Applied Seismology for Engineers

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Week – 05 Lecture - 01

Lecture – 09

Music. Hello everyone, welcome to lecture 9 of the course Applied Seismology for Engineers, myself, Dr. Abhishek Kumar. In today's lecture, we will be discussing an important topic: that is seismic source characterization. If you remember, the basic objective of this particular course is to find out the forces which are going to be mobilized, whether at bedrock level, at the surface, or even the forces which will be applicable on different infrastructure. So, that accordingly, one can have some assessment about the amplitude of the forces, utilize these forces in terms of design as far as any kind of improvement which is likely to happen at a particular site or a building or for retrofitting. So, whenever we go for any seismic hazard quantification or to find out how much expected level of ground shaking is there from a particular source, primarily a fault if identified at a particular source, we can utilize the same information and try finding out how much is expected level of peak ground acceleration or spectral acceleration.

Subsequently, we can also determine what is the design response spectra at your site of interest. If you recall, whatever has been discussed in previous classes, so there is, because of movement of different plates, primarily if we are talking about plate boundaries, there will be plates which are moving towards each other, which are called as convergent plate boundaries; there will be development of stresses along the plate boundaries when the two plates are moving towards each other, and this development of stresses will be happening on a plane which is common or where the two plate boundaries are coming in contact with each other. As a result of this particular movement, there will be development of stresses. Now, considering the length of plate boundaries, it will not be possible that the development of stresses will lead to earthquake all along the plate boundaries, because the medium which is available for the failure as well as release of seismic waves, the medium is also having some limitation in terms of strength, so it cannot keep on storing strain energy up to infinite time. Considering the strength of the material and the rate at which strain energy is getting stored at the interference or at the common area, that is, the fault plane, you can have an expectation about when there will be an earthquake, how big will be the earthquake, and again depending upon the properties of the soil which are available in your epicentral region, seismotectonic region, one can also quantify how much is the expected level of ground shaking possible at the foundation level and even at subsequent superstructures.

So, whenever we are going for hazard assessment, as we discussed, that primarily the sources or the faults, we consider the sources on which the earthquakes are happening; however, if we understand, if there are plenty of faults which are available in a particular region, when we say about the region, firstly we will be referring to the region which is having certain radial distance around your site of interest. So, if you are having one particular location which is your site of interest for a particular important structure, you will try to understand the seismic activity which can happen to any particular source, any particular fault which are happening maybe 100 kilometers, 200 kilometers, 300 kilometers away from your site of interest. Why? Because it has been evidenced in previous earthquakes that even if a fault is happening, if a rupture is happening at 200, 300 kilometers distance from your source, that can also cause significant ground shaking at your site of interest. Further, if the seismic activity of the region is significantly high, such that it can produce major to great earthquakes, so the influence of those earthquakes will be more dominating even in 500, 600 kilometers radial distance. Collectively, if your site on which you are going to construct a building, or you are going to lay a parking space, or any kind of other infrastructure, and you are interested to find out how much is the expected level of ground shaking at a particular site, you will take into account what are the possible sources which are in and around that particular site. If it is belonging to a low seismicity region, you can restrict yourself to maybe 200, 250 kilometers radial distance. If any adjoining region is there which is also having capability of producing major to great earthquakes, certainly those earthquakes will even cause damage or significant ground shaking to 500, 600 kilometers radial distance. So, if such sources are available within 500, 600 kilometers radial distance from your site of interest, certainly those sources also you will take into account, and the possibility of those sources to produce earthquakes primarily within the design period of the structure will also be taken into account while assessing the potential of ground shaking at a particular site of interest. So, when we discuss about seismic source characterization, the objective here is to identify not only the faults, primarily because not at all places there will be information of the fault completely available to you. Even when we will see some maps which are put in later slides, that there are some faults which have happened in the past in a particular region, but if we try to correlate this particular fault earthquake with respect to the fault, we will not find any particular linear source or any particular fault. That means it's not like there is no fault; rather, there is a fault, but the information about the fault, the orientation, length, fault plane solution, strike, dip values, those are not known from that particular fault. So, we cannot completely avoid the possibility that there is a fault and go ahead with seismic hazard estimation, because certainly that will end up in underestimation of your seismic hazard, and subsequently, that can also compromise the safety of your structure, because the design loads which you will be assessing will be significantly low. So, what we generally prefer, we try finding out zones within, again, your 200, 300, 500 kilometers radial distance, keeping the center as your site of interest, and all the sources or seismic activities which are happening within, let's say, 500 kilometers radial distance. So, you will try finding out firstly what are the activities which have happened in the past, take additional features such as tectonic setting, rate of movement, percentage rupture, dominating fault mechanism, which are also varying across this particular 500-kilometer radial distance. All these parameters are suggesting that within a particular radius of 500 kilometers, there are regions which are responding differently during different earthquakes or the seismic activity is different in different parts of this 500 kilometers radial distance. Collectively, if you see, that means we are trying to identify or we are trying to distinguish between different segments which are available within this 500 kilometer radial distance around your site, in order to find out what will be the relative contribution from each of these sources within the design life of the structure in terms of earthquake-related ground shaking. So, the term seismic source characterization, primarily we will be discussing about how a particular source, so far, we have discussed about faults, but as I mentioned, not every time complete information about the fault will be available to you.

Sometimes there will be hidden faults, sometimes more complex tectonic settings will be there, such that you cannot segregate a particular linear feature to be called as fault. But completely, we cannot deny the fact that this particular source has been producing earthquakes repeatedly from time to time. It may be minor earthquakes, it can be major earthquakes, it can be great earthquakes. So again, those sources also there should be a way we can characterize those sources and bring those source-related information such that when we are going for quantification of seismic hazard analysis, there should be a way we can quantify those seismic sources, bring them to your hazard analysis. So, the contribution of whether it is a linear source, whether it is a hidden source in some form, the contribution of those sources should be brought to your seismic hazard calculation. So, whenever we say about characterization, we are actually trying to understand what are the characteristics of such seismic sources. As I mentioned, maybe it can be different from the sources which are there in nearby regions in terms of dominating fault mechanism, it can be in terms of percentage rupture characteristics. When I refer to percentage rupture characteristics, that means whenever there is an earthquake happening on a particular source, with respect to the total area, what percentage of area is undergoing rupture in order to cause a particular earthquake? So, this characteristic, which is the rupture characteristics of the fault, can also be an identifying parameter whenever we are going for seismic source characterization. So, we will be interested to find out the reasons we can identify or distinguish seismic sources, keeping into account what are the characteristics which can differentiate one seismic source from another seismic source in terms of relative contribution of one seismic source and other seismic sources to the seismic hazard of a particular site of interest. So, that is very important because we will be interested to identify the sources. Certainly, the contribution of all sources will be different, so we have to find out some rational manner in which identified seismic sources can be differentiated with respect to each other, and in a more rational form, their contribution in terms of seismic hazard analysis can be taken into account. Even at a later stage, once you know the seismic sources and their contribution in seismic hazard, there are ways you can find out what are the sources which are contributing most. If, let's say, the design life of the structure is 35 years, 50 years, so what are the sources which are contributing most to the seismic hazard of a particular site of interest? That will help in understanding what are the sources which require continuous monitoring in terms of activities happening over there. At times, that can also be used to generate alarms or when more frequent recordings are required on those sources. So, most frequently seismic hazard-contributing sources can also be identified if we are going with seismic source characterization. The second part of the lecture which we will be covering today, this particular term seismic activity will also continue in lecture number 10. So, seismic activity means whenever, in a particular region, earthquakes are happening, how frequently the region is capable of producing those earthquakes. If an earthquake of magnitude 6 is happening today, what is the frequency of this earthquake to get repeated, maybe in another 50 years, 100 years, like that we can find out based on the seismic activity. Certainly, seismic activity is going to give you, again, how frequently the earthquakes are happening at the site, and subsequently, when earthquakes are happening in particular source zones, these will have an effect on your seismic hazard estimation. So, there can be n number of sources within your study area. Suppose this is your site of interest. So, within your study area, there can be a number of sources: linear sources, faults. Now, depending upon the seismic source of seismic activity of source 1, seismic activity of source 2, 3, 4, 5, consider that each of these sources is capable of producing a 5-magnitude earthquake. But the contribution of each of these sources to the seismic hazard at your site of interest will not be the same, primarily because, though each of these sources is capable of producing a 5 magnitude earthquake, considering the design life of the structure, maybe 30 years, the probability that within the next 30 years each of these sources will produce a 5 magnitude, greater than 5 magnitude earthquake, that will change accordingly because of variation in the probability of occurrence of a 5 magnitude earthquake on each of these 5 seismic sources. This will also decide whether the contribution from this particular source, source 1, to seismic hazard at your site of interest will be there or not, seismic source 2, whether the contribution from this particular source will be there to produce a 5-magnitude earthquake, and subsequent ground shaking during 30 years. How we will try to find out that using seismic activity, because seismic activity is going to tell us, depending upon the dimensions of the seismic source and depending upon past earthquake information in terms of how frequently different magnitude earthquakes have happened on this particular source, maybe last 50 years, 100 years, 200 years, how much data is available to us related to that particular site. You can use that particular data and try assessing the seismic activity. So, seismic activity will tell how frequently different magnitude sizes, different sizes of earthquakes are likely to occur or get repeated during a specific time period. Usually, we refer that particular time period to the design life of the structure. Again, the design life of the structure, so if you are talking about routine buildings, it will be different. If you are talking about tunnels, bridges, it will be different. If you are talking about dams, it will be different. If you are looking after nuclear power plants, it will be different. So, certainly, this choice of the structure is basically putting a challenge, like how much is the duration for which your structure is exposed whether it is 50 years, 100 years, for which your structure will be there in the field and will be exposed to any kind of seismic activity which can happen to any of these seismic sources, and subsequently, that will cause ground shaking at your site of interest.

When we discuss about seismic wave attenuation, we also discussed that waves which will be generated at seismic source zone 1, that will interact with the propagation medium between source 1 and the site. So, in 2, it will interact with zone 2 and the site, and subsequently applicable to all the mediums. So, that contribution, whether it is coming from propagation path or it is coming from local side effect, that will be assessed separately. In source characterization and seismic activity, we primarily will be discussing about what is happening at the source, why it is happening at the source. We will try to find out the reasons which can differentiate or which can help in characterizing one source, how it is different from other sources. So, this is about seismic source characterization we will be discussing, and then followed by that, we will have some discussion on seismic activity.

So, seismic sources generally, you can refer to as geological structures; primarily, you call it as faults, because identification of the faults, understanding the seismic activity is generally practiced. When we go for anything which is other than linear faults, the decision in terms of the dimension of that nonlinear feature is again user-dependent because depending upon what parameters of that particular fault one is taking into account, the classification of the source can vary from one user to another user. So, seismic sources are referred to as geological structures, which are primarily faults responsible for generating earthquakes. We have already discussed the two faults, two blocks of the faults which are moving with respect to each other. Depending upon the direction of the movement, there will be development of stresses. When these stresses will exceed the in-situ strength of the medium, the material undergoes failure. Sometimes there will be melting; sometimes there will be rupture. As the process continues, there will be development of waves which will continue from the source in different directions, and depending upon how these waves are interacting with the propagation medium, the characteristics of the wave will change, which we will discuss in later lectures, where we will be discussing about local side effects and some information about seismic wave propagation we have also discussed in previous lectures.

So, seismic source characterization, the objective here is primarily to identify all potential earthquake sources, primarily from the rupture scenario. So, there might be a source which might have produced some earthquake. We will correlate this particular earthquake with respect to the earthquake scenario which has happened on that particular source, whether in terms of fault plane solution, whether in terms of percentage rupture, whether in terms of dominating fault mechanism in that particular region itself. So, source characterization identifies all potential earthquake sources, primarily from geological structures, faults, tectonic processes, such that collectively how each of these are responsible for producing earthquake on one fault and subsequently to other faults. So, we have to identify how these characteristics are varying from one fault to another so that we can utilize it for characterization.

So, though the process of seismic sources, we have to have a deep understanding about the fundamental mechanism. What are the governing forces which are actually leading to development of stresses on that particular fault? Is it primarily because of plate tectonics, or is it because of intraplate stresses which are happening over there, or the contribution, relative contribution, which you are generating from nearby sources? So, that will happen. Identification of seismic sources and the contribution, that can additional conditions, as I mentioned, rupture characteristics, fault mechanism, rate of movement, even focal depth can also be considered as one of the important parameters based on which one can go for identification of seismic sources. Then you can go for to estimate and understand the seismic hazard. Once the seismic source identification has been done, you can even quantify. Now, this is a particular dimension of the source. So, within this particular source, the earthquake can happen anywhere with a known seismic activity which you will be estimating. So, now you are having some information about the site, some information about the potential region which is showing you signature of similar seismic activity in terms of producing earthquake during the design life of the structure. So, that collectively you can use to estimate and understand how much potential seismic hazard is possible at your site of interest.

Collectively, when you are going with seismic hazard analysis, you cannot proceed unless you have complete information about source zones which are responding over the period of time differently from one another. So, identification of seismic source zones in terms of seismic hazard analysis plays quite an important role. Then seismic source characterization, it is the first step. So, you start collecting the information about past earthquakes in terms of magnitude, in terms of time. Then using this information plus additional information in terms of focal mechanism, focal depth, and rupture mechanism, tectonic settings also, or dominating mechanism which has been represented by the earthquake happening on a particular fault, collectively you can use it to start firstly the earthquake catalog, followed by that you will be determining the source characterization. Please remember that when we are going to earthquake catalog preparedness, firstly, we will be preparing the earthquake catalog for the entire region, and then we will try finding out how within that particular region the seismic activity is varying. That will help us in identifying that though the entire region of 500 km was the same, but now, based on the seismic activity, this entire 500 km radial distance is different from each other in some or the other way. So, that will be the part of seismic source characterization.

So, the objective of seismic source characterization, the first one is to determine the location and geometry of all seismic sources. As I mentioned, you will be having a distance 500–600 km radial distance zone, which is the zone such that any earthquake which is happening in that particular zone is capable of producing significant ground shaking at your site of interest. So, here, the first objective will be to find out the location, where are the actual locations which are having similar signatures in terms of tectonic setting or maybe fault mechanism or rupture characteristics, and then collectively joining the points or the grids which are giving you similar activities such that you will be able to come up with a geometry which is having uniform seismic activity, tectonic setting, rupture characteristics, such that you can say with confidence, like, "Okay, this is a polygon which has been identified. Anywhere the earthquake is happening within that particular polygon, the seismic activity remains the same."

So, that is the primary objective when we go for seismic source characterization. That means the seismic activity firstly should be the same. In addition to that, you can also take into account the location of past earthquakes. You can also take into account the rupture characteristics such that the region one which you have identified, all those properties which are actually helpful in contributing in producing an earthquake to that particular source zone will be different from the other particular source zone. So, a complete database will be required, as I mentioned, because the entire analysis in terms of determination of seismic activity, rupture characteristics, one has to have an understanding about what information related to past earthquakes is available to us. So, a complete database is required in order to find out how much seismic activity is available at your site of interest.

So, a complete database is required generally within a few hundred kilometers radial distance, depending upon what is the seismic activity of your particular region of interest. If the region is having very low seismicity, maybe 150-200 kilometers radial distance around the source you can consider. If the region is having moderate to very high seismicity, that means even a source which is available at 400 kilometers radial distance is having the potential to cause you a 6 magnitude, 7 magnitude, or 8 magnitude earthquakes, and if that particular source is going to produce an 8-magnitude earthquake, your site is going to experience moderate to significant ground shaking. So, based on that, you can find out when we say about a few hundred kilometers radius, that means this is your site, and with respect to the site, this is a few hundred kilometers radial distance. It may vary from maybe 120 kilometers, 150 kilometers, to as high as maybe 500 to 600 kilometers distance, and in exceptional cases, depending upon what the guidelines are, you can even expect it to extend to 800 or 1000 kilometers also in some cases.

So, all depends upon how important is your structure which you are going to design, and in addition, what are the seismic activities happening in and around your site of interest. So, that collectively will decide what should be the radial distance within which the past earthquake information or the database one has to determine in order to proceed with seismic source characterization. So, the seismotectonic setting of the site and desired return period for the hazard analysis will also be taken into account as potential inputs for hazard analysis and source characterization. Now, there will be characterization of seismic activity, as I mentioned, whether you are talking about a linear source, whether you are talking about an aerial source, point source, or the sources which are having more complex tectonic settings than point source or linear sources. Certainly, you will take those also into account and try finding out the seismic activity.

When we are talking about seismic activity, certainly we will be determining the seismic activity based on limited information about past earthquakes. So, consider an example of Himalayan seismicity, the earthquakes have been happening for thousands of years, but in terms of recorded ground motion, you might be having information for the last maybe 50 years, 60 years, not more than that. So certainly, when we try determining the seismic activity of a region, which is very evidently producing earthquakes for thousands of years, based on a database which is hardly available for the last 60, 70 years, there will be uncertainty with respect to the seismic activity parameters and other parameters which you will be using for seismic source characterization. So, one has to deal with those uncertainties with respect to the seismic activity.

Additionally, you will be also using different models to understand what is the governing tectonics, whether you will be taking a point source, whether you will be taking a linear source, aerial source, or maybe background sources, one has to take that into account in order to understand why there are earthquakes and how that can contribute, whether as an individual pattern or collectively in the form of a group or a polygon, to the seismic hazard of your site of interest. As I mentioned, whenever we go for whether it is about seismic activity determination or about dominating fault mechanism, every time we are dealing with very limited information about the past earthquake or very limited information about what fault plane solution has been happening on a particular fault dominantly. So, there will be some uncertainty with respect to these observations; one has to take those uncertainties also into account. Unless you take those uncertainties, whatever final assessment, whether in terms of seismic hazard, in terms of seismic activity, in terms of generating target ground motions, always there will be some error to those. So, you cannot certainly go ahead with one target event because there will be uncertainty with respect to seismic activity. So, you have to be very careful about what target events, one event or multiple events which are likely to happen within the design life of the structure, taking the seismic activity and its potential distribution within the seismotectonic province. So, that collectively will help in understanding what are the uncertainties, whether in terms of magnitude of the earthquake, seismic activity, dimensions of the source, distribution of past earthquakes, rupture characteristics, and the potential of producing the same earthquake or bigger earthquakes in the near future. All will be what one has to deal with when we are going with whether about seismic source characterization or subsequently for seismic hazard analysis.

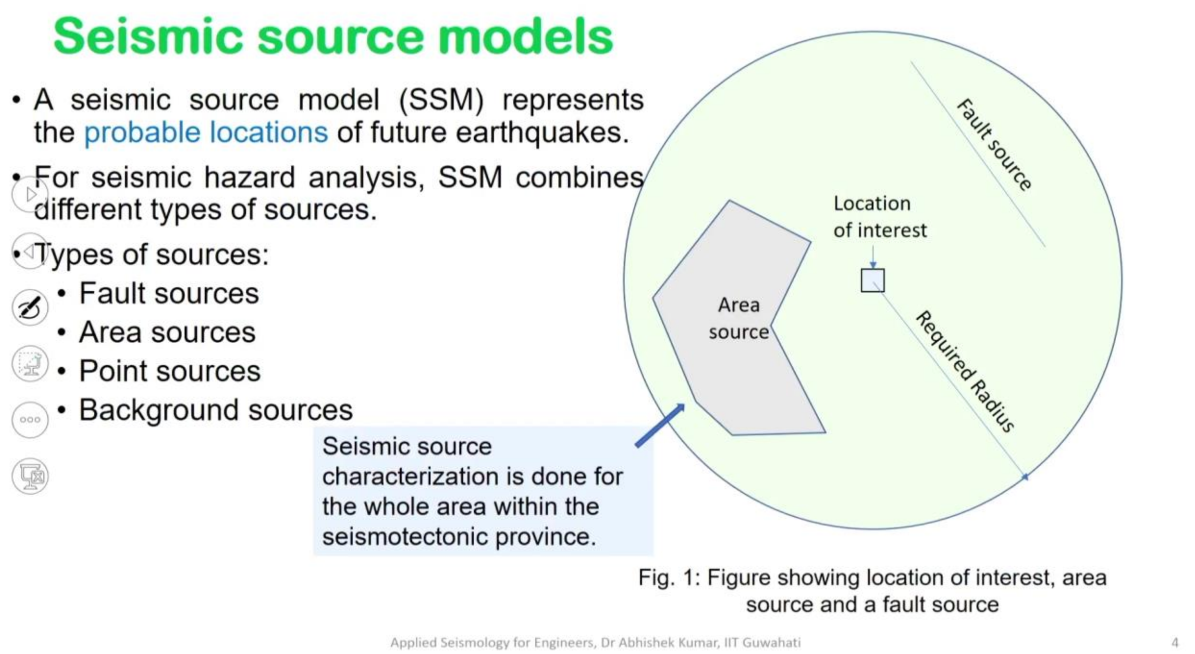

Fig. 1: Figure showing location of interest, area source and a fault source

So, the potential kind of seismic sources which one can encounter when performing seismic hazard analysis. Now you can see over here, so there is one particular site; you can consider this particular site as related to some important structure; it can be a building. If you see you are trying to assess hazard analysis for a dam, you can say this is your dam; bridge, tunnels, you can keep on telling the kind of structure which is likely to be constructed, and you are calling it your site of interest. A dam can also be there; a nuclear power plant can also be there. Now, as I mentioned in the beginning, so this is one particular source; then you found out maybe at 100 kilometers away from your source, there is no fault available. Certainly, that does not indicate that your site is safe against any kind of earthquakes or its induced effect; you have to also take into account if there is an additional source which is located at 200 kilometers or 300 kilometers away because we have seen in later slides, primarily when we discuss about liquefaction and other induced effects, that it has been witnessed during different earthquakes across the globe that even a 300-350 kilometer distance, 6, 6.5 magnitude earthquake, if it is happening at 200 kilometers radial distance, that earthquake can even cause significant ground shaking and even building damage at 200, 300 kilometers radial distance.

So certainly, that indicates you cannot completely ignore a site or a fault which is available at 200, 300 kilometers radial distance, considering the distance, because whenever waves are going to generate at this particular fault, these, by the virtue of transfer from the source, traveling through the propagation path and then finally reaching even at the bedrock level, followed by that there will be amplification between bedrock and the surface. So, even if you take all this process, what is happening at the source, propagation path, and site collectively, the vibration which was produced by the 200- or 300-kilometers distance source, that will be also significant. So, we cannot completely ignore those. In addition, if there are sources which are available maybe at 500 kilometers radial distance and are capable of producing maybe a 7 to 8 magnitude earthquake, though it is at 500 kilometers radial distance, you can check this with trying with some particular ground motion prediction equation; keep the magnitude of 7.5, 7.2, and radial distance of 500 kilometers; you will see even this particular earthquake is capable of producing significant ground shaking at your site of interest. Now, here when we discuss the contribution from the sources, every time we have discussed that there is a source which is well identified at your site of interest. That means you have a site; you started looking at a seismic atlas map or other maps which are going to give you some information about the sources, primarily the linear features available in your seismotectonic region. But at the same time, you will also see there are plenty of earthquakes which have happened in the past, but there is no information related to the faults, there is no information related to the particularly linear feature, so certainly that does not mean that these are happening without any particular source; rather, we do not have complete information about these sources. Remember, the information about the source generation of the source is a continuous process, so whatever information we were aware of maybe 20 years, 30 years in the past might be different from whatever information is available to you now. So, it is a continuous process; you keep on getting more and more information about whether it is a prominent source or maybe a dormant source or relatively weaker seismicity corresponding source. But certainly, you will find out some regions where only information about the past earthquake epicenter is there, but you do not have any information about the source.

When we go for seismic hazard analysis, we cannot simply ignore these sources; you have to find out a way such that the contribution of these sources in a proper rational manner can be contributed to this particular site, how these particular points are contributing with respect to the seismic hazard of this particular site of interest. So then, we will move from linear features, so we have to actually deal with what are the potential models one is likely to adopt in order to understand what is happening within your seismotectonic province. So, this particular region is called a seismotectonic region. Seismotectonic region, that means what is the region whose seismicity can actually contribute to seismic hazard at your site of interest. So, we are looking at this particular seismotectonic region; we identified there are some places where earthquakes are there, and some sources are there where these earthquakes can be contributed to or can be transferred to, but at the same time, there are some sources which do not have any particular linear features related to that.

So, you will try to identify what are the regions which are showing you similar signature of seismic activity, some similarity in terms of rupture mechanism percentage rupture. Try to identify those, and then you will find out you will have some additional feature which is called as area sources. There is significantly larger area where, though you are having information about past earthquakes in terms of points, but if we see the contributing parameters which are leading to the production of earthquakes in these particular regions, you find a similarity over here. Taking that similarity into account, you say, let us see this particular region rather than considering individual points now identified, so the seismic activity within this particular region is constant, or the chance is that this particular region is going to produce maybe 5 magnitude, 6 magnitude, 7 magnitude earthquake is uniform throughout this particular region. That is called as area source. So primarily the objective here in area sources is that the seismic activity within the particular region should be uniform, which was also ensured in your linear source. So, whenever we talk about linear source also during a particular earthquake, some portion, whether you can call this particular portion, this particular portion, some percentage of length, some percentage of width, which might be undergoing rupture during a particular earthquake, that rupture characteristics also linear source-specific, it can be area source-specific. So, we discuss about potentially there are two ways you can classify the regions. One is linear source, which is quite well identified. Then, in addition, we find out a cluster of points representing the earthquake which has happened in the past, and you find out some similarity in terms of seismic activity, which will give you confidence, okay, we can club all these points, and rather than dealing with each of these points individually, now you will have contribution from all these points collectively in terms of area source.

Then, point source. Again, there will be some points, so you don't have many numbers of points in and around of that, just some point is there where some earthquake has happened, maybe 6, 5, 4.5 magnitude earthquake, anything usually greater than 4 we consider important from seismic hazard point of view. So, anything which has produced an earthquake of 4.5, 5, but there are no earthquakes in and around of that, that means this is still, we do not have complete information about what is the source of this. We cannot club this related to this particular linear source which are located maybe 400 kilometers away. We cannot contribute this with respect to nearby aerial source also, because the seismic activity shown on this particular by these particular points, and which is shown by this particular point, is significantly different. Then we will take these point sources individually. We say there is a point which, by virtue of its characteristics, which is different from aerial source and linear source, are producing earthquakes, and this signature will be repeated during the design life of the structure at least. And, of course, we will take the uncertainty with respect to the seismic activity also into account. Then there will be complex tectonic setting happening, how these two regions are behaving with respect to each other, or there are many numbers of crisscrossing faults such that you cannot have just one linear source. We cannot have an aerial source, but it is something more complex than linear source, aerial source, or point source. But since these are contributing also to your seismic hazard, you will take that into account as background sources. So collectively, you can look into the seismotectonic map, so you will have sources as well as superimpose on the source, you will have past earthquake information. That collective map will be called as seismotectonic map. Once that map is ready, you can find out probably there are regions or earthquake sources which are actually contributing to linear source, aerial source, point source, or background source. That means now you have clear-cut information about what is the contribution which is coming from linear source, what is the contribution coming from aerial source, and there are some regions, though these are available in a particular region, these are not actually contributing in any manner related to the seismic hazard of a particular site. So, you need not do the hazard analysis for the entire region rather to point source, aerial source, linear source, and background sources alone. That will be time-efficient also, because you will not be dealing with the seismicity of or seismic hazard corresponding to almost a null zone.

Okay, so fault sources as we discussed about primarily about linear sources. So more general representation of a seismic source is a fault. We have discussed also when we were discussing about fault plane solution, so one hanging wall is there, one footwall is there. Considering the direction in which the two are moving, you can have an idea about the rack angle, the dip value, the strike angle. A fault is a three-dimensional space which represents a zone of weakness, usually at certain kilometers from the ground, primarily relating focal depth plus and minus some dimensions depending upon the dimension primarily of the rupture area, so that will have an understanding how much is the fault dimension. The information about the fault, as I mentioned, is a continuous process. So based on remote sensing data, based on aerial photographs, based on topographical maps and geophysical maps, and even based on value seismic investigation, one can identify the regions which are showing indication of potential source, primarily linear source of the fault in a particular region. So even if a particular event has happened in the past, you can still get an idea about what is the possibility of the event to get repeated primarily on a particular fault. Remember, when we are discussing about the fault, we do not consider you that it is always going to get repeated. What has happened in the past is going to get repeated in the near future also, so that doesn't mean if you have information about last 40 years, you can predict for the next 40 years based on that. So, it's primarily based on the Poisson model. We do not have complete control on how it is going to happen in the future, but certainly, based on the seismic activity which has been generated, based on your information about past earthquakes, one can have an understanding about future earthquakes, and certainly, there will be some probability that the uncertainty which you are going to get, develop, the actual ground motion may exceed that particular predicted value. So, a fault source, is represented by a simple polygon also, which can be three-dimensional space, and you will have some information about the strike and dip value, and if more detailed information in terms of movement is also available to us, we can also find out the rack angle also. In seismic tectonic map, if you see, these will be represented by means of linear features. If an actual ground, it is curved, you can represent it by means of more than one line so that you will be able to find out the probability in different locations for rupture to happen during the design life of the structure. So, number of polygons or line segments, you can find out representing the geometric segments of a fault, if it is other than simply a linear feature.

So, area, so that I mentioned, there might be some reason where you are having active faults, but characterizing individual faults as seismic source will not be possible. One reason may be the dimension which is available on the ground surface will be very limited in order to assign the seismicity which has happened in and around that particular region to that particular linear feature. In addition, if other than one activity, there are not plenty of activities, certainly, you cannot assign to nearby source, or if there are seismic activities, but there are no linear sources available in the nearby region. So certainly, you will not have linear sources, and you cannot characterize those based on limited information as individual faults. So, one has to have some way to accommodate these in terms of area sources. So, if region is experiencing small earthquakes which cannot lead to surface rupture, again, the exact information about the sources will remain partially known. So, we will have more about area sources.

Then subsequently about point sources, as I mentioned there. So, there are not much of activity happening in and around that particular region, which has shown one or two events in the last maybe 50 years, 100 years, so there should be a way we can account for those point sources. These are normally applicable to ground motion models. So generally, when we go for synthetic ground motions also, we will be having some information or point source model, as we mentioned over here. In point source model, we generally do not take the dimensions of the fault; simply, we take there was a point at which rupture initiated and subsequently led to the generation of seismic wave, and then followed by propagation path and site effects. However, for improving the computational efficiency, you can even club more number of point sources and come up with area source, but that can only be done when you find some similarity in terms of seismic activity between different parameters.

Background sources, as I mentioned, primarily if relatively complex seismicity you find out such that it's not possible to identify the known information in terms of linear source, aerial source, or even in point source, we consider it as background source. Usually, the seismicity will be relatively low for linear sources but still it is contributing significantly with respect to the situation at a particular site, primarily if the exposure period is significantly large. Because if you keep on increasing the exposure period, even the low-magnitude earthquakes have more chances to get experienced during the design life of the structure. This can also contribute significantly to the seismic hazard at your site of interest.

Now, there are ways you can help in identifying the seismic sources. One is based on the geological evidences. So, one can look into the relative age, what are the geomorphological features available at a particular site. Then trenching also can be done. Geophysical methods are also there, which will also help in identifying the potential location of the faults, the fault mechanism which is also there. So, that can also help in identifying, even remote sensing data will also give you what are the potential locations which are more or less giving you the same value of ground displacement direction as well as amplitude. So, that can also be clubbed in terms of geological evidence indicating what are the regions which can be clubbed collectively in terms of one seismic source. Historical evidence: you take past earthquake information into account and try identifying or clubbing the regions which are having similar signatures in terms of historical evidence for earthquake occurrence. Even damages which have been produced by different earthquakes can also be taken into account as a representative feature to identify seismic sources. Then instrumental events: with more information in terms of GPS measurements, in terms of remote sensing, you can have more clear-cut information about what signature at the ground is visible, which can be used as evidence to classify or club a much larger area into one seismic source. And, of course, past literature: we can always depend significantly on whatever work has already been done in terms of seismic source characterization for a particular region. That will also give you some clarity about what are the attempts that have been made in the past in identifying seismic sources. We can also utilize that information, of course, bringing more parameters into account and then do seismic source characterization.

So, it is the seismic hazard at a particular site is usually influenced by sources more probably in terms of, if you are talking about some sources which are capable of producing major to greater earthquakes, and the region is also 500-600 kilometers radial distance, taking into account the seismological, tectonic, and geological attributes and their potential variation within the seismotectonic region. So, tectonic setting, when we are talking about geological age, when we are talking about that can also help in identifying that the regions throughout your seismotectonic region are not the same but can be clubbed into more than one seismic source. The next part is the seismic activity. As I mentioned, that will help in identifying how frequently different magnitude earthquakes are likely to occur within a particular linear source, area source, point source, or the sources which are not covered in all these three source types. And usually, it is seen that seismic activity is significantly varying between two adjoining source zones. That means two source zones, though geographically are located adjacent to each other, but their contribution to the seismic hazard at a site is significantly different. So, usually, that will help in, that will result in underestimation of the seismic hazard. If you take the same parameters throughout in terms of seismic activity, you will end up in underestimating the seismic hazard for some regions and overestimating the seismic hazard for other regions because you are talking about two regions which are adjacent to each other. So, for some, there will be underestimation; for some, it will be overestimation. So, better to delineate the seismic sources and identify the regions which are giving you higher contributions, which are giving you lower contributions, and deal with both of them separately because the regions which have low seismicity then chances that these will produce bigger earthquakes will be also relatively different from the regions which are frequently experiencing moderate to great earthquakes.

So, four types of seismic source zones which can be primarily identified: one is seismotectonic zones, taking into account the distance, the correlation between the fault and the earthquakes, primarily the rupture characteristics; then paleoseismic zones, that will have some understanding about the structural history of the region and the possibility of this, based on this possibility, how the seismic activity is going to be witnessed in the future. And usually, there will be a lack of seismic history because such investigations available in particular regions are very limited, so there will always be some issue primarily in terms of lack of understanding of seismic activity which can be generated from paleoseismic investigations. Next one is seismogenic zones, so lack of the development of clear history relating to the contemporary seismic activity. So again, in this particular information, though you are going to generate some information based on the history, but that history is also incomplete, so there will be some information which will add more to the uncertainty. Then seismicity zones: based on the spatial distribution of seismic history, one can identify the zones which are showing you different seismic history zones, which are showing you similar seismic history, you can club those zones and then proceed for source characterization.

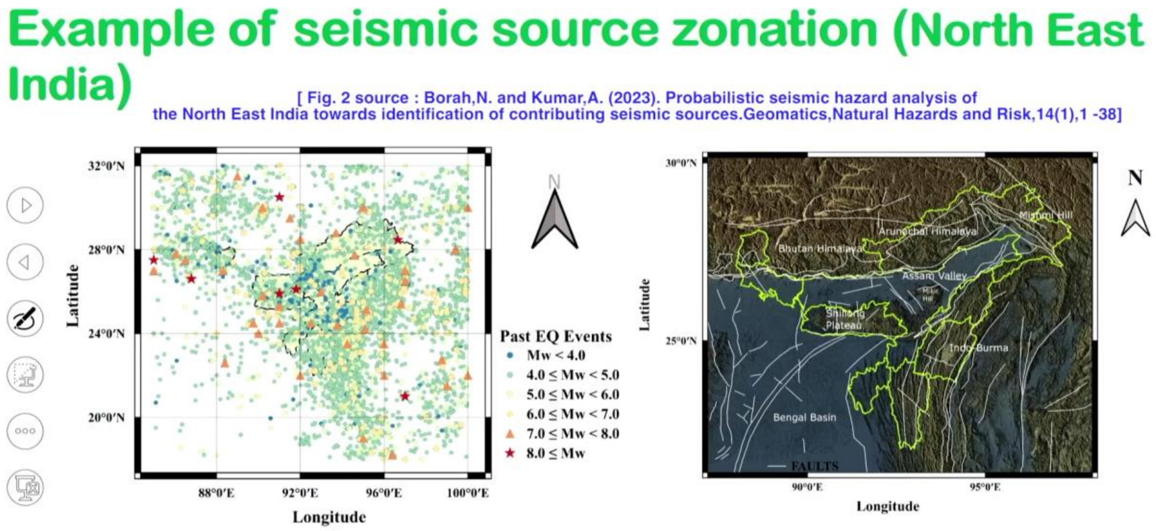

Fig.2 : Past EQ events in and around NE India

Fig.3 : Significant seismic sources (Faults) in and around NE India showing complex tectonic setup

Now there is one example: so, you can see over here this particular picture shows you the information about the past earthquakes, and this is a legend which has been followed in developing this figure. You can see over here the distribution of past earthquakes is not uniform; this is from northeast India. So, you can see over here this side you are having Indo-Burmese subduction zone, this side you are having Indo-Eurasian subduction zone, and then in between, this is northeast India. The distribution of different magnitude earthquakes is not uniform. Even if you superimpose only the location of past earthquakes, it's not uniform. You see over here, it's significantly lower here, significantly higher in these regions and even in these regions, then moderate in these regions. So, based on visual identification itself, one can identify that the signature which is being shown in terms of earthquake occurrence in the past itself is not uniform. That means if an earthquake is going to get produced in 50 years over here, it will be significantly different if the same magnitude earthquake is going to get repeated in this particular region. That means this particular region may be indicating more seismic activity if the site is interested over here in comparison to this particular region, subsequently this region, this region, and other regions. So, that will help in identifying even based on the past earthquake location itself, there is significant variation in terms of the epicentral location of the earthquakes. Then again, you take into account the faults which are available in the particular region and the governing fault mechanism, you will see there are regions which are primarily dominated by plate boundary earthquakes, there are regions dominated by plate boundary over here also, here also, then there are regions which are within the plate itself, and there are regions which are undergoing rotation. Now collectively, so this is behaving in one manner, this is behaving in one manner, this is behaving in a different manner. If you are taking any particular region over here and performing seismic hazard, certainly the contribution from each of these three regions will be different, and again within these regions, there are some faults which might be strike-slip, there might be some faults which are dip-slip, there might be some faults which are purely thrust faults. So, relative to the rotation which is happening over here, the contribution which will be adding up to thrust faults, which will be adding up to strike-slip faults, will be significantly different from each other. That will have an impact on the seismic hazard assessment. So, you can see over here very low and very high seismicity.

Example of seismic source zonation (North East India)

Reference	Numbers of source zones considered	Based on
Sharma and Malik (2006)	10	Tectonic settings: fault locations and alignments.
Gupta (2006) for the entire India.	20 out of 81 zones are near NE India	Seismicity and tectonic features.
Pallav et al. (2012)	7 (based on Goswami and Sarmah, 1982 and Nandy, 2001)	Tectonics settings and geology.
Kolathayar and Sitharam (2012) for the entire India.	More that 25 source zones are near NE India.	Seismic events distribution.
Sitharam and Sil (2014)	6	Event distribution pattern and source orientation.
Das et al. (2016)	9 (based on Angelier and Baruah, 2009)	Tectonics, geology, focal mechanisms and spatial distribution of seismicity.
Bahuguna and Sil (2018)	17 active and 12 inactive	Fault alignment and location of the seismic sources.
Baro et al. (2020)	4	Geology, overburden thickness, seismotectonics, rupture characteristics and rate of movement.
Borah et al. (2021)	12 and 11	Past EQ locations and seismicity parameters

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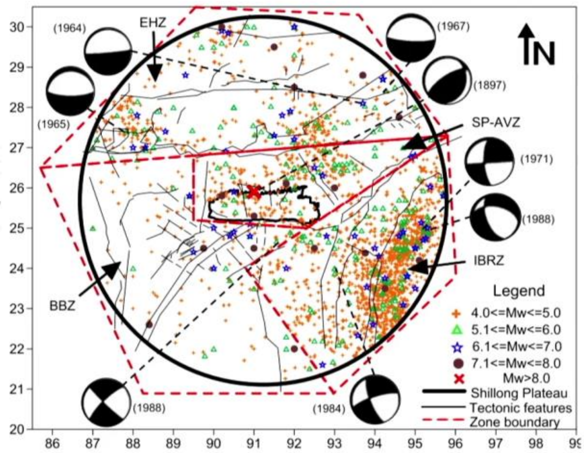
Now, this figure shows some summary of different works which have been done for seismic hazard either for northeast India or for different parts of the country, and while performing these works, there were attempts to do seismic source characterization. So, you see the study area remains the same, but the definition of source zones, the geometric boundary of source zones in each of these are significantly different from each other. You see here Sharma and Malik (2006) just considered 10 zones; on the other hand, if you see Bahuguna and Sil in 2018, 17 active zones and 12 inactive zones. Very recently, some work was done by Borah et al. (2021) where we have identified 12 zones as well as 11 zones: one based on past earthquake information, second one based on seismic activity, and collectively we can find out some source zone which is finally given for northeastern India. So, the study area remains the same, but the definition of source zones, number of source zones, vary from one user to another user. That is what I mentioned in the beginning also, that the choice—unless it is a linear source—the choice of area source may vary from one user to another user, depending upon what parameters each of these are taking into account while performing this seismic source characterization.

Conti...

- Baro et al. (2020) divided NE India into 4 zones:
  - Shillong Plateau–Assam Valley Zone (SP-AVZ)
  - Indo-Burma Ranges Zone (IBRZ)
  - Bengal Basin Zone (BBZ) Eastern Himalayas Zone (EHZ)
- **Based on:**
  - Geology,
  - Overburden thickness
  - Seismotectonics
  - Rupture characteristics
  - Rate of movement.



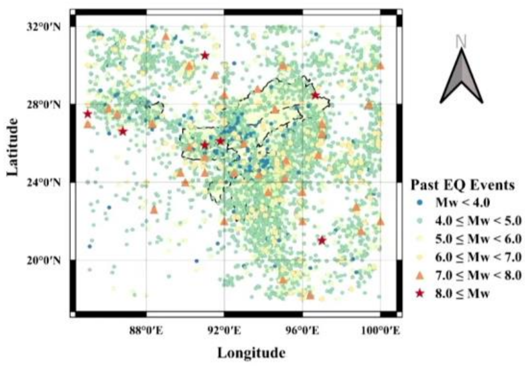
[Fig source : Baro,O., and Kumar,A.(2017). Seismic source characterization for the Shillong Plateau in Northeast India. Journal of Seismology, 21,1229-1249]

Fig.4: The four seismic source zones of Baro et al. (2020), along with the beach ball solution of some of the significant EQs in the different zones **(Baro and Kumar, 2017)**

So, Baro et al. (2020) did source characterization considering geology, overburden thickness, seismotectonic rupture characteristics, and rate of movement into account, and then came up with four zones, which are shown over here, and I have also marked here: Eastern Himalayan Zone, Indo-Burmese Zone, Sri Lanka Plateau, Assam Valley, and Bengal Basin zones. Subsequently, if you bring more than these parameters, you will be able to find out within each of these zones if there is a possibility that the two zones between these two can be clubbed, two zones between these two can be clubbed, or within this, you can have more source zones. So, depending upon the parameters one takes into account, that process of identifying source zones will certainly improve the accuracy of proposed seismic hazard values for your site of interest.

Conti...

- Borah et al. (2021): Used hierarchical clustering to divide the entire region into different source zones.



So again, in 2021, this is the work which our research group published. The details of this particular work you can download from my website. So, this is the same figure showing the past earthquake information in terms of epicenter.

Conti...

- Borah et al. (2021): Used hierarchical clustering to divide the entire region into different source zones.

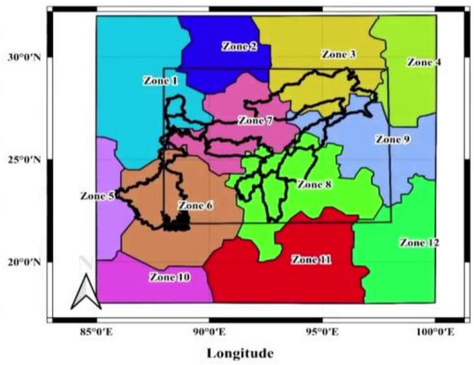


Fig.5: 12 source zones based on the location of the past earthquakes

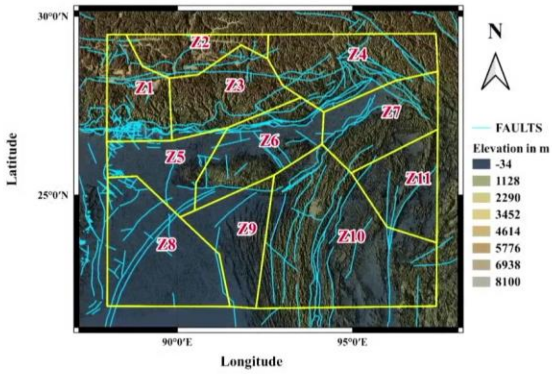


Fig.6 : 11 source zones based on the location of the past earthquakes and seismic activity

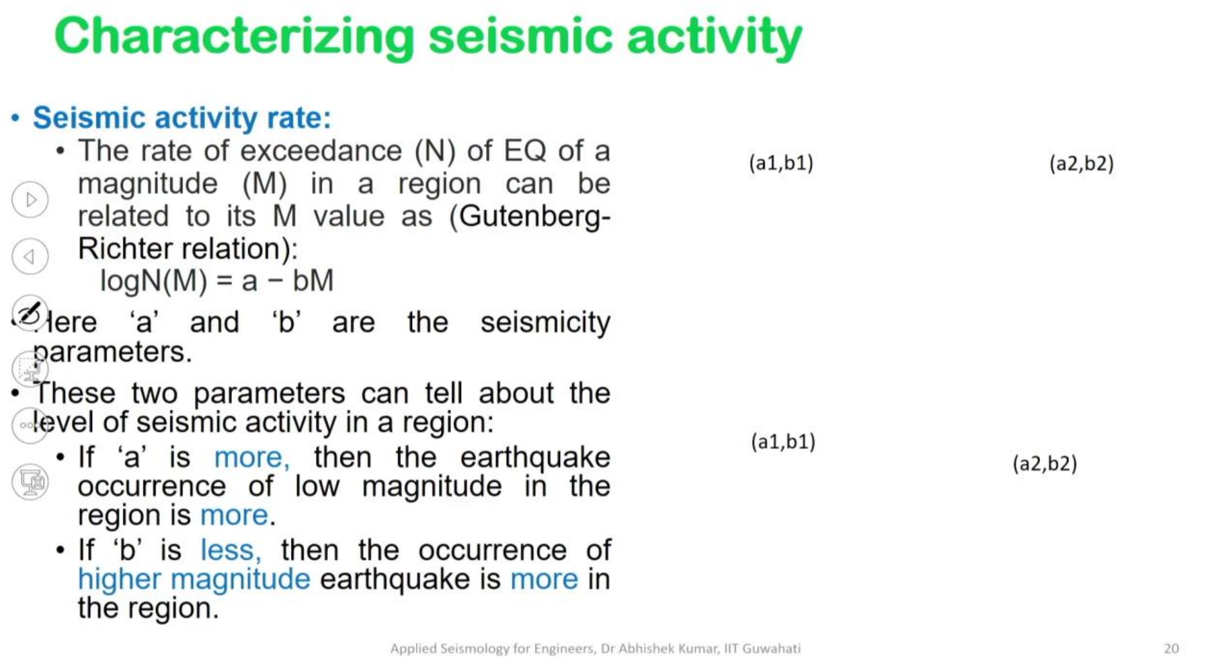
[Fig source: Borah,N., Kumar,A., and Dhanotiya,R.(2021). Seismic source zonation for NE India on the basis of past EQs and spatial distribution of seismicity parameters. Journal of Seismology,25(6),1483-1506]

Based on this, two zones were identified: one was based on the location of the earthquake, the second one taking the earthquake information as well as seismic activity into account collectively. We proposed 11 zones for the entire northeast of India, ensuring the seismic activity within each of these zones: Z5 will remain the same, in Z6 the seismic activity will be uniform, in Z9 also will be uniform, and subsequently for all the 11 zones, the identified seismic activity was uniform.

So, there is uncertainty with respect to whatever is known with respect to the earthquake occurrence process, that will primarily come in Aleatory uncertainty, which takes into account the randomness of the process contributing to earthquake occurrence, and then Epistemic uncertainty, which is primarily related to the limited knowledge of different model parameters, which can help in understanding the shore zones and what is happening at the source. So, one has to deal with Epistemic and Aleatory uncertainties separately, taking into account information about a particular source, information about the tectonic setting, information about rupture characteristics, as well as past seismicity, such that it will help in the identification of these source zones more accurately.

So, importance of source zones is that it will help in getting more information about the structural features, the fault, tectonic settings, and also in terms of contributing to the seismic sources: which are the seismic sources that are contributing more, which are the seismic sources that are contributing relatively less to the seismic hazard of a particular region. And of course, we have to deal with the associated uncertainty with respect to each of these parameters, which is used for seismic source identification. This will also help in the decision-making process once we go for design, when we go for land-use planning also, because that will help in gaining more confidence. If we know what sources are contributing more, we can go for detailed monitoring of those sources, which will certainly help in arriving at primarily the land-use planning, and then even be prepared for emergency situations, because on one side we have identified the most contributing source, on the other side, based on this output, we are regularly monitoring that particular source and then characterizing it.

So, you have to take into account the past seismicity in order to identify what the potential magnitude is that a source can produce, even though we have some information about what maximum magnitude the source has produced in the limited time in history which is available to us. So, if we have some history of the last 80 years, 100 years, there are chances that the source has not produced its true potential. It still can produce larger magnitude earthquakes, so we have to identify what the maximum potential earthquake is. Statistical methods are there, based on which, taking the largest magnitude earthquake as well as seismicity into account, one can find out what the maximum potential earthquake for each particular source is, whether it is a linear source, areal source, point source, and of course, taking into account the geometry and rupture characteristics in a particular region, that will also help in understanding what the maximum potential earthquake is which is likely to occur at a particular site of interest. So, you cannot have a significantly large magnitude earthquake on a very small source, because there are no dimensions available to undergo failure.



Of course, this is the last part. Seismic activity, as I mentioned, is basically correlating the number of particular magnitude earthquakes, which is shown over here. You can see over here the log of the number of any particular magnitude earthquake, and it is there on the y-axis, and the magnitude of that particular earthquake is on the x-axis. So, as per Gutenberg and Richter, correlation exists, which correlates the number of earthquakes with respect to its magnitude. What it means is usually small earthquakes will be happening more frequently; if you go to moderate earthquakes, the frequency of those earthquakes will be relatively less in comparison to small magnitude earthquakes. Similarly, if you go to major earthquakes, again, the frequency of those earthquakes will be less; if you go to great earthquakes, the frequency will significantly be less. So, the Gutenberg-Richter relation is giving you a correlation between how many numbers of earthquakes of a particular magnitude are likely to occur in a particular source zone, in a particular region, depending upon for which region this particular information is known.

When we are determining, ‘M’ is the magnitude, capital ‘N’ is the number of events of magnitude capital ‘M’, which are likely to occur, and these two are correlated with respect to two parameters: one is ‘A’, which is going to tell you how many numbers of earthquakes of lowest magnitude, usually 3, 4, depending upon the designer, are produced in a particular region, and ‘B’ is going to tell you the frequency at which overall the magnitude of earthquakes of—I mean, earthquakes of different magnitudes are potential. So, ‘B’ is basically the slope of this particular line, and ‘A’ is the intercept on this particular. So, higher is the value of ‘B’; that means the frequency of larger magnitude earthquakes is relatively low. Lower is the value of ‘B’; then you can say that the occurrence of higher magnitude earthquakes is relatively more. So, that's how we can have some understanding. So, we have identified source zones based on rupture characteristics, dimensions, dominating fault mechanism, tectonic settings, focal depths, and many more parameters. Then, we brought past earthquake information into account to determine the seismic activity. We get additional parameters, so again, with these additional parameters, we can go back and try classifying your seismic source zones. So, based on this, you can actually identify what the zones are which are having low seismic activity, what the zones are which are having high seismicity. Definitely, low seismicity zones will have relatively low contribution in comparison to high seismicity zones. So, you will get some understanding in terms of relative contribution, and subsequently, these ‘A’ and ‘B’ parameters will also be used when you try determining the maximum potential earthquake from any particular seismic source. So, with this, we have come to the end of this particular lecture on seismic source characterization. We will discuss more on seismic activity in Lecture 10.

Thank you, everyone.