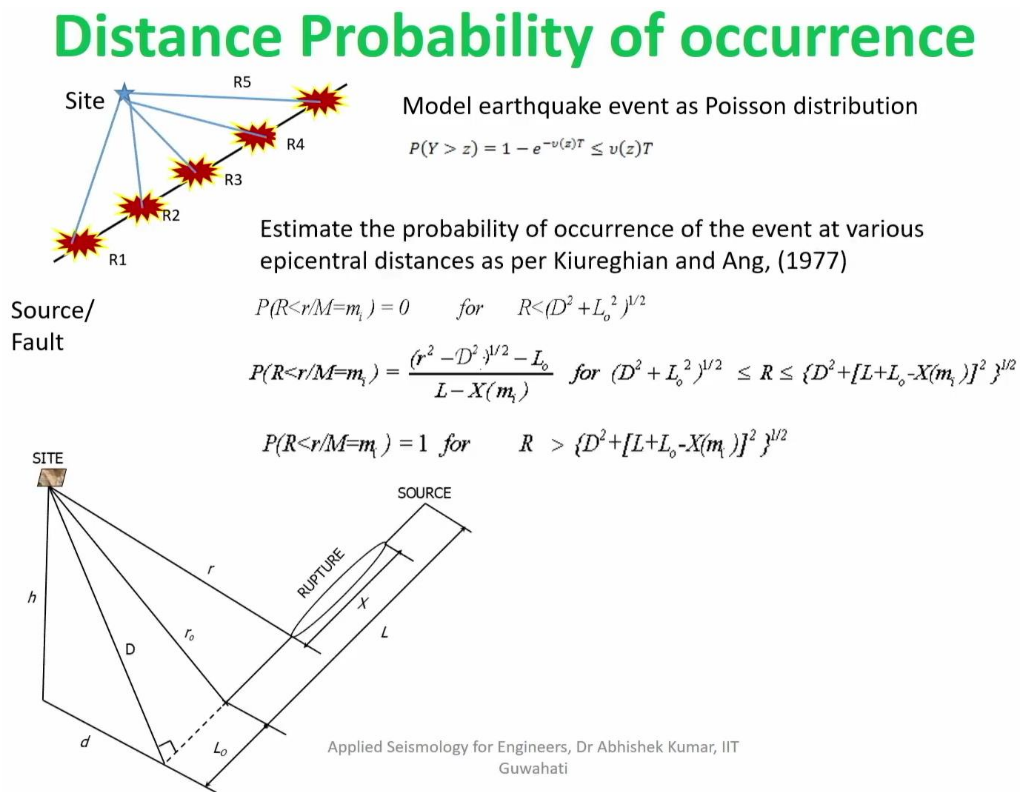


Similarly, with respect to a linear source, this is what I was just mentioning: you can divide the entire fault into a number of sub-faults and try to determine, corresponding to each sub-fault, what the hypo-central distance range is and try determining the probability.

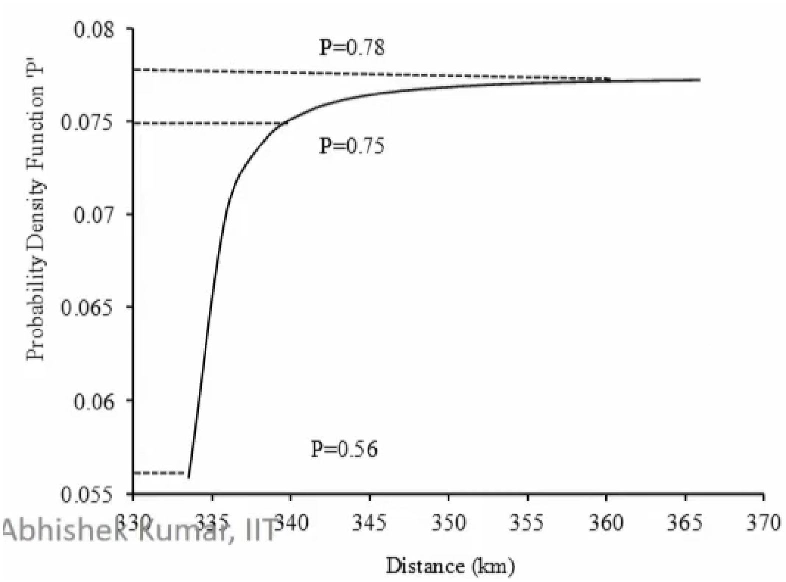


If you are talking about a two-dimensional or area source, rather than dividing the length into different sections, we can divide the entire area into different parts. So, if we recollect what has been discussed in source characterization, we have also got point sources, linear sources, and area sources. That also can be done here. This has already been discussed in lecture 9, so I am not going into those details here. Area sources are also there.

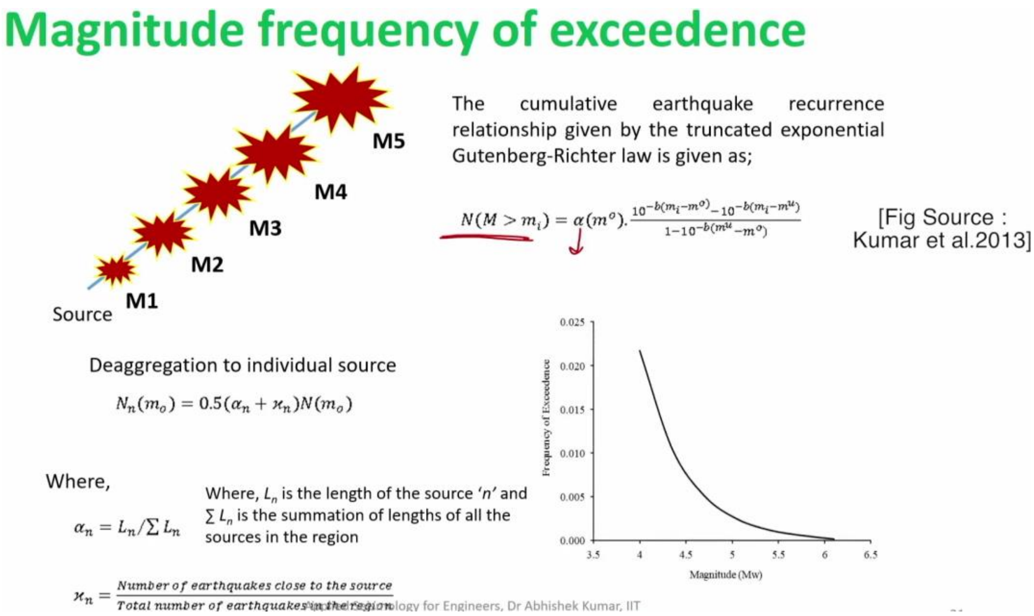
So, we have an earthquake catalogue, which is homogenized, declustered, and completeness analysis is also done. Seismic parameters are also determined, and the minimum and maximum magnitudes have been determined. Based on this, we can find out the distance probability. You can see distance probability that rupture can happen anywhere.



So, Kiureghian and Ang in 1977 gave these equations based on which you can find out what the probability is that the rupture can happen at a distance R, which is user-defined. You can see in this particular figure that if you extend like this, you will be able to find out what is the minimum epicentral distance, what is the starting point distance, and any particular distance (small r) that one has to take into consideration. r is the rupture width. So, every time, whenever you are taking r into account, this is the length available to rupture, and accordingly, we can find out using these two equations. The first one tells you the probability that rupture can happen at any distance other than r. Other than r means anything less than r, which is outside the fault. Rupture cannot happen outside the fault, so that is zero. Similarly, the second equation tells you the probability that rupture can happen anywhere between here, where the maximum distance of R is small r. This probability will be 100 percent, meaning anywhere this will give you the cumulative probability. Based on this, you can find out the frequency. We will try to find out the cumulative frequency corresponding to any particular point, starting from the beginning of the fault to the point of observation. What is the cumulative frequency? If you divide the fault into a number of sub-faults, we will first try to find out the cumulative probability and then, reducing the contribution from just the previous sub-fault, we can find out the actual probability with respect to the fault undergoing rupture.

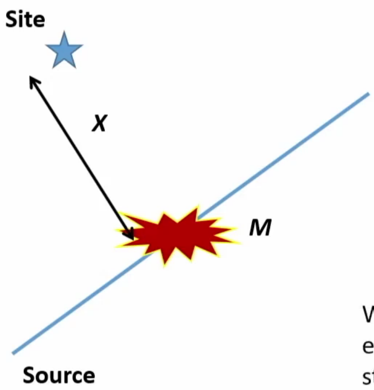


So, based on this calculation, we can find out, typically corresponding to distance, what is the probability density function.



Similarly, with respect to magnitude, as we discussed, magnitude is not going to stay the same, but it keeps changing. Different magnitudes are possible on a single fault, so we also have to find out what magnitude will occur. So, based on this equation, which is going to give you what the seismic scenario is, we can find out from the seismic tectonic map. The value of B is again α and β, which we have used in seismic activity parameters, and we can also determine the value of B corresponding to β. m_i is the minimum magnitude of interest, m^u is the upper magnitude on a particular fault, and m_i is any magnitude for which we are interested in finding out how frequently that magnitude will get repeated over a period of time. And that's how you can find out the magnitude frequency of exceedance.

Uncertainty in Ground Motion Exceedence



$$log\ (y) = c_1 + c_2 M - b\ log(X + e^{c_3 M}) + (\sigma)$$

The condition probability of exceedence can be estimated using lognormal distribution as given below (EM-1110, 1999);

$$P(Y > z|m_i, r_j) = 1.0 - F'\left\{\frac{\ln(z) - E\,[\ln(Z)]}{S[\ln(z)]}\right\}$$

Where, ***E[ln(z)]*** is the log of mean ground motion estimated from the GMPE used, ***S[ln(z)]*** is the log of standard error term obtained from the GMPE used, ***ln(z)*** is the specified ground motion with respect to which the probability of exceedence has to be calculated.

Now, we have distance, magnitude, and a set of scenarios where combinations of distance, magnitude, and hypo central locations can happen. We can then find out what the probability is that, corresponding to magnitude m_i happening at distance r_j, the scenario predicted by the GMP will exceed a user-defined threshold value. So, I'm deciding on a value of maybe 0.05g. Then, this equation is going to give me the probability that my scenario, which corresponds to magnitude m_i happening at r_j, will exceed 0.05g. What is the probability? So, this is where the ground motion prediction equation comes into the picture.

$$P(Y > z) = 1 - e^{-\upsilon(z)T} \leq \upsilon(z)T$$

Now, here we see the probability of the ground motion exceeding a threshold is also a function of 1 minus exponential minus λt.

$$\upsilon(z) = \sum_{n=1}^{N} \sum_{m_i=m^o}^{m_i=m^u} \lambda_n(m_i) \left[\sum_{r_j=r_{min}}^{r_j=r_{max}} P_n(R = r_j|m_i) P(Y > z\,|m_i, r_j)\right]$$

This is the frequency of the seismic scenario, this is the period of exposure (t), and this particular part is also equal to the probability that ground motion, because of N number of faults (N is the number of faults), where each fault's magnitude is varying from the lowest magnitude m^o to the maximum magnitude m^u, and each fault's distance is ranging from r_i to r_j, or from r_{min} to r_{max}.

So, Gutenberg-Richter's relation, we have already discussed this in previous lectures, so I'm not going into details here. Now, this is one thing that is quite important when we discuss the Poisson model, because generally, probabilistic hazard analysis follows the Poisson model, which means that it is given as P(t) = 1 − e^(-λt).

Poisson Model

- Consider an event that occurs, on average, every 1,000 yrs.
  - What is the probability it will occur at least once in a 100 yr period?
    - $\lambda = 1/1000 = 0.001$
    - $P = 1 - \exp[-(0.001)(100)] = 0.0952$
  - What is the probability it will occur at least once in a 1,000 yr period?
    - $P = 1 - \exp[-(0.001)(1000)] = 0.632$

Then, the annual rate of exceedance for an event with a 10% probability of exceedance in 50 years is;

$$\lambda = -\frac{\ln(1-0.1)}{50} = 0.0021$$

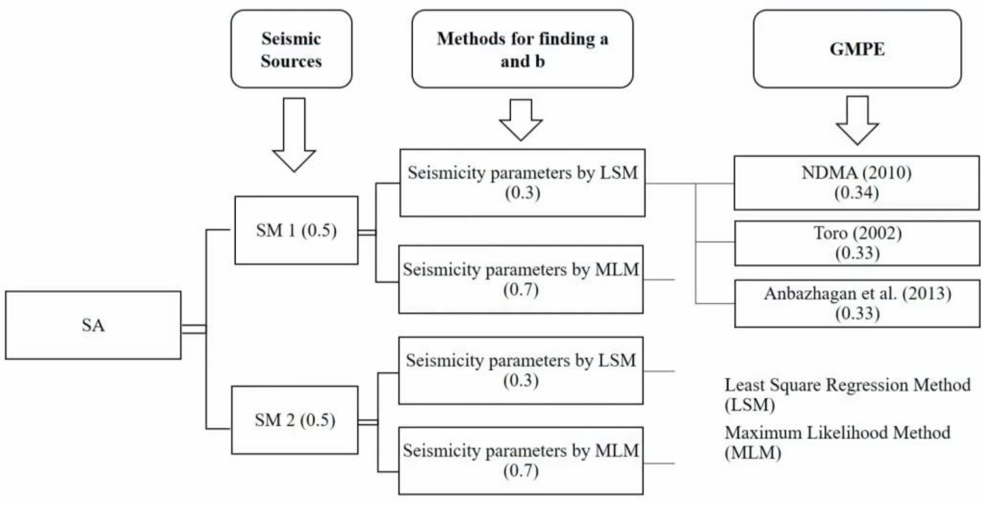
$P = 1 - e^{-\lambda T}$

The corresponding return period is $T_R = 1/\lambda = 475$ yrs.

For 2% probability of exceedance in 50 yrs, $\lambda = 0.000404$/yr $T_R = 2475$ yrs

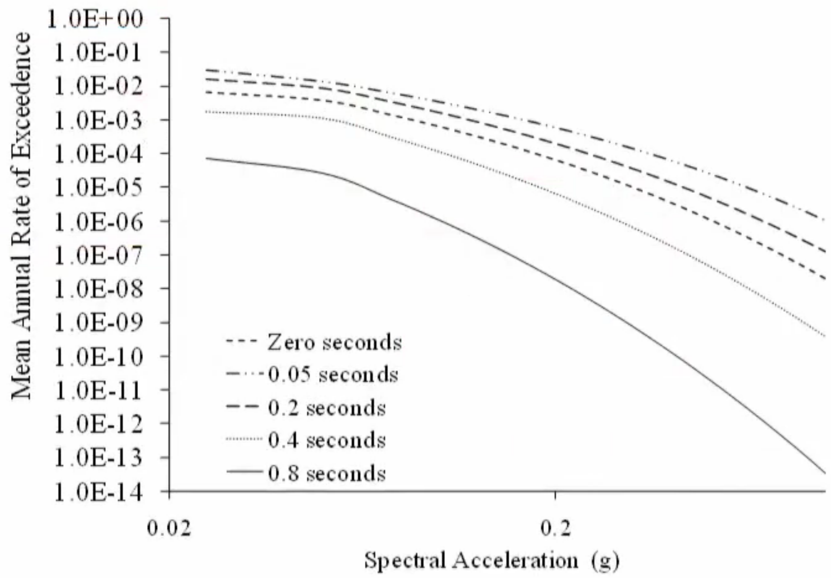
Here, just as an example, consider an event that occurs on average once in 1,000 years. This means the average frequency of that particular event will be 1 over 1,000, which is 0.001. This is the frequency, 0.001 times per year. If I'm interested in finding out the probability of that event occurring at least once in 100 years, we can put the values $\lambda = 0.001$ and $t = 100$ years. Based on this, we can calculate the probability that an event, which happens at least once every 1,000 years, has only a 9.52% chance of happening in the next 100 years. Similarly, as mentioned, two scenarios are given: a 10% probability in 50 years. We can use this 10% probability as $P(t)$ in 50 years, and by using $t = 50$ years, we can find out the value of λ. The value of λ here is 0.0021, which gives us a frequency of 0.0021 per year. This corresponds to a return period of 475 years, meaning that at least once in 475 years, the seismic scenario is going to be experienced at the site of interest. Similarly, with a 2% probability in 50 years, this gives a frequency of 0.000404 per year, which corresponds to a return period of 2,475 years. This means that at least once in 2,475 years, the seismic scenario you're targeting will be experienced at your site of interest.

Logic Tree Approach

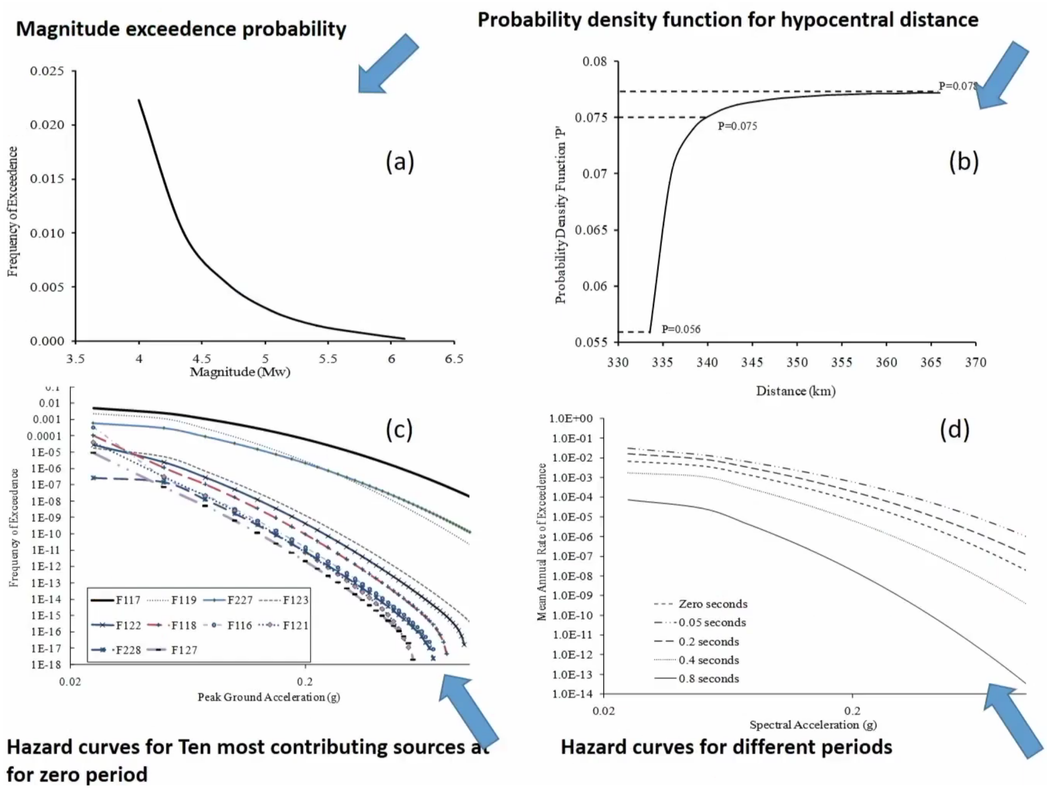


Repeating this particular part again, the logic tree is also quite important. Many times, we will have different source models: a linear source model or an area source model. To take both into account, we can use a logic tree approach so that the limitations of one model can be minimized by using multiple approaches. Similarly, with respect to seismic activity parameters, we can determine values based on different approaches and use all of them collectively, so that the effects or limitations of one method can be minimized by taking different methods into account.

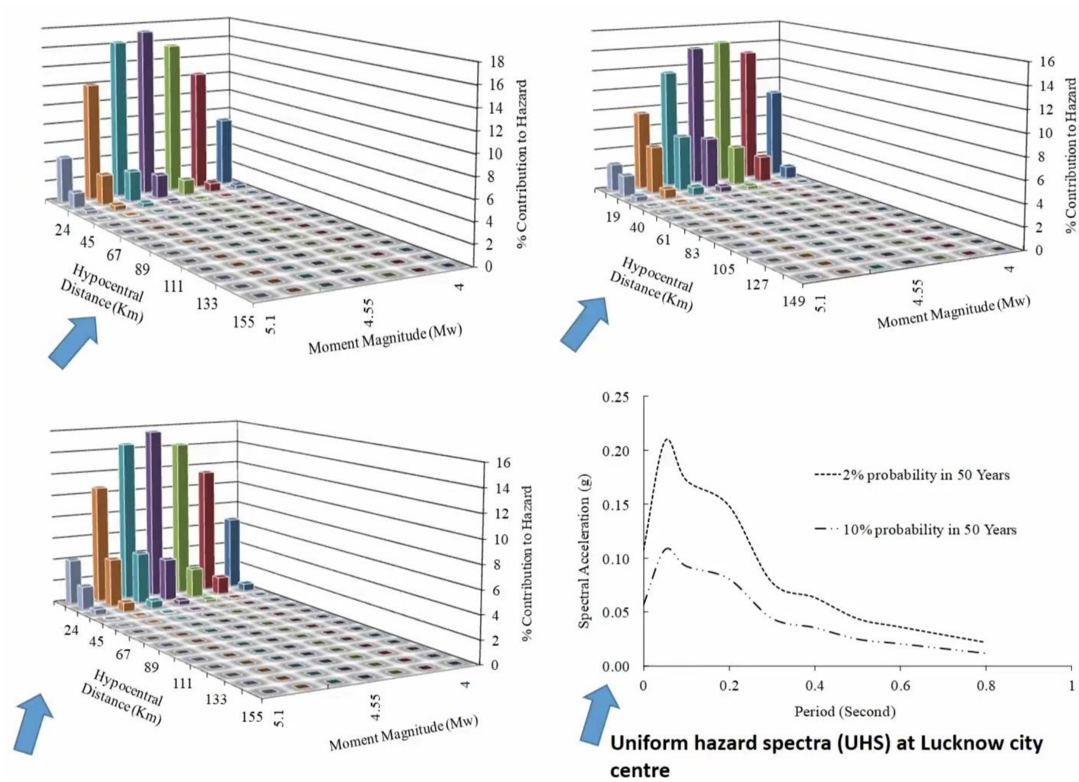
Thirdly, with respect to ground motion prediction equations, we can use a greater number of GMPEs, because each of these equations is empirical, and whenever we predict ground motion, there might be some standard error. This standard error can be minimized by considering more GMPEs. This process is called the logic tree approach, where we follow multiple approaches related to seismic sources, seismic activity, GMPE, and other factors, and combine them to find the spectral acceleration values.



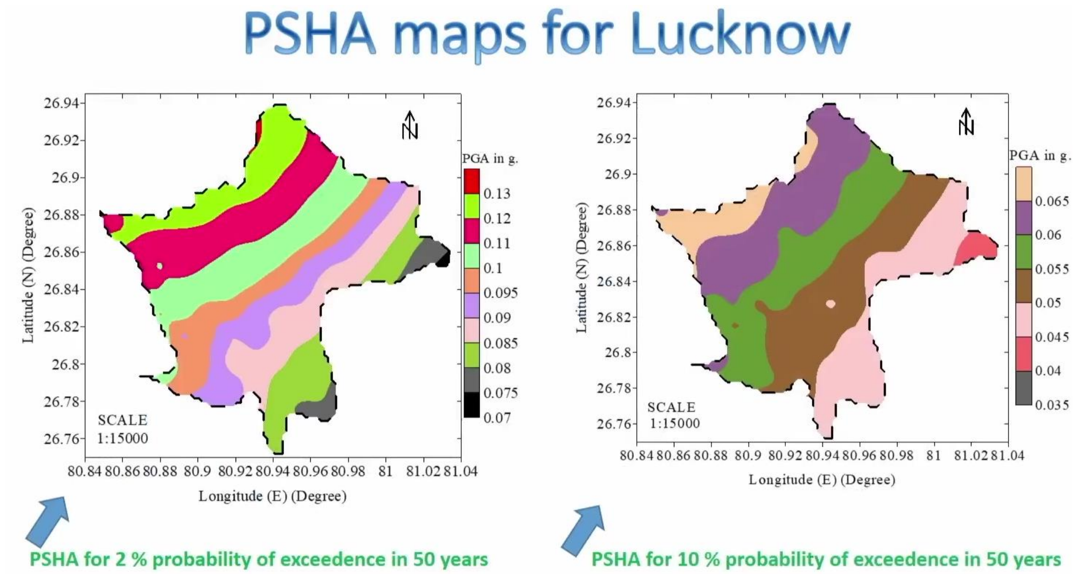
This is the typical hazard curve, as mentioned. This is the hazard curve given for different periods of interest. Depending on the period, I have taken into consideration what the coefficient in the GMPE is and performed the seismic hazard analysis. The probabilistic seismic hazard analysis gives us the value.



Similarly, we can repeat the same procedure to get different values of the hazard curve for different locations.



We can also get the deaggregation part, which is the plot showing how much contribution different magnitude and distance combinations are making at a site of interest. This can help us find out if there's an important fault, and what magnitude on that particular fault can be considered the worst-case scenario for our site of interest. This is the uniform hazard spectra. I have taken this from Kumar et al., 2013, and the reference is given in the next slide.



So, thank you all. This concludes the discussion on probabilistic hazard analysis. Thank you.