Applied Seismology for Engineers

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Week – 05 Lecture - 02

Lecture – 10

Hello everyone, welcome to lecture 10 of the course Applied Seismology for Engineers; myself, Dr. Abhishek Kumar. In lecture 9, we have discussed that whenever there are earthquakes in a particular region, these may trigger damages to the building; these may cause other kinds of induced effects. So, whenever one is interested in finding out what the potential ground motion is expected to occur at a particular site of interest, we can go for hazard assessment. Now, hazard assessment, or as far as earthquake occurrence is concerned, mostly these will be associated with respect to faults.

However, considering the information or considering limited information about faults which are present in a particular region, many times we will encounter an event, but there is no fault which has been mapped so far, or there is no information about a fault in a particular region. So, how in such cases one can go for source characterization, we have discussed in the previous class. Also, we discussed in brief about what area sources are, what linear sources are, what point sources are, and how this information about the sources, in conjunction with information about past earthquakes, collectively can be given more information about seismic activity, more information about what areas are experiencing more frequent earthquakes, and what areas are experiencing relatively fewer earthquakes. In the end, we also touched upon the seismic activity parameters.

So, we just discussed about what the Gutenberg-Richter law is, which correlates the cumulative number of earthquakes of M or greater magnitudes happening in a particular region of interest in terms of A minus B times M. So, we discussed what will be the influence in terms of interpreting the seismic activity when we have a very high A value, when we have a very low A value, and subsequently what will be the interpretation if we are linking the seismic activity with respect to the B value. Higher is the B value, we can say the lower is the B value, the lower the seismic activity. So, with that brief discussion about source as well as seismic activity information, we will continue this particular topic. As I mentioned in earlier classes also, usually there will be damages which will be witnessed in maybe the last couple of decades, maybe one, one and a half century; but whenever it comes to the design part, whenever it comes to the assessment of what is the potential earthquake loading likely to come during the design life of the earthquake, we have to have a broader understanding about what has happened in the past in terms of primarily when the earthquake has happened, where the earthquake had happened, and what was the size of those earthquakes.

In later classes, we will also discuss about paleoseismic investigations, which will help us in identifying historic earthquakes that might have happened 600, 700, 1000 years back. At present, we do not have any information, but based on paleoseismic investigations, looking into primary signatures and then going for detailed investigation, one can identify many more characteristics of historic earthquakes which were not known before such investigations were taken up. So, continuing with the topic of earthquake catalogue and seismic activity, seismic activity we discussed in the last class. In today's lecture, we will also discuss what an earthquake catalogue is, and what the importance of an earthquake catalogue is. As I mentioned just now, very limited information about the earthquakes happening in a particular region is available, primarily because, firstly, the recording or instrumentation of earthquake recording instruments in a particular region has been a very recent activity in the last 40 years, 50 years, 60 years.

So, if you see the number of earthquakes which have been witnessed since the recording stations have been installed, it will give you some information about maybe small to moderate earthquakes. But when you talk about earthquakes which are happening maybe once in 500 years, once in 1000 years, meaning the earthquakes which are corresponding to very high return periods, certainly with limited information generated from earthquake records for the last 40, 50 years, getting information about earthquakes that have a frequency of one earthquake in at least 500 to 700 years will be almost impossible. So, on one side, we have to have an understanding about what the potential seismic potential of a particular region is, but at the same time, we are having the earthquake catalogue, which is very limited in terms of spatial distribution as well as temporal distribution. So, let us look at the earthquake catalogue, what the meaning of an earthquake catalogue is, and what the processes, minimal processes, are which one has to do on the earthquake catalogue before you can start looking at and analyzing this earthquake catalogue for further information. So, an earthquake catalogue, as we know, that preparedness, once we are told like I have to design a particular building or I have to look into the retrofitting of a particular building, then certainly I will take into account what damages have happened in the past. Similarly, if I am interested in finding out what seismic force, story shear, is likely to be witnessed by a building which I am going to design and construct today and which will be exposed to earthquake loading conditions for the next 35, 40, 50 years depending upon the design life of the structure, then I have to definitely refer to whatever information is available with us in terms of past earthquakes as well as seismic sources.

So, in lecture 9, we discussed about seismic sources; in lecture 10, we will be discussing particularly about earthquake events. So, earthquake catalogue, if we go with that part, the preparedness for future earthquakes in a particular location is only possible if one knows about the true potential in terms of earthquake occurrence or the seismic potential of a particular region. When we say about seismic potential, that means we are interested in knowing how accurately we can get the information about what size of earthquakes are potential to occur in a particular region. If we are talking about a stable region, we may look into 4, 4.5, 5 magnitude earthquakes, but on the other hand, if we are dealing with a very highly seismically active region, given the example of northeast India, then we can have even major to greater earthquakes also likely to occur in the design life of the structure.

So, this is one possibility. So, in order to understand the true potential, one has to also understand how it has responded in the past. When we say about responded, definitely one piece of information which will be required is an earthquake catalogue. So, in order to understand the true seismicity or true seismic potential, what is the potential of a particular region to create different magnitude earthquakes, how frequently these earthquakes can be repeated during a particular fault or collectively in a particular region, that is the meaning of true seismic potential. So, what is the true seismic potential of a particular region? Such information about a particular region of interest can be determined from many agencies.

So, in addition to seismic sources, one can refer to the seismic atlas map provided by different agencies; in India, the Geological Survey of India also provides a seismic atlas map. So, one can refer to those maps to get updated information about seismic sources. Similarly, about past information, we can get to know from many sources. Some of them are listed over here also. So, when we talk about past earthquakes, what we are actually trying to understand is what was the location of earthquakes that have already happened, what was the size of the earthquake, and what was the magnitude of that earthquake.

Mostly, we are interested in magnitude. If some earthquake has happened prehistorically, we can have some understanding about the intensity of that earthquake, and using available correlation, maybe regional correlation or global correlation, such intensity values can also be converted to how much was the expected peak ground acceleration at different levels. So, time and date when the earthquake happened throughout a particular time, which month, which day, and which year the particular earthquake happened. So, we are interested in knowing more and more about the earthquake, as the earthquake has happened in today's date; the same thing we are interested to know about past earthquakes. It can start with the location; it can start with the time; it can start with the size; even the focal depth, if there is a possibility of getting focal depth, we can determine the focal depth, we can gather the focal depth. Similarly, focal mechanism, we discussed in earlier slides also, in earlier lectures also, that whenever there is a release of energy happening at the fault plane, it might be a result of a particular movement of two fault blocks; it can be related to normal faulting, reverse faulting, strike-slip faulting, dip-slip faulting, thrust faulting.

So, what was the tentative focal mechanism of historic earthquakes or any earthquake that has happened in the past? So, these are primarily the pieces of information which one should look into when we are exploring past earthquakes in a particular region, and remember, the objective is how accurately one can determine the true seismic potential of a particular region. Now, any earthquake catalogue, when we say about an earthquake catalogue, that means we are trying to develop a comprehensive database, a very systematic database of earthquakes which have happened in comparison to present in the past and most likely should be covering all this information which is listed over here, including the location, the size, the focal depth, focal mechanism, when it happened, all this information. If some information is not there, we will try to get the other information and try to get more and more information such that whatever events have happened in the past, I should have complete information about those events. Later, once I start analysing those events, I will get more and more interpretation about the true potential, true seismic potential, true seismic activity of a particular region, or I can say accurate seismic potential, accurate seismic activity of a particular region.

So again, if I am interested in going for hazard assessment in a particular city, I can go with a particular region. How many earthquakes have happened in, maybe, if this is my site of interest, then how many particular regions in your site of interest have happened, which might be ranging from 500 kilometers, 600 kilometers radial distance, or to as low as 200, 250 kilometers radial distance? So, within this particular site, and keeping a radial distance of, suppose, 500 kilometers, so within this particular radial distance, what are the events which have already happened in the past? We will try to gather information, what is referred to as past earthquake information. In addition, source information will come as we discussed in the previous lecture. So, the information about past earthquakes can be referred to various sources or various catalogues. There are different agencies which can provide you information about past earthquakes. Some of these are listed over here also.

- *Indian Meteorological Department (IMD)*
- *Geological Survey of India (GSI)*
- *United States Geological Survey (USGS-catalogue),*
- *International Seismological Centre (ISC-catalogue),*
- *National Center for Seismology (within India),*
- *Global Centroid Moment Tensor Catalog (GCMT-catalogue)*

So, at the national level, international level also, there are different agencies. At times, you can just enter the center point coordinates or the coordinates that lead you to longitude of your site of interest and also tell how much radial distance, whether in terms of kilometers or in terms of degrees, whatever these agencies ask, and then you can get information about past earthquakes which have happened within that particular radial distance, giving your latitude and longitude of the site or within latitude and longitude range of your area of interest or region of interest, and that will give you past earthquake information. As I mentioned over here also, there are a number of agencies. Some agencies will give you data more about historic earthquake data. Some agencies will give you region-specific data.

So primarily, I have mentioned over here also, Indian Meteorological Department one can refer to. Whenever there is an earthquake, they will give updated information about where the earthquake has happened, focal depth, and, at times, focal mechanism also. Geological Survey of India, as I mentioned, seismic atlas maps are there, based on which you can get more information about historic earthquakes, and this keeps on getting updated at regular intervals. So, you can get more information in terms of earthquakes as well as in terms of seismic sources which have been identified up till the current time. Then, United States Geological Survey you can refer to, you can get a lot more information about past earthquakes. So, 1, 2, 3, and then International Seismological Center (ISC) is there. Again, from there, you can get more information about past earthquakes and information, again, referring to size, location, focal depth, focal mechanism, and when the earthquake has happened. Then, GCMT catalogue also is there. Again, when you go to the GCMT catalogue, in addition to the information which was mentioned over there, many times we will also get to know focal mechanism in terms of nodal plane solution. So, you can get to know what the strike and depth value for nodal plane 1 is, what is the strike and depth value for nodal plane 2. Here, I am referring to the nodal plane related to one being the fault plane and the other one being the auxiliary plane. You can refer to the corresponding node, which we have discussed about fault plane solution. So, one is the auxiliary plane, one is the fault plane; using these two, we can determine what is the potential fault plane mechanism during a particular earthquake.

So, these also can be obtained from different agencies. Then, in addition, one can refer to existing literature because, in India particularly, many times we also refer to Oldham catalogue, which is composed of a lot more information about historic earthquakes. Recently, in 2010, there was a report on the probabilistic seismic hazard map of India, development of the probabilistic seismic hazard map of India by National Disaster Management Authority. So again, from there, you can refer to and get more information primarily related to India and adjoining regions, which might govern the seismic hazard of Indian territory. So those things you can get more information about past earthquakes so that whether you are going with agencies which are listed over here or whether, in addition to those agencies, you are also referring to some additional literature which is also presenting historic earthquakes.

So, you can refer to more and more agencies to ensure that none of the events which have actually happened will be missed in your earthquake catalogue. In the background, when you are going through these agencies collecting the data, you are basically developing a dataset of which particular year, which particular latitude, longitude, which magnitude, when a particular earthquake of what focal depth has happened, and potentially what was the focal mechanism of that earthquake. So, once you start analysing it, you see in the end, you will come across a large number of datasets or a large number of earthquakes which have happened. One can refer to Lecture 9 also, so there I have shown some seismotectonic maps where information about past earthquakes was clearly highlighted. So, if you collect past earthquake information and superimpose it on a map where the site is located based on latitude, longitude, and the radial distance around the site within which one is interested to develop an earthquake catalogue, if that particular map is ready, one can simply superimpose the past earthquake information which is collected from these sites, and then you can see what is the distribution of earthquakes in that particular region.

Now this is about collecting information about past earthquakes. Here it is very clear that whenever we are collecting information from more than one source, while on one side we are ensuring that we should not leave any one event which has actually happened to be a part of the earthquake catalogue, at the same time, because we are collecting for the same region, past earthquake information from more than one source, there are definitely chances that one event which has actually happened might be repeated, might be reported by IMD also, GSI also, USGS also, ISC also, GCMT catalogue also, or any of these more than one catalogue or resources. In such a case, once you are developing a catalogue, definitely you will be having more than one particular event or many numbers of events which have actually been reported in your earthquake catalogue more than once. Now, try considering that there is a reason in which, in actuality, four earthquakes have happened, but because of the repetition of events or collection of events from different sources, the catalogue consists of the same event multiple times rather than four events which have actually happened. You will end up in stating that this particular region has experienced 12 events. In comparison to four events which have actually happened, if you came to know that 12 events have happened, then suddenly the question comes to mind: suddenly there is a significant increase in the seismic activity of a particular region.

In actuality, there is no increase in seismic activity, but if you have not removed those dependent events or you have not removed those repeated events from the earthquake catalogue, you will mostly end up in overestimating the true potential of a particular region or overestimating the seismic activity of a particular region. So, this is one scenario. The same way, many more things are there which will help in processing this earthquake catalogue such that this kind of repetition of events or other complications which may arise if you do not treat the earthquake catalogue properly. So how that has to be dealt with, we will discuss these in the coming slides. So, for the development of the earthquake catalogue, now we have collected past earthquake information so far. Now we have to develop this earthquake catalogue. That means now whatever earthquake catalogue or database I am going to develop is going to give me true information about seismic potential, maximum magnitude of the earthquake, and even in terms of focal depth distribution, even in terms of dominating fault mechanism also, and of course, you will continue this to determine the seismic activity and true potential rupture characteristics of a particular region. So, a lot of applications or requirements are there which can be fulfilled once a particular earthquake catalogue is developed.

So here, as I mentioned, you can collect information about past earthquakes from multiple sources. Since you are collecting from multiple sources, there are chances that the same event might be getting repeated more than one time. Definitely, that will result in overestimation of the true seismic potential of a particular region. In such a case, these duplicate events—duplicate means one was the event which has actually happened and a similar event has been repeated more than once because the same database, the information, or past earthquake you are also collecting from GSI, you are also collecting from IMD, you are also collecting from NDMA report, you are also collecting from USGS—so the same event which has happened once but is getting repeated 3 times, 4 times. So, one event might be correct, and the rest all are duplicate events. So, these are not actually the events which have happened but are other duplicate events which are being reported because you are collecting data from more than one site. So, these duplicate events are there which must be removed; otherwise, you will end up in overestimating the true potential, and it is not like overestimating is okay because later on, you may use it for the design of different utilities; you may also help in determining the ground shaking surface ground motion scenarios. So certainly, this will have a multiple-fold impact on your design parameters. So, one cannot continue with the duplicate parameters and determine the true potential or seismic activity of a particular region.

So, in general, not all the earthquake magnitudes— in addition, we discussed about multiple events—so one is the actual event and the other is duplicate events. In addition, whenever we are collecting data about different sources and even in different times, like from 1980 or from 1985, the majority of the data is available in one magnitude scale. Before 1985, data is available in a different magnitude scale. So that means, though you are collecting data from different sources, data is also available in different magnitude scales. As we discussed in our earlier lectures, the recording of earthquakes can be in local magnitude or rectilinear magnitude scale. Magnitude can also be determined in terms of surface wave magnitude, body wave magnitude, and then very recent moment magnitude. So, again, to look at the entire earthquake catalogue collected from understanding the true potential, we should have all the past earthquake information on the same scale. So that is called homogenization. In homogenization, what we will do is convert all the data—whether it was reported in body wave magnitude, local magnitude, surface wave magnitude, or moment magnitude—to one particular scale.

Mostly nowadays, we convert every magnitude to seismic moment magnitude or M-W scale. So, one can refer to different correlations; one can explore literature to come across the correlations which have been developed across the globe. Even if you are interested in doing a region-specific study, you can again search for region-specific correlations. Many times, such correlations are available at the regional-specific level. If not, then one can refer to regions which have similar seismic activity across the globe and other tectonic setting comparisons. Also, if there is similarity, one can adopt correlations for such terms of conversion from different parts of the globe. Now, here, just to quote, there is a correlation which is given; again, of course, this correlation is also applicable to a certain range of magnitudes. Using this correlation, the earthquake catalogue which is available in body wave magnitude can be converted to moment magnitude.

$$M_w = 0.85 \times m_b + 1.03 \text{ (Scordilis 2006)}$$

$$M_w = 0.67 \times M_s + 2.07 \text{ (Scordilis 2006)}$$

Similarly, if it is given in surface wave magnitude, you can convert it to moment magnitude. So, applying these correlations, and similarly for local magnitude also, one can refer to some correlations. And, of course, when you are using this particular correlation, one has to also refer to what is the range for which this particular correlation is applicable. What is the range for which this particular correlation is applicable? One has to only apply the correlation in the range in which the correlation you are going to use is valid. So that is how we have. Simply, more than these two correlations which are available, even for global scale, even for regional scale, one can refer to those correlations and convert the data which is reported in different magnitude scales to a uniform magnitude scale or the same magnitude scale, which in this particular case is moment magnitude scale. So, before using an appropriate correlation, one has to make sure that the correlation which you are using is actually applicable to that site of interest.

Same way, the correlation you are using is applicable to that range of magnitude which is available in your earthquake catalogue. So, using these two pieces of information, one can definitely refer to and select many more correlations and pick up the most appropriate correlation which can be used for homogenization of earthquake catalogues or for conversion of earthquake catalogues from different magnitudes to the moment magnitude scale. Now, removal of duplicate events, as I mentioned, now you have converted all the magnitudes to the moment magnitude scale, but still, there are duplicate events which are there. If you do not remove those events, you will end up in overestimating the true potential of a particular region. Now, duplicate events can be identified from the catalogue by observing that there are events which are happening almost on the same date. After date, you go to the location, of course, the location-wise if you say in terms of latitude and longitude, of events which—some of the events are happening on similar dates, even latitude and longitude-wise, also are happening in closer range. Mostly, it will be exactly, or maybe you can refer to what is the range in which one can refer to as a similar event.

In addition, if you refer to the magnitude value of such events which have happened almost at the same time, at the same location, even the magnitude is the same. So, all three conditions—that means the date of occurrence, the time of occurrence, the location of occurrence, and even the magnitude of those earthquakes are almost matching—are clearly giving you a hint that this is not certainly that at one place more than once the same event has happened on the same day. Rather, it is like the event has been repeated because it has been collected from different sources. After identifying different duplicate events, only one event, which generally we say, like if 10 events are there which are exactly falling at the same location and that happened at the same time, then the event which is generally corresponding to the maximum magnitude, suppose even magnitudes are different—I mean all the duplicate events are having a difference in magnitude of 0.1, 0.2—then the magnitude of the event which is having the highest magnitude, you consider that as the main event and the rest of the events you consider as duplicate events.

So that is how one can remove duplicate events. Firstly, you find out similarity in terms of location, in terms of time of occurrence, then in terms of magnitude. So, magnitude, as I mentioned, 0.1, 0.2 difference, you can observe. But if there is similarity in terms of location and time of occurrence, one can separate those events, and among those events, the event which is corresponding to the maximum magnitude is generally considered as the actual event, and the rest of the events are considered as duplicate events. This can be removed from the earthquake catalogue. The information about the past earthquake left in the catalogue can be utilized to understand the past seismic history of the region, which is primarily related to what is the seismic activity rate of a particular region.

Now, you have removed the information about duplicate events, and the earthquake catalogue is also homogeneous. Now it can be used to understand about what the seismic activity rate of a particular region is or, at times, we can also forecast what is the return period of different earthquakes if you go to completeness analysis, which we will discuss later. Then, what is the maximum magnitude which has occurred in a particular region? So, in the last 50 years, 60 years, 100 years, if one has not witnessed an 8-magnitude earthquake but while collecting data for historic earthquakes you came across another event which was of magnitude, suppose, 8.5, 8.6, certainly it will raise an alarm. Though my region of interest has not experienced any earthquake of above 6.5, 6.7, historical records say that even this particular region is capable of producing an 8.7 magnitude earthquake. So, that is going to give you what is the true potential of seismic activity in a particular region.

Now, whether this magnitude is going to get repeated or not, one has to take a decision and appropriately, one will take with a suitable probability of occurrence in the hazard assessment. So, earthquake catalogue de-clustering—de-clustering generally we use so that once, even after removing duplicate events, there will be some events. Generally, whenever there is building up of strain energy, there will be some shocks which might be happening before the main shock. Similarly, there will be some events which will be a resemblance of redistribution of seismic energy at the source after the actual event has happened, which are generally referred to as aftershocks. So, after you have removed de-clustered duplicate events, again in your earthquake catalogue, there are some events which are not actually independent. That means some event has happened before that particular event has happened; there were some small, small foreshocks. So, those are not actually representing the seismicity of a particular region because those are an indication that some larger earthquake might happen at a certain time.

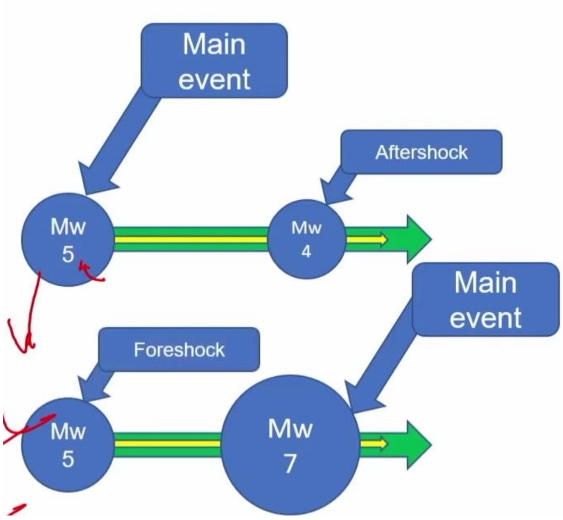
Similarly, whenever some aftershock has happened, which is again the redistribution of energy after a main shock has happened, so whether you talk about aftershocks or whether you talk about foreshocks, these are basically considered as dependent events of the main event. In other words, it is like these events have happened because one main event—whether it is about to happen or had occurred in the past. So, these events are again considered as dependent events. If we do not remove aftershocks and foreshocks, again, very much similar to duplicate events, we will end up in overestimating the true seismic potential of a particular region. So, then we will go for de-clustering of the earthquake catalogue—that means removal of dependent events and only taking into account main events or independent events. So, independent events or main events are the events which are assumed to be mostly caused by tectonic loading.

So, these are the governing features which are leading to the cause of independent and main events. If you talk about dependent events, these are the events which might be related to static or dynamic stress change. It might be because of after-slip reaction of the fault plane or any other mechanical process which actually releases whatever pending energy was there before there is subsequent building up of strain energy for the next earthquake event. So, these are dependent events, and the previous one was the main event or independent event. The process of separating dependent events from independent events is called de-clustering. So, generally, it is very important to separate those events so that now, once you have removed dependent events, you have also removed duplicate events, and now the earthquake catalogue that is available with you consists of each event which is independent in itself. The repetition of each of these events has to have some understanding about the seismic activity of a particular region of interest.

So, independent events can help us to find out the relation about the long-term seismic hazard of a particular region. Similarly, dependent events can help us in understanding the potential aftershock after a large magnitude earthquake, and this can also help in short-term earthquake occurrence understanding. So, de-clustering—there are different ways based on which one can identify where is an independent event and where is a dependent event. The window method, which is mentioned over here, is very popularly used. So, here one can refer to the window method, and then I have given some references to some of the papers based on which one can refer to the window method. Different correlations have been given based on which one can pick up whether what is the spatial window, what is the temporal window, within which if a particular event is falling, you call that particular event as a dependent event. Consider the equation which is given over here.

$$t_s = e^{-2.87+1.235M} \text{ and } d_s = e^{-1.024+0.804M}$$

If I pick up a particular event of magnitude M, now put it in this particular equation, you will get what is the temporal distribution within which, if another event has happened, that might be a dependent event of this particular magnitude M. In addition, we will also find out what is the spatial distribution. So, from d_s, we will try to find out the same event which has shown some dependency with respect to time if it is also falling within the spatial or distance window of the same event. Suppose I am having an event of magnitude 6. I am interested to find out what other events are there which can be considered as dependent events of this 6-magnitude earthquake. I will put magnitude 6 over here also, and here also, then try to find out within a particular d_s distance what additional events have happened. These events might be dependent events of the 6-magnitude earthquake. In order to further qualify it, again, I will determine the t_s value. So, within that particular time window, all the events which are within d_s will be considered as dependent events of the magnitude 6 event. Similarly, if after the 6-magnitude, also some bigger earthquake has happened, again, the bigger earthquake will try to determine the value of t_s as well as d_s. It may happen that for the next event, the 6-magnitude earthquake becomes a dependent event. So, because of the 6, smaller magnitude earthquakes being removed, now, because of further larger magnitude, within whose d_s and t_s values even 6 magnitude earthquake is also identified as a dependent event, now that will also be removed. So, all depends upon what is the distance and time windows of the event of interest with respect to which you are trying to quantify what are the dependent events. So, finally, using this window or other methods, one can refer to identify what is the independent event or main event and what are its dependent events which are supposed to be removed in the process of de-clustering.



So, the same thing we can see over here. There is a temporal window; there is a spatial window. Consider an event of magnitude 5. Based on these guidelines which are given in the previous slide, I can find out how much is the spatial distribution of an event which should be called a dependent event of this magnitude 5 event. In addition, we will also try to find out what is the temporal window within which an event, if it has occurred within this spatial window, will also be classified as a dependent event, and at the same time, magnitude 5 has occurred. So, in the first case, you see a 4-magnitude earthquake has happened which is falling within the temporal and spatial window of magnitude 5. Now, this earthquake, in the first case, has happened based on this understanding. As I mentioned, if there are multiple events, generally the event corresponding to higher magnitude will be classified as the main event because that will have more effect in terms of hazard assessment. So, this becomes the main event, and magnitude 4, because it has happened after, can be called an aftershock. In the other case, there was a magnitude 5 event based on which you started finding out magnitude 4 as an event which is a dependent event of magnitude 5. Once you went to another earthquake which has happened again in the same, or when you start analysing other earthquakes' spatial and temporal windows, you found out that this magnitude 5, which earlier was an independent event, now will be classified as a dependent event because it is falling within the temporal as well as spatial window of the magnitude 7 event. Now, these two may be correlated; these two may not be correlated also. That means this magnitude 5 event and this magnitude 5 event may be the same event or they may be two dependent different events happening in two different geographical locations. So, in the first case, because a 4-magnitude earthquake was identified as a dependent event of magnitude 5 and also occurred after magnitude 5, it is called an aftershock of the 5-magnitude earthquake. In this particular case, in the second case, a 7-magnitude earthquake, which actually happened after the 5-magnitude earthquake, but based on the spatial and temporal window, classifies this magnitude 5-earthquake as a dependent event of the 7-magnitude. In this particular case, magnitude 5 will become a foreshock, and magnitude 7 will become main event. And after the 7-magnitude, there can be another earthquake of smaller magnitude which can be classified as a dependent event or independent event depending upon whether it is falling within the temporal and spatial window of the 7-magnitude earthquake or not.

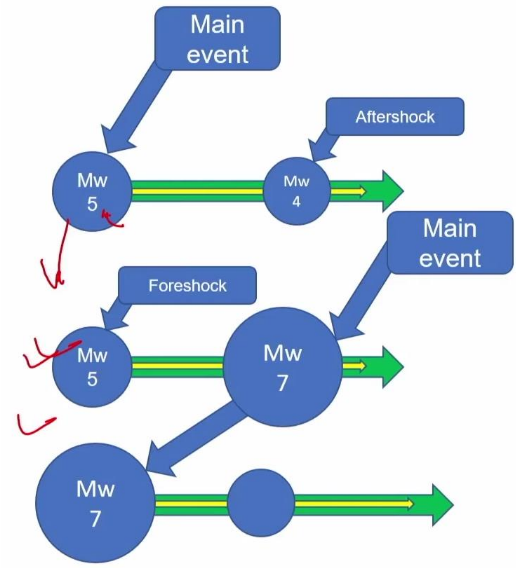


Fig.1 Windows method of declustering

So, you can see more than one event is there, so because of the 7-magnitude, the 5-magnitude earthquake was declared as a dependent event. Because of the 7-magnitude, later on, even if this was the main shock, there might be some aftershocks because of this particular earthquake as happened in this particular case. So, another event which was maybe 6 magnitude, 5 magnitude, 4 magnitude will now become an aftershock of the 7-magnitude earthquake. So, in this particular case, the 7-magnitude earthquake has magnitude 5 as a foreshock and subsequent events as aftershocks.

Now, there are clustering methods again based on which you can refer to and find out what are the events which are basically defined as dependent events. This is another method which is widely used to find out the spatial as well as temporal interaction of one event with respect to another event. As mentioned over here, two events are considered in a cluster when a new event is associated with another event which was previously associated with the cluster. Then this particular new event will also be a part of the cluster, and then the cluster will start growing. Same way, if there are two events from two different clusters, and based on a later event, it is found that these two events are also linked with respect to each other. So, what we will do is, we will club these two events as well as the independent cluster of these two events, and then the cluster will grow. So, what all events are falling within that particular cluster corresponding to maximum magnitude, you call it as the main event, and the rest are generally classified as dependent events. So, that is called the clustering method. You have to find out the linking of the cluster based on the events which have been reported within a particular spatial and temporal distribution. So, in this particular case, as far as you are finding there is a linking between the clusters, the cluster keeps on growing. If you do not find any kind of linking, smaller clusters will be there all throughout, and within each cluster, there will be one main event, and the rest will be dependent events, which, based on the de-clustering process, will be removed.

In particular, the largest event, or the largest magnitude event, as I mentioned, why largest magnitude, because if a larger magnitude is there, that will have more effect in terms of hazard assessment or even in terms of damage because all these earthquakes are more or less happening at the same time and more or less in the same location. So, if we discuss in terms of distance or in terms of time of occurrence, that is not changing between the dependent event and an independent event; the only thing which is changing is a slight change in the magnitude. So, to consider the worst scenario, we will go with the magnitude which is corresponding to a higher value as the main event, and the rest of the events are dependent events and will be removed. So, other events are considered as dependent events and later on, in the process of de-clustering, one can refer to remove those events. So, now you are having earthquake information, you started collecting, then remove the duplicate events based on the location, size, and magnitude. Later on, you homogenize the catalogue, convert all the earthquakes into the same magnitude scale. After that, whether you are going with the window method or you are going with the clustering method, you have actually separated what are the independent events and what are the corresponding dependent events to those independent events.

So, after de-clustering, you will only have an earthquake catalogue which is homogenized and only consisting of independent events. So, more clusters—this is again completeness analysis. What is the meaning of completeness analysis? It is how much complete, how much information, which where I can say I have the complete information about the earthquake which is happening in a particular region. So, that is called complete information. That means if I am interested to find out the return period of a particular earthquake or I am interested to find out the seismic activity of a particular region, I have to have complete information. Unless I am ensured that the information which is given to me about past earthquakes is complete, I cannot accurately determine the seismic activity of a particular region. Given the example here is for accurate—firstly, for accurate assessment of seismic potential, one has to have confidence that the information, though I will be having an earthquake catalogue for 2000 years, but if I am asked, suppose before 1950 some damages have happened or some intensity maps are available, that is how information about earthquakes were available to me. So, definitely, in comparison to the time when recordings are there, a large number of seismic arrays are also available such that no earthquake event can be missed. Certainly, before 60 years, before 100 years, as you go deeper into history, the information about actual earthquake occurrence will be very limited; some damage might have happened, some field investigation might have happened, someone might have correlated with respect to the intensity scales.

So, this will go back maybe 100, 150 years, but beyond that, though earthquake information is available, whether that information about all the earthquakes is available will be highly uncertain. So, once we are trying to understand the seismic activity for the future, we have to have more confidence about the information which is available to us. That comes under completeness analysis.

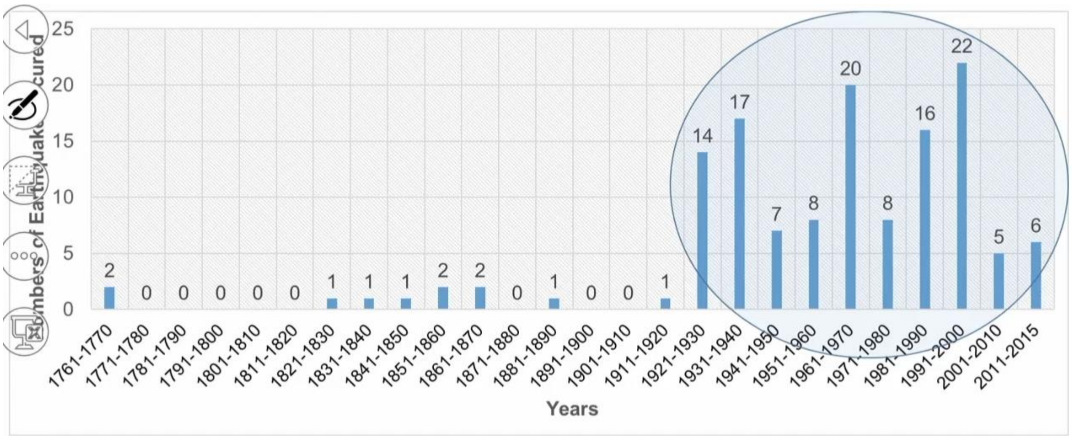


Fig. 2 Figure showing number of EQs occurred per decade since 1761 for a location

Then, over here also, one can see on the left-hand side, you are having on the x-axis the number of events which have happened in a particular region in every decade; on the y-axis, you are having cumulatively, I mean, how many number of events have happened. So, on the y-axis, you are having the number of events which have happened, and on the x-axis, you are having in which particular decade. Now, if we see very much similar to the current situation, 2015 onward, because we are having good distribution of seismic arrays, there are a number of ground motion recording instrumentation also available. So, you can say more or less I am able to detect each and every event, but before 1940, you see hardly there is any information about earthquakes; some years are there where even in one complete decade no event has been reported. Certainly, it is very unlikely that in 10 years not even a single event was reported, and on the other end, sometimes in the year 1991 to 2000, you are having 22 events. So, that does not mean that in this particular decade there was no event at all, but that also adds up that you do not have complete information about earthquakes that have happened, but because as a result of it, there are complete zeros in this particular decade, and not only zeros; whatever single digits are also mentioned, it might also happen that there were many events, but since we do not have any information about those events, we ended up in getting maybe one event, two events, three events like that. In such a case, if you go, let us see, since 1761, a total in the last 254 years, 134 events have happened as per this particular chart. Now, going with that particular logic, the number of earthquakes which are happening per year is 0.53. So, because I have taken the entire catalogue as complete, if I am interested to find out the frequency of earthquake occurrence, I ended up in getting 0.53 events. That means only 0.53 events per year are happening, collectively independent of magnitude. On the other hand, as I mentioned, from 1920 onward or 1930 onward, suppose there was more monitoring of earth-related earthquakes in a particular region, then you see in total 123 events from 1921 itself. So, in the last 94 years, close to 123 events, and in the last 250 years, close to 134 events. So, there is a significant jump in the number of earthquakes just because my information about past earthquakes is more accurate or a greater number of earthquakes which have actually happened in the past is known to me. So, that will give me more confidence about the earthquake catalogue which I am dealing with. So, the first one is definitely an underestimation, whether the second one we should go for or not, that we will discuss once one is done with completeness analysis with respect to magnitude and as well as with respect to time.

So, now see completeness analysis with respect to magnitude. Here we are interested to find out what is the minimum magnitude above which I can say that the information about past earthquakes is completely known to me.

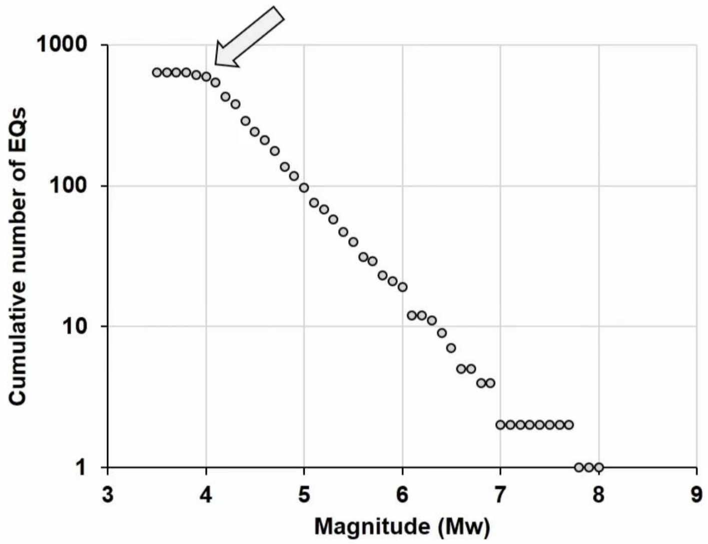


Fig.3 Cumulative frequency distribution plots

So, here what we have is a cumulative frequency distribution plot; that means the cumulative number of earthquakes of different magnitudes which are known to me is there on the y-axis, and the magnitude corresponding to those numbers is there on the x-axis. So, the maximum curvature method suggests where there is maximum curvature, corresponding to that particular point, whatever magnitude you are getting, this magnitude is basically the magnitude of completeness. Other methods are also there, the Wiemer and Wyss method, and many more methods are there. So, this is going to give you the minimum magnitude with which you can say, okay, corresponding to this particular magnitude, because we are more interested in larger magnitudes because that causes more damage also and even significant ground shaking also. So now I can say magnitude 4 is the magnitude with respect to the earthquake catalogue given to me, above which I can say the magnitude of completeness is there.

Similarly, with respect to time, so Stepp had given the method in 1972, which I am referring to over here. So, suppose x1, x2, x3 are the number of events which have happened in each time interval, just like I have shown in the completeness chart.

$$\lambda = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Now I am interested to find out what is the mean rate, so I can find out the mean rate. n is the number of bins through which this average number of events are available to me; I can determine the value of mean rate, and accordingly, I can determine the variance given by this particular equation.

$$\sigma_\lambda^2 = \frac{\lambda}{n}$$

So, I am having the mean value; also, I know how many bins are available or the time interval within which these x1, x2, x3 are given. It is corresponding to 1 year; that means now the number of bins which I had taken into consideration will be equal to the duration for which I will be analysing the data, which is T.

$$\sigma_\lambda = \sqrt{\frac{\lambda}{T}}$$

So, Stepp considered this particular variation follows a Poisson distribution, and then accordingly proposed that the standard deviation of such information will be equal to the square root of the mean rate of occurrence in a particular region, which is corresponding to 1 particular year divided by capital T, which is the total number of bins or the total duration for which the data is available.

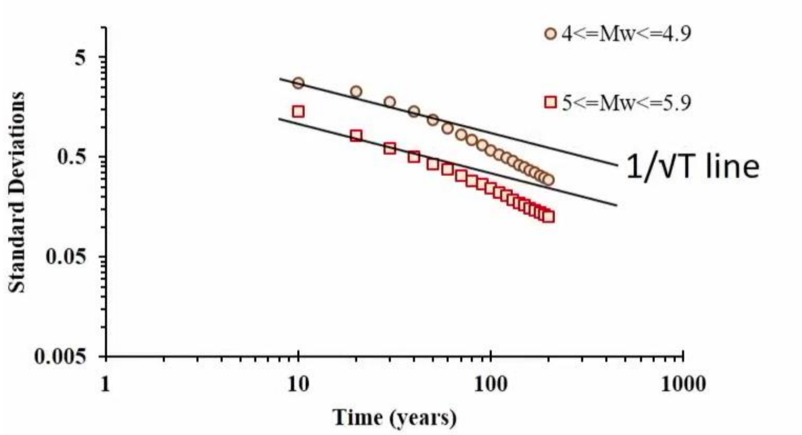


Fig.4 Standard deviation versus time interval plots for different magnitude classes

So, going with this particular part, if one is interested to find out the completeness duration, we can determine, based on the equation given in the previous slide, how much is the standard deviation corresponding to different time intervals for the last 10 years, 15 years, 20 years because the value of capital T keeps on changing, and remember when I say 10 years, that means from today 10 years in the back, from today 20 years, 30 years, 200 years in the past. So, I will be starting from this particular side; I will plot T versus standard deviation or sigma plot. In addition, I am also plotting another line which will be equal to 1 by square root T line, till the moment sigma versus T plot and the line which is again 1 by square root T. So, one side you are having T and the other side, rather than standard deviation, there will be 1 by square root T. Till the moment these two lines are parallel, or these two plots are parallel, I can say my earthquake catalogue is complete in that particular duration. Suppose in this particular case, these two are approximately up to this particular part are parallel, and after that, you can see there is a significant change. So, I can say starting from present 10, 20, 30, 40, 50 years, this might be developed for one particular magnitude. I can say for that particular magnitude, for which this particular plot is developed, the earthquake catalogue is complete for the last 50 years. Similarly, in this particular case, 10, 20, 30, 40, 50, 60, so last 60 years my earthquake catalogue is complete. The earthquake catalogue was having a magnitude of completeness developed based on the previous chart and corresponding to the last 50 years or 60 years, whatever information is available in my earthquake catalogue corresponding to the magnitude for which this particular plot is developed, as shown over here. This is corresponding to 4 to

4.9; this is corresponding to 5 to 5.9. So, I can say all the earthquakes which are in 4 to 4.9, if I take for the last 50 years, those are giving me complete information based on which I can determine my seismic activity. Similarly, 5 to 5.9 in the last 60 years, how many data are there, based on which I can determine the seismic activity of a particular region very accurately. Now, completeness with respect to time, you can also find out based on the cumulative visual method which was proposed by Mulargia and Tinti in 1985.

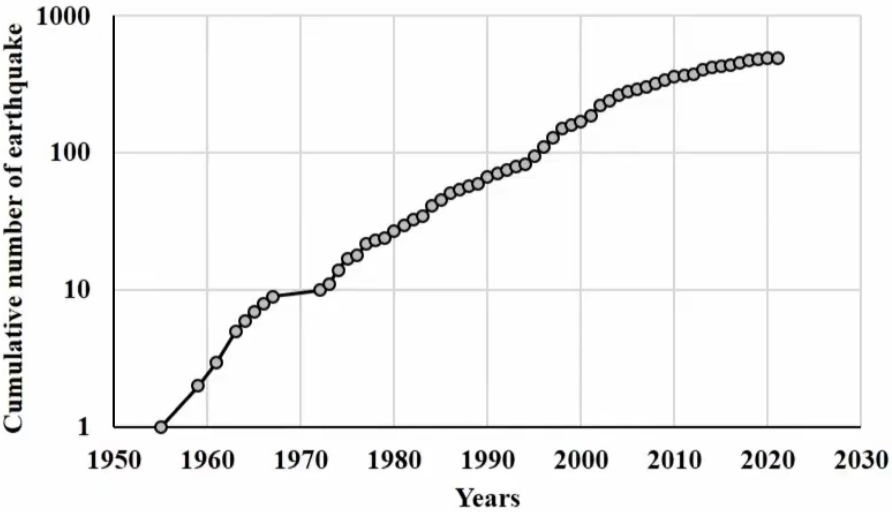


Fig. 5 Cumulative number of EQs vs the year of occurrence

So, again here you can see you start plotting cumulative number of earthquakes over the decade, and then suddenly you will see after a particular event there is, more or less, it is following a uniform trend, but there was some stability which you are getting in between the points. So, this particular duration, you can say after 1970, 1972 onward, my earthquake catalogue is more or less complete. So, this is another method based on which one can refer to the earthquake catalogue and determine its completeness.

Now, seismic activity. Now, we have de-clustered the catalogue which was already homogenized. Then, based on completeness analysis, I have found out that I need not analyse further based on the last 200, 300, 500 years data; rather, I will only focus on the data, which qualifies the completeness criteria with respect to magnitude as well as with respect to time. So, based on this, you will be having some number of events of different magnitudes. Using those events, just plot how many numbers of what is the magnitude and how many numbers of events corresponding to one particular magnitude and above it. That will help you in determining what is the cumulative frequency of different magnitudes per year occurring in a particular region of interest.

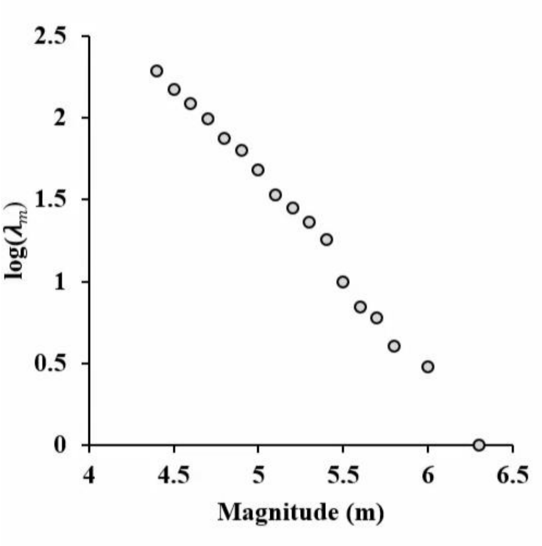


Fig. Gutenberg-Richter relation

So, log λ_m is basically giving you an indication about the logarithm of the annual rate of accidents or annual frequency of a particular magnitude and above it which are happening in a particular region of interest.

$$\log \lambda_m = a - bM$$

So, log λ_m equals a minus bM. Now, here you can see a is an indication of this particular part, which can also be interpreted as the number of earthquakes corresponding to the lowest magnitude; here it is given as 4. So, I can say the number of earthquakes corresponding to 4-magnitude, if the plot is given from 0 to maybe 7, 8, then the a value will represent the number of earthquakes of 0 and above magnitude which are possible in a particular region, and b is definitely indicating what is the rate at which different magnitude earthquakes are on average happening in a particular region of interest. So, b is basically an indication of seismic activity and b is an indication of the cumulative number of earthquakes of particular magnitude and above, usually referring to the minimum magnitude which you have used here in the development of the seismic activity plot. So, based on this, one can determine the seismic activity parameter.

Then, determination of seismic activity parameters, one can go with the least square method, where based on simply the plot between frequency distribution and cumulative number of earthquakes, one can determine what will be the a and b parameters as shown over here. So, least square method linear regression is done to find out the slope of frequency magnitude distribution and obtain the seismic activity parameter that is a and b. The advantage is least square method or LSM, is simple and easy to apply. It has also been observed that estimating the probability of the largest magnitude earthquake, the least square method is more suitable. However, as the cumulative number of earthquakes is primarily correlated to higher magnitudes, some people have told many researchers have highlighted that LSM should not be used for cumulative data.

So, similarly with respect to that, the maximum likelihood method is also proposed, based on which one can determine the probability density function which can be correlated with respect to mean magnitude and minimum magnitude of interest, taking into account some increment in terms of magnitude values. One can determine the value of b, usually taking the increment to as small as maybe 0.1, 0.2, depending upon how much earthquake event in your complete earthquake catalogue is available to you. So, using those parts, again using the governing equation which I mentioned over here, you can determine how much will be the value of seismic activity parameter b.

So, that is all related to the determination of seismic activity parameters, as well as, before you start developing the seismic activity parameter, how the completeness should be done with respect to magnitude and with respect to time. Similarly, how declustering of earthquake catalogue to identify independent events or main events and to remove independent events or main shocks or aftershocks such that in the end you will get a catalogue which is complete in itself and directly can be used using the maximum likelihood method or least square method to determine how much will be the seismic activity of a particular region. So, if we continue the discussion related to lecture 9, we understood how to identify seismic sources. Now, based on this, we have also gathered an earthquake catalogue which is complete in itself. So, this particular earthquake catalogue, if you superimpose on seismic source maps, that will help in developing the seismic tectonic map of a particular region of interest. In further lectures, we will also see how this information about seismic sources as well as past earthquakes collectively can be used to determine what is the most likely or what is the worst scenario seismic hazard at your site of interest because that is the sole purpose to determine because of an earthquake or its associated information known to a person or to the analyst, how is the expected level of ground shaking at a particular site of interest.

So, thank you everyone. We will continue this particular discussion in the next class. Thank you.