Applied Seismology for Engineers

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Week – 06 Lecture - 02

Lecture – 12

Hello everyone, welcome to lecture 12 of the course *Applied Seismology for Engineers*. In this particular lecture, we will be discussing about how to go ahead primarily with the quantification of seismic hazard analysis following a deterministic approach. In earlier lectures, we have discussed in detail primarily about the reason for earthquake occurrence, then whenever earthquakes are happening on a particular source, how to characterize that particular source, how to identify and express the dominating fault mechanism on a particular fault.

And as we have also discussed that in a particular region of interest, once we are interested to find out the expected level of ground shaking which can be used for earthquake-resistant design of buildings, for quantification of induced effects, and even in case if you are going for ground improvement, what should be the expected level of ground shaking for which one can design a strategy for ground improvement. So, all these things we have discussed in earlier lectures, and then we also discussed about fault plane solutions, both starting with beach ball solution, then discussing about the stereonets. Overall objective, if we take into account from lecture 1 to 11, was primarily related to how earthquakes are happening, where earthquakes are happening, what are the important sources on which earthquakes have been reported in the past, how one can go with the identification of such sources so that once we are going for detailed hazard assessment in a particular region, we should be having a clear-cut idea about what are the sources which can be considered as active sources. And taking into account the past of earthquake occurrence, that means the seismic history of a particular region, we will be in a better condition even to assign the value of seismic activity parameters in a particular region as well as on a particular seismic source.

This will give an indication about how frequently earthquakes have been happening throughout the history of known seismicity in a particular region or on a particular source. So, this is about earthquake occurrence, but finally whenever we are going with respect to the quantification of induced effects, whenever we are going for characterization of earthquake loading for seismic design of buildings, we have to have an understanding about what should be the level of ground motion one has to take into account such that this ground motion I should take for building design, this is the ground motion for which I have to check my site related to maybe slope stability problems, maybe related to liquefaction, maybe related to ground improvement, or in the same way in terms of any other induced effects. So, we have to find out basically what is the expected level of ground motion. This expected level of ground motion is generally classified as seismic hazard analysis.

So, in today's lecture, we will be discussing primarily about what is hazard and then we will be moving gently towards seismic hazard analysis, and then specifically about deterministic seismic hazard analysis. So, deterministic seismic hazard analysis is the topic which we will be discussing in today's lecture, that is, lecture number 12. Now, if we recall the discussions which we did in lecture 11, we primarily focused on that the characteristics of ground motion during a particular earthquake is the collective effect of what is happening at the source and what are the parameters which can approximate the source mechanism by means of different, different measurements. Then, the seismic wave which started from the source will be propagating through different media, primarily the crystal medium, and geometric spreading, heat, heterogeneity which will be encountered by the seismic waves when passing through a particular medium. So, we will be having some parameters which are used to characterize the propagation medium.

Thirdly, once the seismic waves, reach to a particular site, again there will be weathered rock, there will be engineering rock, then different soil stratifications which are available between the location where the seismic waves have just arrived through the crystal medium from the source and where your building is located, where your tunnel is located, where your underground or superstructure is located. So, in order to take that particular ground motion, we have discussed that one can refer to available ground motion prediction equations which are empirical correlations. These empirical correlations are going to give you a direct indication about what is the expected level of ground motion at my site of interest when some earthquake of magnitude M has happened at a certain epicentral distance or hypo-central distance or any other measure of distance parameter. So, this is going to give you an indication about what is the expected level of ground motion. We generally refer to it as spectral acceleration in general.

So, depending upon the period of interest, that means the period corresponding to the natural frequency of the system, we can have different, different values of spectral acceleration. So, the spectral acceleration is a function of the natural period of the structure. If we go with respect to design response spectra which are given in earthquake-resistant design-related codes, we will be seeing that the spectral acceleration which is plotted on the y-axis is basically a function of the natural period of the structure, or structure, or any, it can be concrete structure, it can be stratification beneath the ground surface. So, depending upon the period of the natural period of the structure, one can pick up using the design response spectra what should be the value of spectral acceleration. So, that means overall whenever we are going with hazard analysis, we are interested to find out corresponding to different natural frequencies or natural periods of the structures, what is the expected level of ground shaking.

This ground shaking is an indication of the approximate ground shaking which is likely to occur considering what are the important sources available within your periphery or within your seismotectonic province or within your seismotectonic map. This seismotectonic map as discussed in earlier class also related to source characterization, the range of or the radial distance of seismotectonic map may vary from 300 kilometers to 500, 600 kilometers depending upon the importance of the site, depending upon the seismic activity of your surrounding region. So, before going to seismic hazard analysis, let us discuss what is hazard.

So, hazard generally refers to a potentially damaging physical event, any event which is happening physically, it may be related to ground shaking, it may be related to fire, it may be because of blasting, it may be a terrorist attack, anything which is responsible, so it may be a natural phenomenon, or it may be a human activity. As I mentioned also related to explosion, may be related to bombing, so those are also part of hazard but those will be called as anthropogenic activities, and which are happening because of natural reasons like tsunami, like fire, like flood, drought, earthquake, so all these things will come under the broader category of natural hazards.

So, hazard can further be classified into natural hazards which are responsible or the phenomena which are happening naturally, those are called as natural hazards, and there can be anthropogenic hazards or human-based hazards. In both cases, these are called as hazards because every time there is a, there is a hazard occurring, it will result in loss of lives, there will be casualties, there will be people who are getting injured, then at the same time there will be economic loss, and at the same time third one will be property damage or building damage. So, the first one is loss to lives, the second one is economic losses, you might be having some bridges undergoing collapse, you might be having some buildings undergoing collapse, so property damages and collectively because of property damages there will be a lot of economic losses.

So, whenever there is a hazard hitting your site of interest, maybe a city or a region, we might come across some reports from time to time like because of a particular war this was the economic loss or during a particular earthquake these many casualties, building damages were there, and now a significant amount of finance is going into rehabilitation works. So, there again the money which otherwise would have been used directly for developing better infrastructure, now a significant portion of that money is going into rehabilitation work and restoration of at least basic infrastructure in the affected area.

So, hazard can be classified as any phenomena which is happening naturally or maybe by means of human interventions. Primarily it is leading to loss of lives, even injury can be accounted because of earthquake or any other natural or human-based hazard, property damages and attempts, socio-economic disruptions are also there. Environmental consequences or environmental degradations are also an outcome or consequence of hazards, both anthropogenic as well as natural hazards. So, as this is the definition of hazard which is as per ISDR Secretariat.

So, hazard can include, even we can take into account, what is the latest condition, what is the existing condition or latent condition in a particular region, which also gives an indirect indication about what might be the future related to a particular hazard. It can be because of growing economic crisis, it can be because of conflict between two nearby economies, or it can be anything which is likely to occur in the near future, primarily because of the high seismic potential of a particular region. So, the policymakers have to be, always ready in terms of taking into consideration that there is a possibility that certain natural or anthropogenic activities are likely to hit my site of interest, hit my region of interest, and I should be better prepared for these kinds of situations, such that if we are going to be better prepared well in advance, at least we will be in a better situation to deal with the casualties in terms of economic losses, in terms of building damages, in order to supply essential commodities, medical teams, medicines, foods, and even in case of strategy-making, we can also locate important structures like medical camps and rehabilitation plants to relatively safer locations. So, keeping in account what is the existing condition in a particular region, that is also going to give you an indication about what are the potential possible future threats which are likely to hit your site of interest.

Maybe we can forecast for 20, 30, 40 years, depending upon how much information is known to us and how much finance is involved, which helps us in narrowing down to suitable decisions in order to forecast for the next 20 years, 30 years, or 40 years. So, it can also be used in terms of planning important infrastructure, planning important cities, taking all those induced as well as natural hazards into account. Now, each hazard, whenever we say, is characterized primarily, we can take hazard to mean either it is a natural hazard or manmade hazard. We can say what are the locations which are potential or prone to such hazards, what is the intensity, whether we can say it is a moderate hazard, low hazard. So, we are talking about different hazards and, corresponding to each hazard, suppose fire, where it is most likely to occur, that is going to give you the location. Again, when there is a fire breakout, what is the intensity of that particular breakout?

Thirdly, what is the frequency at which we are witnessing these kinds of hazards? An avalanche is there; that is, again, a natural hazard unless it is triggered by means of some human intervention. So, what is the frequency at which these kinds of natural phenomena are occurring? That certainly is going to give you an indication about what is the probability that we may experience, or a particular society or infrastructure will be exposed to, a set of natural or human-based hazards. When we go for hazard analysis, we are interested to find out potential sources where it is going to happen and its assessment, how big the hazard will be, how frequently the hazard is going to get repeated, and subsequently, we are able to narrow down to important sources of the particular hazard.

That means, if you are talking about an avalanche, what are the potential locations through which an avalanche is likely to occur? Maybe in the next 5 years, 6 years, like that. If you are talking about slope stability, what are the important slopes which are just on the brink of failure? So, we can go with in-situ monitoring, and that will give us some early warnings in terms of whether there is some slope stability issue which is going to happen in the near future. Similarly, related to tsunamis, also there are a lot of tsunami warning systems in different parts. So, similarly, with respect to earthquakes also, a lot of early warning systems are in place in specific countries, which primarily help humans to go to shelters and prevent themselves from falling debris or any other induced effects of earthquakes. There are high-speed trains that come to a complete halt rather than running, followed by ground vibration because of earthquakes. So, those trains will come to a complete halt primarily because of certain warnings which are generated during earthquake early warning systems to those utilities.

So, seismic hazard, when we talk about, we are interested to find out the expected level of ground shaking which is liable for damage to properties because there is a building, there is infrastructure. When we are talking about seismic hazard, we are basically interested to find out what is the potential ground shaking which is likely to occur at your site of interest, or which is likely to hit your infrastructure, or a building, or tunnel, or maybe a transmission tower. So, what is that particular expected level of ground shaking?

So, seismic hazard means any hazard which is happening because of seismic activity or primarily earthquakes, which are responsible for damage to property as well as casualties. Seismic hazard analysis, when we are talking about, as the name suggests, we are analyzing using seismic source information, using past earthquake information, using regional parameters, indicating how the source, propagation path, and site characteristics can be accounted for future earthquakes, taking into account the past experience of earthquakes in the region so that one can come up with a quantitative assessment of expected ground shaking at your site of interest.

So, I will be in a better situation once I do seismic hazard analysis. My site, located at such x and y coordinates, based on hazard analysis, now I know my building is exposed to a ground motion of maybe 0.12g, 0.2g, 0.25g, like that, where 0.2g is the value of peak ground acceleration, which my building is supposed to experience if the seismic hazard is experienced by the building. So, generally, these studies are again related to other hazards also. When we are going with seismic hazard analysis, these are very specific to a particular site because, as we know, with respect to seismic sources, if the location of the site keeps changing depending upon the distance, depending upon the orientation of the site with respect to fault orientation, the ground motion characteristics will change.

So, this is, again, we are talking about some scenario earthquake. So, we are interested to find out whether it can be a maximum ground shaking or whether it can be the most likely to occur ground shaking, which is going to hit my building, which is going to hit my infrastructure during its design life. Primarily, we will be interested to ensure the safety of the building during the design life for routine buildings. If we are going with important structures, even, we have to be surer about any kind of minimum level of damage should not be created in such buildings. So, there the finance will not be a deciding criterion; rather, the safety of the infrastructure will be the deciding criterion.

So, the knowledge of seismic hazard analysis for a particular region is beneficial. Why we require it? Because now, once we are going for the design of a particular infrastructure, we know what the expected level of ground is shaking in the near future, at least during the design life of the structure. So, if the design life of the structure is 30 years, based on seismic hazard analysis, I am telling you the next 20 years, 30 years, what is the maximum ground motion or what is the most likely to occur ground motion to hit my site of interest. If I am going to design my building for that infrastructure, that level of ground shaking, certainly when this ground shaking is going to hit my building, my building will remain safe. It will not undergo minor damages or complete collapse. As a result, we are actually minimizing the damages as well as fatalities. So, right now, we will be discussing hazard analysis. Later on, hazard analysis is going to give you what is the amplitude of ground shaking because of earthquakes likely to occur in a particular region. Taking this into account, and also taking into account the building classification, we can continue this study towards vulnerability as well as risk assessment.

So, later on, it can also lead to a reduction in the economic losses because we have forecasted accurately about the expected level of ground shaking, we have taken into account the building classification, we have also taken into account its intended use by its users. So, we can continue this related to vulnerability and risk assessment, which will be covered in later lectures of this particular course. So, seismic error analysis rationally estimates the possible seismic scenario at a site of interest, taken into consideration that this scenario is going to be witnessed during the future earthquakes, also taken into account. So, when we say about the scenario for future earthquakes, definitely significant inputs in terms of the magnitude of the earthquake, in terms of the potential location which can trigger an earthquake in the near future, also significantly depends upon where the earthquakes had happened in the past, how bigger were those earthquakes, and thirdly, how frequently those earthquakes were happening. So, if we refer to the lecture where we are talking about determining the minimum magnitude as well as the maximum potential earthquake on a particular source, that is certainly going to give you what is the maximum potential each source is capable of producing an earthquake. And, once we know the true potential, definitely we will expect like this particular source or fault will produce a particular magnitude earthquake even when the building is at a particular site of interest. Separately, we will be assigning that this is the potential, but what is the probability this maximum magnitude will occur or will not occur during the design life of the structure or during the period at least where the structure is in its in-situ position and trying to cover its design life. So, available seismic sources in the vicinity certainly will be taken into consideration unless, because, if seismic sources are there, certainly these are going to narrow down the potential locations for future earthquake occurrence.

So, seismic sources also we have to take into account, we have to take into account the location or the distance which have shown earthquakes in the past and the magnitude of the earthquake. The final outcome in seismic hazard analysis will be the seismic hazard map. So, just like your contour maps which give you points joining locations of equal elevation, in seismic hazard maps, we will be having contour maps joining the points having the same value of seismic hazard. Primarily, if you are going with deterministic hazard analysis, we will be having some points which are indications of the same level of peak ground acceleration or spectral acceleration. So, those are called as seismic hazard maps.

Now, depending upon where we have discussed actually in ground motion prediction equation, that whenever we are going with ground motion prediction equation, this ground motion prediction equation is going to give you the expected level of ground shaking due to a particular magnitude earthquake (M) happening at a certain hypocentral distance (R). And, depending upon whether the GMPE is going to give you the value of the ground motion parameter at the bedrock level or outcrop level or specific site level. That means you have to take into consideration what is the site class at the top of which your GMPE is going to give you the ground motion. So, accordingly, we can say if my ground motion prediction equation I have taken into hazard analysis gives me the value of ground motion at the bedrock level, certainly my hazard map is corresponding to bedrock condition. If my GMPE is going to give me a value corresponding to the outcrop level, then your seismic hazard map, which you are developing based on using this particular GMPE, will give you a hazard map corresponding to your outcrop level. Similarly, if you are talking about site class A, B, C, D, E, so you can refer to any HRV site class classification.

So, if your ground motion prediction equation is determining your ground motion parameter related to each any of the site classes, and you are using that particular ground motion equation in seismic hazard analysis, certainly your seismic hazard map will be corresponding to that particular site class. Many a time, people are confused with respect to which particular site class your seismic hazard map is valid for. So, the answer to that particular question lies in the condition for which the ground motion prediction equation has been developed. If your ground motion prediction equation is developed for site class A condition, definitely your hazard map will also be corresponding to site class A condition. If the GMPE is corresponding to the bedrock condition, your seismic hazard level will also be corresponding to the bedrock condition.

So, seismic hazard is considered as severity or repeatability, depending upon what methodology you are using. So, how big is the ground shaking? How high is the ground shaking? Repeatability, how frequently this ground shaking is expected to hit your site of interest. Generally, it is referred to the inertial forces because there will be ground shaking, there is mass involved, mass of the superstructure involved, which is actually undergoing some kind of shaking. So, inertial force will take into consideration, and it is corresponding to ground deformation. At times, if you are talking about induced effects, there are failures such as liquefaction, landslide, avalanche, tsunami, which are also the effects of when the system is responding to seismic waves.

So, this will also give you an indication about how big the shaking will be and how frequently the shaking is likely to occur at your site of interest. So, factors which can affect your seismic hazard at a particular site include the magnitude of the earthquake. Now, magnitude means in a particular region of 300- or 400-kilometer radial distance around your site of interest, what are the magnitudes of past earthquakes which have triggered, and taking those into consideration and referring to previous lectures, we can find out what is the maximum potential earthquake which a particular seismic source or a fault or an aerial source or a point source is capable of producing. Then, we are taking the seismic source into consideration, another parameter which will come into the assessment or understanding is how far is that particular source with respect to your site. So, if my site is located somewhere over here, and I have a number of seismic sources. So, corresponding to each of these sources, what is the distance? Now, depending upon the methodology you are using for hazard analysis, we will be taking sometimes minimum distance, sometimes all the distance into consideration while using them in a suitable ground motion prediction equation to determine the ground motion parameter.

The third part is the earthquake rate of occurrence, that means how frequently earthquakes are happening on that particular seismic source. So, we can refer to seismic activity parameters which have been discussed in earlier lectures. So, seismic activity parameters, in the end, you will get what is the amplitude of ground shaking, can also get what is the duration significantly for which ground motion, you can generate actually those ground motions using a synthetic ground motion model and correspondingly we can also find out the spectral acceleration at different periods. As I mentioned, depending upon the ground motion prediction equation here, we are using, we can comment on that seismic hazard values are corresponding to what site condition.

Now, representation of seismic hazard values is primarily done in terms of three parameters. So, in most of the cases, seismic hazard level is represented in terms of values like the amplitude or probability density, probability distribution in terms of how frequently a particular ground motion will exceed or will not exceed during the design life. So, depending upon the methodology you are using, you can go with the values, specific values, or you can go with what is the frequency of such values to get repeated during the design life, which is again user-defined. So, there we can go with probabilistic hazard analysis. Probabilistic hazard analysis will be covered in lecture 13.

So, in today's one, we will be discussing deterministic one, but in a nutshell, when we are going with hazard analysis, we can perform hazard analysis in terms of acceleration values. That means it is going to give us how a particular site is experiencing acceleration because of ground vibrations. Why? Because it is going to give us basically the inertial force for the infrastructure because the product of the mass which is undergoing disturbance with respect to the acting acceleration because of vibrations at a corresponding site condition, it is going to give us what is the magnitude of inertial force acting on your targeted infrastructure, acting on your targeted maybe underground certifications. Many a time, we have seen that peak ground accelerations generally occur in certain frequency pulses which is happening at not regular intervals during the design history of the time duration of ground vibration. As a result, the peak value will be only corresponding to a small fraction of energy. So, acceleration values which we are taking into consideration, it is not suitable as a single parameter related to ground motion representation.

So, in addition to the peak value, at times, we will also be taking into account the corner frequency, cut-off frequency, and maybe bracketed duration. These are the durations or the definitions that will give us a clearer idea about the duration properties of your ground motion. Similarly, we can go with the velocity values. Even when ground motion recordings are happening, generally, it is about how the displacement values are changing with respect to time at your recording station. Subsequently, based on recorded ground displacement values, we can estimate velocity values and acceleration values by means of differentiating the former values. So, peak ground velocities are also, at times, available in the ground motion record. If it is not available, then using the integration of acceleration time history or differentiation of displacement time histories, one can also get to know how much the peak ground velocity values are.

Now, at a particular site, if the peak ground velocity is available, the product of the square of peak ground velocity and the mass of the structure undergoing deformation or showing some kind of response is going to give you how much kinetic energy the mass undergoing disturbance has. Usually, it has been seen that ground motion of smaller amplitude generally results in a longer duration, or we can say that when we are talking about intermediate frequency natural structures or structures having natural frequency in the intermediate range, those are more susceptible to velocity-related ground motions. The third one is displacement. As I mentioned, most of the time, when we take up any particular recording station, it is going to give us the ground motion as to how the displacement is changing with respect to time at a particular recording station when the seismic waves are passing through. So, peak ground displacement, or PGD, and at times, you also get response spectral displacements. These are generally useful in terms of longer periods. So, particularly, those structures that have very long natural periods are more susceptible to displacement-based ground motions.

So, we can say that damage to high natural period structures, the structures having very high natural periods or very low natural frequencies, will lead to designs that are displacement-based. Ground velocity, ground acceleration, and ground displacement, as I mentioned, depend on the record. If there is a displacement time history, you can go with velocity and acceleration time histories. Based on differentiation, you will get from displacement to velocity, and again go for differentiation; then you will get from velocity to acceleration values. If you are having acceleration time history, then you go with integration. You will get velocity time history, and further integration will give you displacement time histories. That is how we can correlate. But as I mentioned, displacement time histories are more sensible or more affecting to longer-period structures. Velocities are targeted for intermediate structures or structures with intermediate natural frequencies, and acceleration time histories correspond to structures with very low natural periods.

The methodology for seismic hazard analysis generally has two approaches: one is deterministic seismic hazard analysis, or DSHA, and the other is probabilistic seismic hazard analysis. In DSHA, we calculate the expected level of ground shaking at your site of interest, considering specific seismic sources and taking into account that these seismic sources will be dominated by one particular earthquake—more precisely, the maximum magnitude of the earthquake that the site is capable of producing. When taking the highest magnitude that the site is capable of producing, in order to maximize that effect, we assume that this particular earthquake will occur at the minimum distance from the site. So, if this is your site and this is your seismic source, then we will try to find out the maximum potential earthquake because that is the maximum earthquake this site is capable of producing. How we do this has already been discussed in earlier lectures on maximum potential earthquake magnitude.

This will give us the maximum magnitude likely to occur at a particular site of interest. When the source is capable of producing or is producing the maximum potential earthquake, the effect on a particular site will be maximum when we consider that this earthquake, or maximum potential magnitude, is happening at the minimum distance from the source. This indicates that when the distance is minimum and the magnitude is maximum, based on our understanding of the ground motion prediction equation, the ground motion parameter at a particular site will also be maximum. So, in deterministic hazard analysis, we try to find out the maximum scenario. I have explained this corresponding to one source. Similarly, there will be several sources with different orientations within your seismotectonic province. Deterministic hazard analysis attempts to understand the overall maximum seismic scenario that a site is capable of witnessing during its design life.

Similarly, when we are talking about maximum ground amplitude, it means we are not at all interested in the site undergoing any kind of failure—whether it is minor cracks or complete collapse. We are not ready for any chance of failure. Probabilistic hazard analysis, on the other hand, incorporates a different perspective. In deterministic analysis, we do not consider whether the maximum potential earthquake will occur during the design life because larger magnitude earthquakes happen less frequently than low-magnitude earthquakes. Taking the maximum potential earthquake means it might be a moderate earthquake, a great earthquake, or a major earthquake, but as the magnitude increases, it happens less frequently. It may or may not happen during the design life of a structure, which is typically 35–40 years. However, because safety is the prime concern, we go with deterministic hazard analysis to find the actual maximum ground motion that a site can experience, irrespective of whether this ground motion will be experienced during the design life or not.

In a practical scenario, there can be several scenarios. A site may produce minimum magnitudes of 4, 5, or 6 earthquakes, or perhaps 5.5 or 7.2. Based on past experience or earthquake information, the site has indicated its capability to produce these magnitudes from time to time. When different magnitudes are possible, there are chances that, in the near future, or at least during the design life of the structure, the site will not only experience maximum magnitude earthquakes but also earthquakes of 5 or 6 magnitude. Although the site may be capable of producing a 7.8 or 8.2 magnitude earthquake, these are not the only earthquakes that may occur. In probabilistic hazard analysis, we try to cover the different magnitudes likely to occur and the associated uncertainty. A detailed discussion of probabilistic hazard analysis will be covered in lecture 13. PSHA, or probabilistic hazard analysis, was developed by Cornell in 1968. DSHA was the earliest approach considered for seismic hazard analysis. It is primarily used for nuclear power plants because, as a designer, we prioritize safety. In such cases, the nuclear containment facility or reactor building should not reach a state where radiation leaks, even if minor cracks occur. Therefore, the design considers the maximum potential earthquake or maximum ground motion amplitude the site is capable of experiencing, based on past history. This ensures that the worst-case scenario at the site of interest is addressed, fulfilling the purpose.

So, some of the significant structures for which deterministic hazard analysis is primarily used include nuclear power plants because radiation leak is there; larger dams, again, these are important structures, so any kind of failure, whether it is a earthen dam or whether it is a concrete dam, if there is a crack developed across the cross section, then certainly we know that will subsequently lead to failure. Similarly, with respect to bridges, also, these are important structures, and a lot of finances are also involved. So, when we are talking about larger bridges, in order to ensure that the safety of the structure should remain intact, again we can take into consideration what is the worst scenario to which my structure is exposed at a particular site. Similarly, with respect to hazardous waste containment facilities, also, we do not want this waste to undergo any kind of failure. So, any kind of containment facility should also be able to withstand the potential ground shaking, which my site is prone to experience, maybe in the next 50 years, 100 years. Generally, waste containment facilities are designed to last much, much longer than nuclear power plants, dams, and bridges, as can be seen in some of the nuclear waste containment facilities or hazardous waste containment facilities in recent times.

So, typically, one or more earthquakes with respect to the site can be identified, which have happened along different sources. Now, usually, the earthquakes are occurring at each source in deterministic hazard analysis at a section of the fault which is closest to your site of interest. As mentioned earlier, also, if there is a fault running maybe 600 kilometers in length with respect to the site, certainly during the design life it will not happen that the location which is closest to your site will undergo rupture. This particular section may undergo rupture; this particular section may undergo, or any particular section may undergo rupture in order to produce maybe a 5, 5.5 magnitude earthquake, and so on. So, actual rupture is happening over here, but the worst scenario I am considering is that rupture will be happening at a location within a fault, which is an indication of the closest distance, and this is done in deterministic hazard analysis.

So, the ground motion corresponding to maximum potential magnitude and happening at the closest distance from the site is going to give me the worst scenario earthquake, which is called as deterministically determined seismic hazard values. So, three basic elements related to hazard analysis in deterministic: one is what is the location of seismic sources in and around your site of interest; then, what is the controlling magnitude of the earthquake, or we can say, like, what is the maximum potential earthquake which each of these earthquake sources can be. If a fault is not identified, we can take into consideration past earthquake information and try developing maybe aerial sources, which have been discussed in earlier lectures.

And then, by adopting suitable ground motion prediction equations, taking the earthquake magnitude and the epicentral distance, or hypo-central distance, or any other definition of distance which my ground motion prediction equation uses, we can develop the ground motion parameter. So, the steps involving ground motion in deterministic hazard analysis: firstly, one has to develop a seismotectonic map where all the active faults, at least the faults for which past earthquake information is known to us, we can take into consideration. If we have a map corresponding to showing all the active faults in a region, whether those have shown an indication of earthquake occurrence in the last 200-300 years, if it is not, we can maybe assign minimum seismicity of maybe 4-4.5 to those faults and then take them into consideration in hazard analysis, or we can follow whatever guidelines which are proposed by different agencies while performing the hazard analysis.

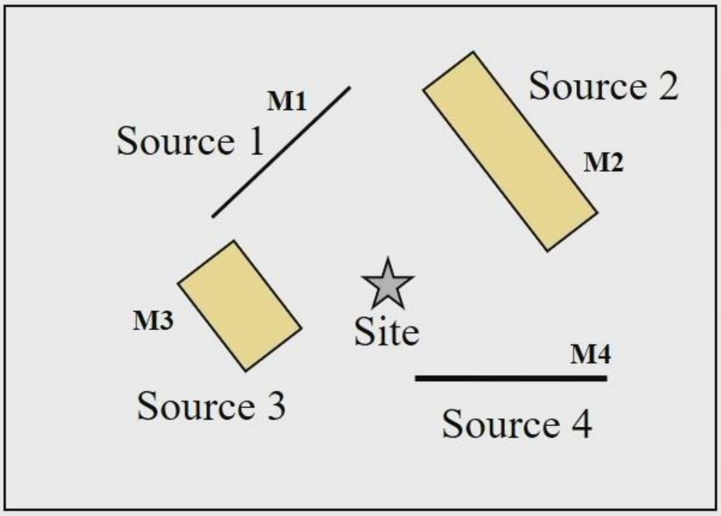


Fig. 1: Step 1 of DSHA

So, overall, if this is my site of interest for which I am interested to do seismic hazard analysis, I have basically found out all the seismic sources within your seismotectonic region, or seismic sources which are located maybe within a 500-kilometer radial distance with respect to the site as the center. Then, I found out that though in some locations well-identified seismic sources or faults are known, there are some locations in which, though past earthquake information is there, information about sources or faults to be present in that particular region is not there. So, we can go ahead with the seismic source characterization and then again find out these are the aerial sources, which can be further taken into consideration while performing maybe deterministic hazard analysis or even in probabilistic hazard analysis. So, in this particular photo, we are having actually 4 seismic sources. Then define the geometry of those sources: what is the length of those sources. So, depending upon the dimension, we can even find out what is the maximum potential earthquake each of these sources can produce using empirical correlations existing, which will help us in identifying the maximum potential earthquake on each seismic source.

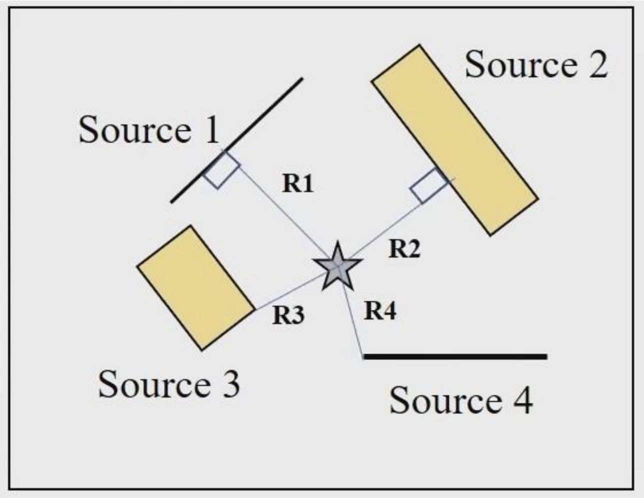


Fig. 2: Step 2 of DSHA

Then, going to step 2, we will find out what is the minimum distance. So, again, we can see whenever this is an aerial source, depending upon the orientation of the aerial source, we can find out the location which is corresponding to the minimum distance from the site. Now, in this particular source 2, the minimum distance is somewhere in between along this particular boundary where the perpendicular from the site can be drawn. However, another seismic source 3 is there, where we can see the minimum distance is corresponding to one edge of the seismic source. Similarly, with respect to the linear source, depending upon the orientation of the linear source with respect to the site, you can see for seismic source 1, the minimum distance will not be from any of the ends but somewhere in between the ends where the perpendicular from the site is falling. So, that should be considered as the minimum distance between the source and the site in deterministic hazard analysis. Now, again, you take seismic source 4. So, here, the perpendicular distance might be falling like this, but certainly, we will not take this part as the minimum distance because the source itself is starting from here. So, we have to find out the minimum distance from the source, not wherever the perpendicular distance is falling. So, we have to take, if in this particular case for seismic source 4, the perpendicular distance or the point where the perpendicular from the site is falling is located outside the fault, that is not the part of the fault where it is not the part of the fault. Certainly, this is not the region in which rupture will happen. When this is not the region for rupture to happen, why will we take that into hazard analysis estimation? We will take the minimum distance, which is maybe from this particular end of the seismic source. This will be the minimum distance which will go into your ground motion prediction equation, and based on the true potential or the rupture dimensions or the dimensions of the fault, we have already determined what is the minimum hypo-central distance, the maximum potential for a particular seismic source.

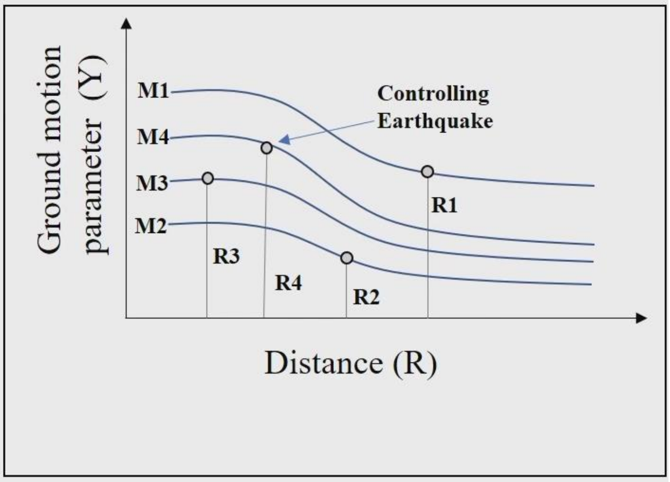


Fig. 3: Step 3 of DSHA

So, once we get all these minimum distances and maximum parameters, we can go to step 3, corresponding to each of the sources, corresponding to different values of seismic epicentral distance or hypo-central distance, and taking the maximum potential earthquake or if we know the minimum distance from each source, taking the minimum distance and maximum magnitude, we will try finding out which is the source that is giving you overall the maximum ground motion parameter. So, here we can see the magnitude of M1: the magnitude might be larger, but the source it is corresponding to larger distance. So, magnitude is higher, but distance is also higher; as a result, the ground motion parameter corresponding to a combination of M1 and R1 is lesser. However, the combination of M4 happening at R4 distance from seismic source 4 is giving you overall the maximum or the highest amplitude at your site of interest. Once this particular part is ready, we can repeat the same procedure. So, firstly, it is going to give me this is the controlling earthquake scenario based on deterministic seismic hazard analysis. Then, define the hazard: we can pick up all those, whatever has been, whatever just now I mentioned over here. We will take all the possible scenarios for all seismic sources and pick up what is the overall maximum in step number 4.

$$Y = \begin{matrix} Y_1 \\ Y_2 \\ Y_3 \\ . \\ . \\ Y_N \end{matrix}$$

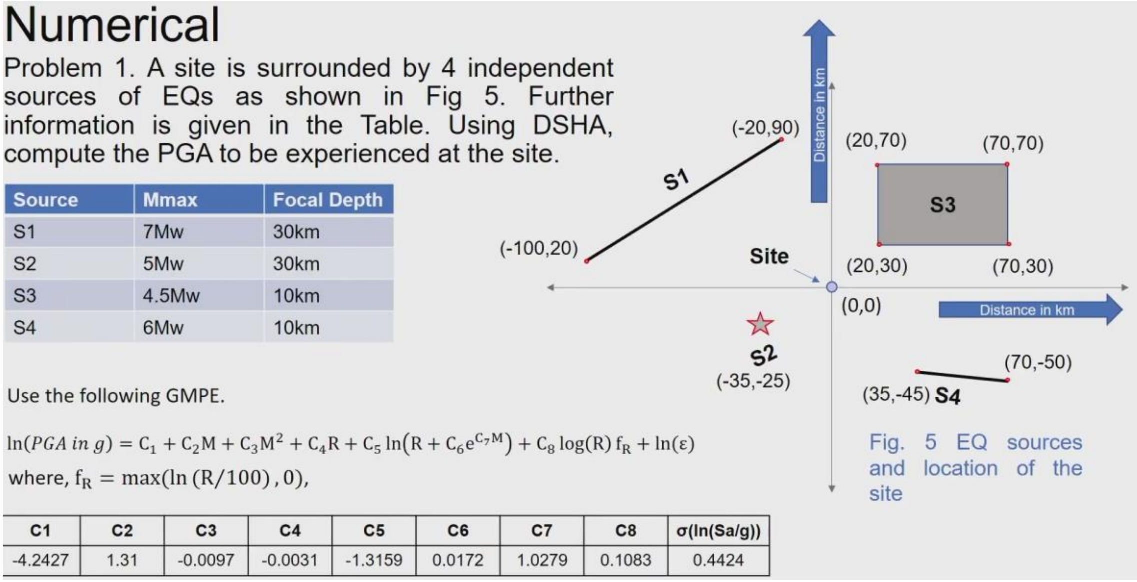
Fig. 4: Step 4 of DSHA

So, if you are going with the GMPE, which is acceleration-based, we may get peak ground acceleration or spectral acceleration. If we are going with velocity-based GMPE or displacement-based GMPEs, your hazard analysis will be giving you peak ground velocity, peak ground displacement, or spectral velocity or spectral displacement values at your site of interest, determined based on your deterministic seismic hazard analysis. Further details on ground motion prediction equation and synthetic ground motion can also be referred to in my lecture.

Now, based on deterministic hazard analysis, we have understood that M4, happening at R4, is an indication of the controlling earthquake. So, if we continue with this particular finding and if I am interested in finding out the liquefaction potential of the site, what I will do, again corresponding to the liquefaction potential, one can refer to my lecture of this particular course. What we will do in order to find out the A_{max} value, which will be required to find out the cyclic stress ratio in liquefaction related lecture, is I will be using some synthetic ground motion model. Taking synthetic ground motion and reasonable parameters, I will be generating ground motion corresponding to magnitude M4 at distance R4 from the site. Based on this particular combination, I will be generating some synthetic ground motion, then picking up the motion corresponding to maximum amplitude as peak ground acceleration, which is referred to as the A_{max} value in the simplified approach for liquefaction assessment.

Now, regarding the earthquake potential, that means we are interested in finding out the maximum potential of the seismic source. So, there is a need to refer to combined decisions with respect to what should be the true potential of a particular seismic source in terms of maximum magnitude. There are a number of experts required, maybe seismologists, geologists, engineers, risk analysts, economists, and many more people; even government officials will have a significant role in terms of giving inputs. One can also refer to zonation maps of the country to narrow down what the potential magnitude of an earthquake in a particular region or on a particular seismic source is. So, different terms are generally used. Some terms are like "maximum credible earthquake," which is an indication of what is the maximum earthquake that appears to occur under a known tectonic framework, considering known tectonic frameworks, what is the maximum earthquake that can appear in a particular region or a particular site.

Similarly, the "design basis earthquake" is the earthquake corresponding to which you will be designing your infrastructure. Next one is the "safe shutdown earthquake." If we are talking about nuclear reactor buildings, then corresponding to what ground motion, what seismic scenario, I should design my infrastructure such that it gives an indication that the ground motion reaches a certain level at which I have to shut down my facility. So, in order to decide that, again the corresponding scenario will be called the "safe shutdown earthquake." Next is the "maximum probable earthquake," which is the maximum historical earthquake, also called the "maximum earthquake," which your site is likely to experience in the next 100 years. So, everything, all the equations are like with respect to the present definition. Similarly, the "operation basis earthquake" is the earthquake expected to occur during the design life of the structure. So, one is the "maximum potential earthquake," one is the "design basis earthquake," and the other one is the "operation basis earthquake," and some of them can be distinguished in terms of what is the probability of occurrence of these earthquakes in terms of quantifying hazard analysis.



Numerical

Problem 1. A site is surrounded by 4 independent sources of EQs as shown in Fig 5. Further information is given in the Table. Using DSHA, compute the PGA to be experienced at the site.

Source	Mmax	Focal Depth
S1	7Mw	30km
S2	5Mw	30km
S3	4.5Mw	10km
S4	6Mw	10km

Use the following GMPE.

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

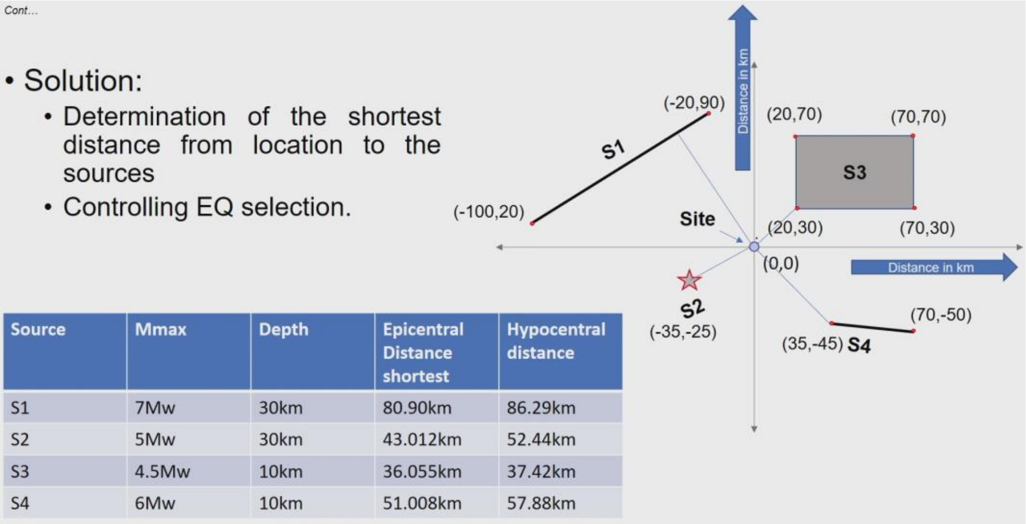
where, $\mathrm{f_R} = \max(\ln(\mathrm{R}/100), 0)$,

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

Fig. 5 EQ sources and location of the site

So, one numerical problem, just to discuss with whatever we have been discussing so far. A site is given; the coordinates of the site are also given over here. With respect to this particular site, 4 seismic sources are given. Seismic source 1 is a linear source, seismic source 4 is also a linear source, then seismic 3 is there, which is an aerial source, and seismic 4 is there, which is basically a point source. The coordinates are also given over here (latitude, longitude), and then the maximum potential earthquake each of these 4 seismic sources is capable of producing is also given in this particular Mmax value. So, seismic source 1 is capable of producing magnitude 7 on the Mw scale (or moment magnitude scale), and so on with the others, or we can say the maximum potential is given in terms of moment magnitude. The focal depth corresponding to each source is also given over here, because many times your ground motion prediction equation you are going to use takes into consideration not the epicentral distance, where the site coordinate as well as the source coordinate can be used alone. We have to have an understanding about the focal depth. So, in order to find out the hypocentral distance, we will be taking into consideration the focal depth as well as the epicentral distance between the source and your site corresponding to the minimum distance.

Again, it is suggested that one has to use the following ground motion prediction equation, where M refers to the magnitude, and R refers to your hypocentral distance. $\mathrm{f_R}$, which is given over here, is for a known value of R (hypocentral distance). The natural log of R by 100 or 0 (whichever is the maximum value between these two) will be considered as the value of $\mathrm{f_R}$. So, $\mathrm{f_R}$ will go over here, and C1 to C8 are the regression coefficients. One can refer to the ground motion prediction equation and find out the value of these coefficients corresponding to different periods, and epsilon is the standard error term in terms of the predicted ground motion parameter. These are the details given.



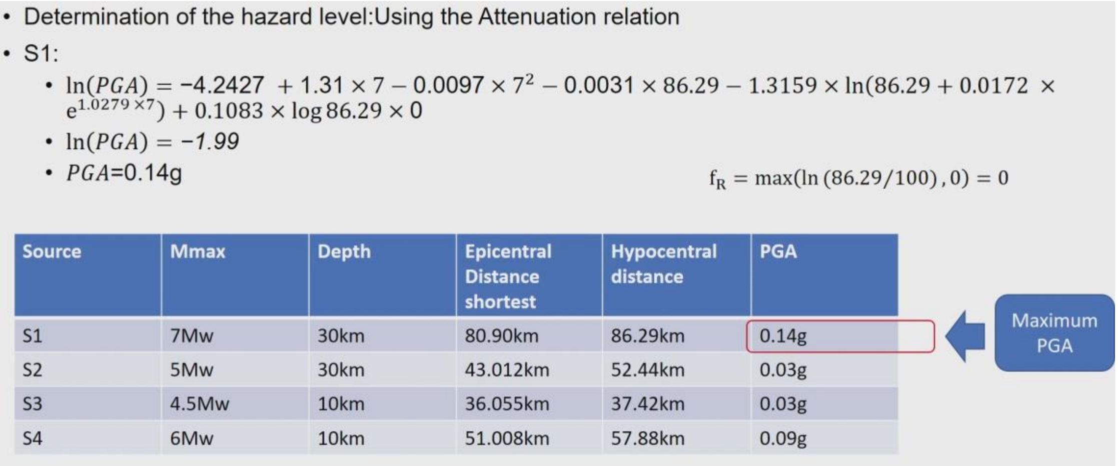
Cont...

- Solution:
  - Determination of the shortest distance from location to the sources
  - Controlling EQ selection.

Source	Mmax	Depth	Epicentral Distance shortest	Hypocentral distance
S1	7Mw	30km	80.90km	86.29km
S2	5Mw	30km	43.012km	52.44km
S3	4.5Mw	10km	36.055km	37.42km
S4	6Mw	10km	51.008km	57.88km

What we will do in deterministic hazard analysis, corresponding to each of the sites, we will try finding out the minimum distance. You can see here the minimum distance for the area source; this will be the minimum distance. For the linear source, depending upon the orientation of the source for S4, this is the minimum distance. For S2, we draw a perpendicular, and then we will be able to find out the minimum distance with respect to S1 from the site. S2 is just a point source, so you will have one value of epicentral distance. So, taking those coordinates, we can find out the epicentral distance or minimum distance in kilometers. Taking the focal depth into account, which is given in the question itself, one can find out how much the hypocentral distance is.

Now, the magnitude is known, the value of R is known, we can put these equations, these values of M and R, and the value of regression coefficients from C1 to C8. What we can do is find out the value of peak ground acceleration, because the ground motion equation which we have taken is to find out the value of peak ground acceleration. So, corresponding to each of these values of M and corresponding to each value of hypocentral distance, we will be getting PGA value of 1, 2, 3, and 4. So, four sets of PGA values we will get. Now, what we will do is compare all these four values and pick up the overall maximum value of PGA that will be considered as the deterministic seismic hazard base peak ground acceleration for your site of interest.



- Determination of the hazard level:Using the Attenuation relation
- S1:
  - $\ln(PGA) = -4.2427 + 1.31 \times 7 - 0.0097 \times 7^2 - 0.0031 \times 86.29 - 1.3159 \times \ln(86.29 + 0.0172 \times e^{1.0279 \times 7}) + 0.1083 \times \log 86.29 \times 0$
  - $\ln(PGA) = -1.99$
  - PGA=0.14g

$f_R = \max(\ln(86.29/100), 0) = 0$

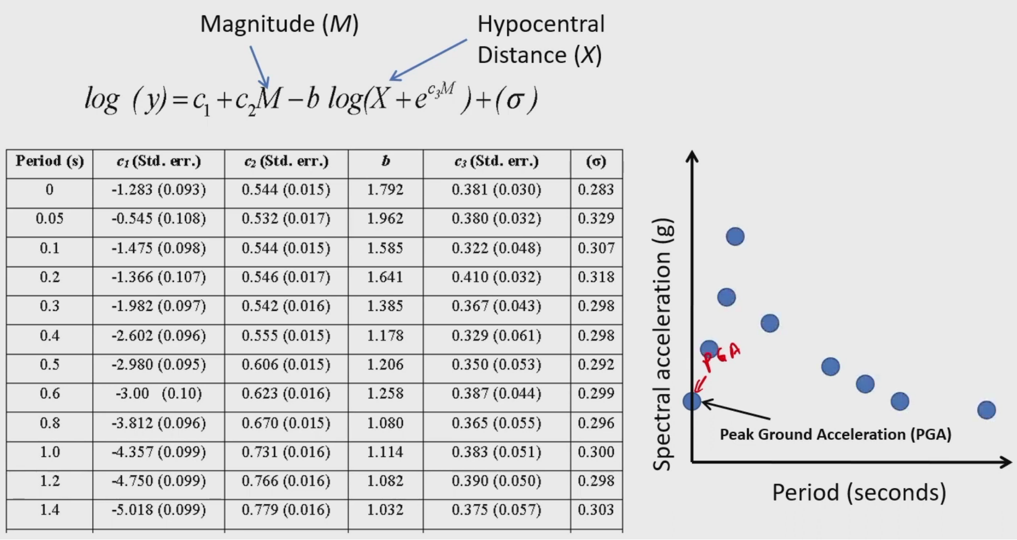
Source	Mmax	Depth	Epicentral Distance shortest	Hypocentral distance	PGA
S1	7Mw	30km	80.90km	86.29km	0.14g
S2	5Mw	30km	43.012km	52.44km	0.03g
S3	4.5Mw	10km	36.055km	37.42km	0.03g
S4	6Mw	10km	51.008km	57.88km	0.09g

This is the value of PGA, and among all those, what we got is that the 7-magnitude earthquake happening at source 1, occurring at a minimum hypocentral distance of 86.29, with respect to source 1 (not where we will not be finding out the minimum distance among all the sources), so now we will be finding out only the minimum distance at source 1. Similarly, for other sources, individually, when source 1 is capable of producing magnitude 7 happening at a hypocentral distance of 86.29 kilometers, my site is experiencing a peak ground acceleration of 0.14g. Similarly, we can repeat the same, changing the location of the site. Again, these are the seismic sources, four seismic sources. Perform hazard analysis for another grid point and repeat the same thing.

If you are trying to attempt the deterministic seismic hazard map for a particular study area, divide the entire area into a number of grids, and then perform the steps shown over here. After finding out the maximum potential earthquake and minimum hypocentral distance, you will be able to find out the deterministic seismic hazard value at each of the grid points. When those values are there, you can join the points corresponding to equal peak ground acceleration values or equal spectral acceleration values, which will give you the value of the deterministic seismic hazard map for a particular study area.

Now, in addition to hazard maps, many times you will be asked to find out what is the developed design response spectra. So, based on the two values, magnitude and hypocentral distance, we found out what is the maximum value of peak ground acceleration. We know that this particular value, that means the coefficient values which are given over here, these will be corresponding to some value of period.

So, you say this one is corresponding to 0 period. Similarly, there will be subsequently more values corresponding to maybe 0.1 second, 0.2 second, as given in the corresponding GMPE report or journal paper. So, every time you are taking the coefficient, you are trying to find out the value of spectral acceleration corresponding to this particular period. So, if you are taking the value of the coefficient mentioned over here and performing hazard analysis, you will be getting the spectral acceleration corresponding to 0 second. Similarly, values you are taking values corresponding to 0.1 second will give you spectral acceleration corresponding to 0.1 second, and then that is how you keep on repeating the procedure. Taking the value of coefficients at different periods, what you will be getting.



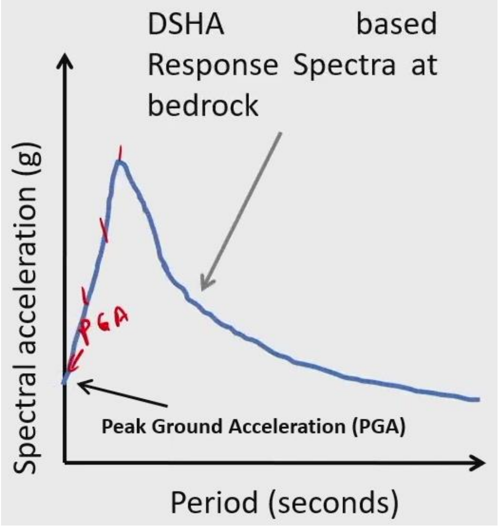
Magnitude (*M*)

Hypocentral Distance (*X*)

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

Period (s)	*c₁* (Std. err.)	*c₂* (Std. err.)	*b*	*c₃* (Std. err.)	(σ)
0	-1.283 (0.093)	0.544 (0.015)	1.792	0.381 (0.030)	0.283
0.05	-0.545 (0.108)	0.532 (0.017)	1.962	0.380 (0.032)	0.329
0.1	-1.475 (0.098)	0.544 (0.015)	1.585	0.322 (0.048)	0.307
0.2	-1.366 (0.107)	0.546 (0.017)	1.641	0.410 (0.032)	0.318
0.3	-1.982 (0.097)	0.542 (0.016)	1.385	0.367 (0.043)	0.298
0.4	-2.602 (0.096)	0.555 (0.015)	1.178	0.329 (0.061)	0.298
0.5	-2.980 (0.095)	0.606 (0.015)	1.206	0.350 (0.053)	0.292
0.6	-3.00 (0.10)	0.623 (0.016)	1.258	0.387 (0.044)	0.299
0.8	-3.812 (0.096)	0.670 (0.015)	1.080	0.365 (0.055)	0.296
1.0	-4.357 (0.099)	0.731 (0.016)	1.114	0.383 (0.051)	0.300
1.2	-4.750 (0.099)	0.766 (0.016)	1.082	0.390 (0.050)	0.298
1.4	-5.018 (0.099)	0.779 (0.016)	1.032	0.375 (0.057)	0.303

So, this is again an example of what you will be getting. Corresponding to 0 period, if you are taking the value of magnitude and distance, you will be getting on the spectral acceleration versus period plot, one value. This is corresponding to 0 period or called as peak ground acceleration. Repeat the entire procedure, which has just been discussed, corresponding to different periods. You keep on updating the value of regression coefficients and perform the analysis. What will you get? You will get many more points, and corresponding to every time, like this is corresponding to 0.05, 0.1, and like that. So, you will get many points.



Join all those points, and you will get the hazard analysis-based response spectra. Again, if I am using GMPE corresponding to bedrock condition, this is going to give me DSHA-based response spectra for the bedrock condition. So, repeating the same procedure, which is mentioned over here, one can perform hazard analysis, and one can develop the response spectra for bedrock condition or outcrop condition of a different site class condition.

The advantage in DSHA is that it is very straightforward, quite simple, and you can even review if someone has performed it. You can review your own calculation very easily and find out if the steps are clear. But, as I mentioned, deterministic hazard analysis does not account for whether the scenario, which is coming as the outcome of deterministic hazard analysis, is going to get repeated during the design life. So, there is no concept of frequency or the frequency that ground shaking is occurring exactly. Whether the ground shaking in the future will happen only at minimum distance, it is not going to tell either. It is not also going to tell whether the proposed seismic scenario is going to get exceeded or will remain exposed during the design life of the structure. Thus, it completely ignores that always, when there is magnitude involved, the magnitude happens at a certain frequency at a particular site or a particular region or a particular source. So, that is completely ignored.

Similarly, it also ignores where the earthquake is going to come. It also ignores whether this seismic scenario is going to get repeated during the design life or not. As mentioned, the objective of deterministic hazard analysis is to find out what is the maximum overall scenario, for which, if I design my building, it will remain safe without being worried whether the scenario will actually hit my site of interest or not. And there are a lot of subjective decisions that are required, because the value of hazard which you generally get from deterministic seismic hazard analysis will be significantly higher. So, many a time this is also a matter of discussion that the value is significantly higher with respect to codal provisions or with respect to probabilistic hazard values. So, there, the subjective decision will come into the picture.

So, thank you, everyone. With this, we have come to the end of lecture 12. In lecture 13, we will be discussing probabilistic hazard analysis. Thank you.