Applied Seismology for Engineers

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Week – 03 Lecture - 01

Lecture – 05

Hello everyone, myself Dr. Abhishek Kumar. Welcome to lecture 5 of the course Applied Seismology for Engineers. In today's lecture, we will be covering an important topic that is seismic gaps. So far, based on our understanding and the lectures which we have discussed prior to this particular lecture, we have an understanding that there are different layers that exist at different depths within the earth, and depending upon the physical properties as well as the temperature variation at different depths, there is the generation of convection currents. Primarily, because of the convection currents which are generating in the mantle, that will result in movement or development of thrust at the base of the crystal medium, as a result of which the medium of the crust will start moving in different directions. This can also be witnessed on the surface in the form of continental crust as well as oceanic crust.

If we bring the GPS-based measurements into account, we can see that across the globe there are different plates which exist, and such plates are moving in different directions at different rates. So, depending upon the zone where the two plates are coming in contact with each other, there can be a possibility that the two plates are converging towards each other, or the two plates are diverging away from each other, or there is a slight pass movement between the plates. Depending upon the stresses which are going to develop or mobilize at the interface between the two plates which are in contact with each other, there will be the development of strain energy which is getting accumulated at the fault interface. Once the strain energy accumulation exceeds the in-situ capacity of the medium, the medium will undergo rupture. There can be the generation of heat, there can be the generation, there can be melting of the material, there can be rupture taking place. Subsequently, there will be the generation of seismic waves from the source, and when these waves start moving away from the focus or from the epicenter and reaching different locations, you may experience, if you are located maybe 50 kilometers, 100 kilometers, or 150 kilometers away from your epicenter, with some delay of the order of a few seconds, you may see some kind of shaking experience at your site of interest. This shaking is basically the response of your system, whether it is a building, it is a ground, how the system is going to respond to the seismic waves which have been generated from the source, modified by the propagation medium, and then reaching subsequently to your site of interest. Now, whenever we are interested in finding out the seismic loading conditions, because when we discuss seismic waves, the primary objective here, as far as this particular course is concerned, is to identify what is the potential loading in a particular region, which is going to be experienced by a particular structure. It can be at bedrock medium, it can be at surface medium, or subsequently, you can generate ground motion or response spectra for a particular building as far as earthquake-resistant design is concerned.

So, whenever we target to carry out such studies, we will be interested in finding out what are the potential locations which are actually capable of producing earthquakes. Generally, we take into account the faults which are located within 200, 300, 400 kilometers radial distance from your site of interest, because even if there is some seismic source located at a 400-kilometer radial distance, and if this particular source is capable of producing earthquakes, maybe major to great earthquakes, certainly a great earthquake that happened at 400 kilometers can also cause significant ground shaking, taking the propagation path effect and local site effect into account. Once this modified ground motion reaches your site of interest, the building may experience severe shaking, the soil undergoes loss of strength, or there can be significant amplification in the ground shaking between bedrock and the surface. As a result, the earthquake loading, which is going to be transferred from a distant earthquake, also can cause severe ground shaking, and subsequently, if the building is not designed properly, it can lead to partial damage to complete collapse of the building. So, in order to find out what are the potential loadings which are going to come because of earthquakes happening in the surrounding regions, one has to find out what are the potential seismic sources.

In addition to that, we will also find out what are the potential earthquake magnitudes which have happened in the past. Usually, past earthquake information one can collect from different sources, maybe from the Indian Meteorological Department, United States Geological Survey, Northern California Earthquake Data Center, and many more such repositories are there, based on which, depending upon your site location and the radial distance within which you are interested in finding out information about past earthquakes, you can go through these sites and collect more and more information. So, once you have information about faults, information about the source as well as events, you can prepare a seismic tectonic map that will help you in understanding what are the seismic sources which have produced maybe magnitude 4, magnitude 5, 6, 7, 8, 8.5 in the epicentral region of 400 kilometers, 300 kilometers with respect to your site as the center. And then we can determine, in seismic hazard analysis, we will discuss how one can determine the expected level of ground shaking because of potential earthquakes. One is potential earthquakes, and the second one is the worst scenario earthquake.

So, that we will discuss in coming slides. Now, whenever we are interested in finding out what are the potential sources which can produce earthquakes, usually that particular information is significantly dependent on what information about historic earthquakes or the earthquakes which are known to us before actually recording ground shaking started, recording of ground motion has started. So, any earthquake which has happened before the recording of ground vibration has started, you can refer that to a historic earthquake because there is actually no record available. There is evidence suggesting some damages have happened to that particular earthquake and how much damage has happened that one can refer to different intensity scales, and the kind of damage which has been experienced by people living in the epicentral region and at distant locations as well. Sometimes there are trained people who can also help in determining the intensity of ground shaking during a particular earthquake. So, using the intensity values, one can determine the isoseismal maps, and again, using the isoseismal maps, if later on, you are having isoseismal maps as well as ground shaking, one can establish correlation between the two and then try to find out how much probably the level of ground shaking in terms of peak ground acceleration, in terms of spectral acceleration might have been generated during a particular earthquake which happened maybe 50 years, 100 years before present. So, that will give you an understanding about even though there was no information about ground motion records, but using the information available from the isoseismal map or intensity map, you can have significant understanding about the earthquake and its damage characteristics.

Now, when we are referring to faults, when we are referring to our understanding about seismic activity in a region, solely it will be governed by two factors. One is the seismic sources which are available in a particular region. Secondly, what is the information about past earthquakes known to us? We often come across the information that such and such earthquake has happened at some place, which triggered a lot of damages, even though the site was very vulnerable to earthquake-induced damages, but still, during a particular earthquake, the amount of damage that happened is significantly larger. That means, though you have some understanding about faults, some understanding about past earthquakes, maybe 100 years, 150 years, still there is some information that is lacking with us, which will help in understanding the correct seismic activity of a particular region. That means once the complete information about past earthquakes is known to us, then we can say how many 4 magnitude, 5 magnitude, 6 magnitude, and subsequently different magnitude earthquakes can happen, maybe per year across your entire seismic tectonic province. But certainly, the confidence of this particular estimation also depends on how much data about past earthquakes is known to us. If we discuss the correlation between the frequency of earthquake occurrence and the magnitude of the earthquake, we will understand that as you go for larger and larger magnitude earthquakes, the frequency of those earthquakes to occur in the same location will significantly reduce. It can also be understood from the analogy that with larger magnitude for an earthquake or larger magnitude will happen, it requires a large amount of strain energy to get accumulated and subsequent release of seismic energy. So, in order to accumulate the seismic energy which can produce a 3-magnitude earthquake, certainly you will require less time.

Consider that 2 faults are there which are slight past each other, as a result of which there will be some strain energy generating at the interface. So, in order to cause a 3-magnitude earthquake, you require a significantly low value of strain energy. That is how, so if some process is going on such that every 6 months, every 7 months, the strain energy which is getting accumulated is capable of producing 4 magnitude earthquakes, and the conditions in presence of barriers and other complexities are not there, then you can experience 4 magnitude earthquakes very frequently. On the contrary, if you are talking about maybe 7 magnitude earthquakes, 8 magnitude earthquakes, the amount of strain energy required, the amount of seismic energy which will be released during those earthquakes, will be manifold higher in comparison to a 3-magnitude earthquake. So, consider that situation that an 8-magnitude earthquake is going to happen, and/or a fault which is actually having a slight past nature. Now, this particular fault block will require maybe 500 years, 600 years, maybe 1000 years, 5000 years, such that a continuous accumulation of strain energy along this particular fault segment should be sufficient enough to cause, to trigger, seismic energy equivalent to an 8-magnitude earthquake.

The other way of seeing this particular problem is, if we have complete information for the last 100 years, we can be more confident about lower magnitude earthquakes, but as you increase the magnitude of the earthquake, more uncertainty in terms of its repetition primarily during the design life of the structure is coming into the picture. So, that means if we are having some data, let us say for the last 100 years, 200 years, we will be more confident about 4 magnitude earthquakes, 5 magnitude earthquakes return period in comparison to maybe an 8-magnitude earthquake, because hardly you will see a maximum of 1 or 2 earthquakes of maybe 8-magnitude, and that too are happening at two different locations, not at the same fault. So, based on one earthquake alone, it is very difficult to find out how frequently this earthquake is going to get repeated. This is one scenario. The second scenario is, if this particular 8 magnitude earthquake, which considering the rate at which strain energy is getting accumulated at the fault block, the situation is like it can happen only once in 700 years, 800 years, and this 800 years' time is falling outside the 150 years, 120 years of the duration from which the earthquake catalog is available to the user. That means at present, I am having data for the last 150 years, but an 8-magnitude earthquake in my region of interest has happened maybe 170 years back. So, certainly, that particular earthquake magnitude will not be part of my present catalog, and if I even monitor, if I try to forecast for the last maybe next 400 years, 500 years, then there are chances because this earthquake of 8 magnitude can repeat every 500 years. So, though it happened last maybe 160 years, 170 years, and it was not a part of your earthquake catalog, there are more chances that in 300, 350 years, again in the future, this earthquake can cause repeated damage. Now, this was a critical example where the duration of the earthquake catalog and the duration when an 8-magnitude earthquake happened was very close.

That means an 8-magnitude earthquake happened 150 years from the present. However, the earthquake catalog is there till 120 years. So, there is only a gap of 30 years. Another possibility which may arise is you are having an earthquake catalog of 120 years, and an 8-magnitude has earthquake happened just 480 years from present. So, this is like though we do not have supporting information at present, these are historic earthquakes. So, in order to understand historic earthquakes, one has to have detailed information about paleo-seismic investigations, and historic earthquakes, to understand the seismic activity of each of the faults, rupture characteristics, and many more information which may give you a complete picture, but it is not available at present. So, that is the scenario where an 8-magnitude earthquake has happened maybe 480 years from present. That means, considering that an 8-magnitude earthquake can happen once every 500 years. Your site, though as a designer, though as a person who is dealing with the estimation of earthquake magnitude, the information that the site can also experience an 8-magnitude earthquake is not there. So, certainly, that may or may not be taken into account, but that does not deny the fact that an 8-magnitude earthquake actually occurred at a particular site and keeping that the return period of that particular earthquake is 500 years, your site may experience another 8-magnitude earthquake in the next 20 years. So, there was no mention of an 8 magnitude earthquake in your last 100 years, 120 years, 150 years' earthquake catalog because it has not happened, or you have not so far collected information in the literature or based on your field investigation suggesting an 8 magnitude earthquake actually occurred at the site, but later on, someone does information analysis related to historic earthquakes and finds out, okay, 400 years, 480 years from present, there was an earthquake of 8 magnitude.

Now, you have constructed a building that is having a tentative life of 35-40 years, taking into account that an 8-magnitude earthquake is not going to happen to the building, and then suddenly, in the future, 20 years from now, there is an 8-magnitude earthquake which happens in your seismotectonic region, which will trigger significant ground shaking. Since the building is not designed for that particular earthquake loading, it may experience minor shaking, it may experience major cracks, or complete collapse, depending upon what is the loading you have designed the building for and what is the loading that is going to generate because of an 8 magnitude or 8.5 magnitude earthquake. So, that means as far as information about the return period of the earthquake is concerned, you can always gain more and more confidence in terms of return period only when you have more and more information about historic earthquakes. At the same time, keeping in mind that the higher the magnitude of the earthquake, the more time it will take, there will be a longer return period for that earthquake to occur to get repeated during the design life. So, there will be a chance that 7-magnitude, 8-magnitude earthquakes, at present, your earthquake catalog is not showing, but might have happened in the past. So, taking that possibility also into account, we have to see what best we can do in order to find out earthquake loading conditions.

So, today's topic, seismic gap, basically suggests that keeping the rupture characteristics, keeping the current tectonics at different segments of the fault, there can be a possibility that once we discuss the possibility that considering the longer return period for larger magnitude earthquakes, such an event is not present in your earthquake catalog. Seismic gap suggests that in terms of space, in terms of time, there might be some locations which have not triggered an earthquake in the last maybe 200 years, 300 years, 400 years, or some sections are there which are showing almost very low seismicity in comparison to surrounding regions. So, there might be something additional going on in those particular locations, certainly, one cannot consider that those locations or segments of a particular fault, where other segments are quite active and this particular segment is inactive, will not produce earthquakes. That is why it is called seismic gaps.

So, basically, there are events, there are faults on which such events are happening, and suddenly you will realize that there are events happening on one side of the segment and on the other side of the segment repeatedly, and there are some segments which are actually lying dormant with no sign of seismic activity, at least in the last 100 years, 200 years, because you do not have complete information prior to those 200 years. So, the question comes: why are such seismic gaps important? Now, these are important because these are segments of faults which at present may not show some seismic activity, but other segments on the same fault exist which are also showing seismic activity in terms of maybe moderate earthquakes, in terms of larger earthquakes. So, one has to take into account that it is not actually an inactive portion of the fault; it is rather a gap. Gap means some gap is pending, which is actually prolonged, which is actually pending for any kind of major to great earthquakes in the near future. So, the first discussion was like we do not have complete information in terms of historic earthquakes because the return period is significantly larger than the size of the earthquake at log one has. Second one is, during the last 500 years, there has not been an earthquake. In the last 500, 1000 years also, there has not been an earthquake because, considering the seismic activity of the fault, a 7-magnitude earthquake, 8-magnitude earthquake may happen once in 1500 years, 2000 years. Now, certainly, either you will—I mean, you cannot wait for 2000 years to correctly understand the seismic activity, or you will not have the complete information of what has happened on each and every fault in terms of repetition of different earthquakes. So, in such a case, there will be some seismic gaps because, of course, ground deformation is happening; fault movements are also a continuous process. So, there is some other activity happening at those particular segments which are identified as gaps. Importantly, these are identified as gaps, so that means these are the locations where potentially major to great earthquakes are due. Yet, there is no complete information on when this earthquake is going to come, but considering the size of the earthquake, which is like 7, 8, and the kind of damage which, if an earthquake in this particular gap happens during the design life, what sort of damage scenario it can create, what kind of devastation it can create.

So, we cannot completely ignore the segment which has not shown any sign of seismic activity in the last 300 years, 400 years, considering the earthquake rate law. So, those segments which are actually showing complete inactivity for the last 500 years, but in addition to those, based on current GPS measurement, triangulation survey, there are some indications that some other seismic activity, strain energy buildup, in terms of thermal images also, that which directly or indirectly suggests that there are some seismic activities or strain energy which is getting built up in those locations. So, one cannot deny the fact that these locations will certainly show some sign of activity in the near future. Thirdly, once we go for hazard analysis, particularly when we are thinking about hazard with respect to the probability of its occurrence, we will see that the larger the magnitude of the earthquake, though it can cause significant ground shaking, the chance of that earthquake to get repeated during the design life of the structure will be relatively less. So, the probability of larger magnitude is less, but at the same time, if these earthquakes are going to come, these may cause devastation. So, one has to have relative judgment about whenever we are talking about seismic gaps, whether to take the seismic gap and what is the worst scenario corresponding to those seismic gaps, whether it is justified to take those worst scenarios and perform seismic hazard analysis, or you can completely ignore those seismic gaps and go ahead with the seismic hazard analysis. So, this is one thing where one has to make a suitable decision.

So, seismic gap, as I suggested here, we will be discussing in today’s lecture, that is lecture 5. So, we have already discussed that the earth’s crust is divided into multiple layers or plates which are moving with respect to each other. Primarily, when we discuss about earthquake occurrence, we will be more focusing on convection currents which are actually generated in the mantle region. As I mentioned earlier, as you go into deeper regions, though there are convection currents, their contribution related to the movement of the plate is significantly low. So, we can avoid such contributions to the occurrence of the earthquake. So, building up of strain energy is a continuous process. Somewhere it will happen slowly; somewhere it may happen very fast, depending upon the tectonics and depending upon the rate at which the two plates are moving, as well as in addition because it is not only that just two plates are coming in contact with each other. There might be some other activity happening in the peripheral region or there might be other plate boundaries existing with different rates of convergence or divergence in the epicentral region. So, we have to take those also into account and then see what is the rate at which building up of strain energy is happening and subsequently, up till elastic strain accumulation, everything is okay. When the strain energy accumulation exceeds the shear strength of the soil, you will have failure, and that will result in the occurrence of the earthquake. Usually, these are located with respect to linear features because, again, if you explore with respect to the faults, most of the time you will see linear features which have been identified in the literature for a particular region. In addition, because identification of the fault is also a continuous process and it usually takes longer time, so many times you will see that there are some epicenters, but there are no faults identified so far in a particular region. So, how to deal with those we will discuss in subsequent lectures, which are like a bit advanced topic.

So, when strain accumulation exceeds the in-situ shear strength, there will be a release of energy in terms of earthquakes, and as the name suggests earthquakes, so that means there will be some quake happening in the earth. As a result, disturbances in terms of seismic waves will propagate, starting from the epicenter and propagating in all directions.

As I mentioned, the strain accumulation is a continuous process, but whether the accumulation of strain and subsequent release of strain—these two processes are happening simultaneously or are happening continuously in a particular region, will decide how frequently earthquakes are experienced at a particular site. So, there might be some locations where the accumulation of strain energy is happening at a relatively low speed. So, you may say at one location the rate of strain energy or the rate of convergence might be happening at 5 centimeters per year; other locations are there, it is happening maybe 1 centimeter per year. So, certainly, those locations where the strain energy is accumulating at a slower pace, that means those may show some sign of seismic activity in the longer run, not in maybe 100 years, 200 years like that.

So, keeping the strain accumulation as a continuous process, at times there might be ruptures frequently witnessed at a particular site. In addition, there might be segments which are not showing rupture despite the fact that strain energy accumulation can be witnessed, can be verified with respect to GPS measurements, with respect to in-situ measurements. So, such locations which are indications of locations without rupture for a prolonged duration are called seismic gaps. As mentioned earlier, there can be seismic gaps both in terms of space—that means if you consider a particular fault length, some segments of the fault length are showing very frequent seismic activity, that means strain accumulation, release of strain, strain accumulation, release of strain. However, at the same time, certain segments in the same fault are existing which, though showing some sign of strain accumulation, there are no earthquakes happening over there. So, those are called as temporal in terms of there was some earthquake maybe 700 years back, 500 years back, but no sign of seismic activity in the last 500 years. So, you call it as a temporal seismic gap. In addition, as I mentioned, some segments are there which are not showing signs of seismic activity, but others are showing signs of seismic activity. So, those are called as spatial locations potential seismic gaps. So, when we say about seismic gaps, it is both in terms of space as well as time.

So, locations which are not showing any sign of earthquake occurrence for the last 500 years, 600 years, maybe longer than that, certainly these are prominent locations because in-situ measurements show some strain energy accumulation continuously happening in those locations. When the strain energy accumulation is happening, certainly the strain energy building up will also happen at some segment in that particular fault block which may trigger an earthquake maybe in the next 15 years, 10 years, 30 years, 40 years, depending upon the rate at which strain accumulation is happening and what is the ground deformation which is resulting in the release of some portion of strain energy. At the same time, temporal, because generally the process dominating fault mechanism along the fault length more or less remains uniform, so you may see some segments which are showing continuous signs of earthquake occurrence, and then some segments which are completely inactive. So, you may say those are like spatial distribution of seismic activity and regions which are potentially identified as seismic gaps. But every time we will say some locations which are not producing any earthquakes as seismic gaps. So, one has to take into account what are the ongoing processes at present based on in-situ measurements, based on remote sensing-based measurements also, and then cross-verify with respect to the ground that actually there is some process happening continuously in the region. Though there is no seismic activity, all the surrounding evidence suggests that some seismic activity can be experienced in the next 30 years, 40 years, 50 years.

So, that is called as seismic gaps. So, gaps available in terms of seismic activity, in terms of occurrence of earthquake events, that is called as seismic gap.

The absence of larger earthquakes in one region, generally along a tectonic front or a fault. So, surrounding regions on the same fault are showing maybe a 7-magnitude earthquake, a 6-magnitude earthquake at least once in 50 years, 100 years—but then there are segments which are completely inactive, or there is no absence. If you take the earthquake catalogue into account and superimpose that on source information, you come across segments which are not showing any sign of seismic activity at all. Those will be identified as seismic gaps. So, these are the segments with gaps in spatial distribution of rupture zones. Usually, when there is an earthquake, that means the material has undergone failure. Now, depending upon how much strain energy was involved, that will define how much of the area which has undergone rupture is of the order of maybe a few hundreds of kilometers in length and maybe a few tens of kilometers in width—that is generally the area which may undergo rupture, maybe where a 7, 7.5 magnitude earthquake has happened. So, one can explore in the literature, like some papers suggesting what is the tentative area which has undergone rupture primarily during different earthquakes. One can refer to papers where, in 1934, there was an earthquake in Bihar-Nepal which had undergone rupture; so, calculation then, in 1833 again, there was some area which has undergone rupture. So, how much was that some area? You can see the area which has actually undergone rupture along the fault length; it is extending maybe a few hundreds of kilometers to maybe 60 to 70 kilometers, or maybe this is a rough idea about what is the range of area which undergoes rupture, which undergoes failure when earthquake events which have happened in the past, triggered.

So, there are the segments which are showing some sign of gaps in terms of spatial distribution of rupture. Rupture means the area which has undergone failure in terms of heat, in terms of melting, in terms of breakage. So, these are potentially the zones of the largest earthquakes in a seismic belt. These gaps are tectonically time bombs. Time bombs means energy accumulation is going on and then it may trigger someday. We still do not have complete information to say whether it is going to trigger in the next 5 years, next 10 years or so, but certainly, because there is accumulation of strain energy and adjoining sections of the same fault are showing signs of ruptures, signs of frequent earthquakes, so certainly this particular gap will also show some seismic activity. Right now, it is acting as a bomb which is ready to get triggered. So, waiting to go off in the form of major to even great earthquakes. Usually, whenever we talk about seismic gaps, we will be interested to find out locations which are due for major to great earthquakes because usually minor earthquakes are happening so frequently that primarily if you compare the kind of damages which are likely to happen during major to great earthquakes, they will be significantly larger in comparison to small earthquakes. So, generally, we refer to seismic gaps as those locations which are due to the occurrence of major to great earthquakes.

So, specifically, we can say seismic gaps are the sections of unruptured faults. As I mentioned, there will be some faults, some segments of the fault which are showing rupture or earthquakes—that means they have undergone rupture—but there might be some segments which remain unruptured during a prolonged duration. That will be called as spatial distribution or specially identified zones of seismic gaps. So, these segments have a high tendency to produce larger magnitude earthquakes in the near future whenever the rupture is going to happen; certainly, that will cause maybe major to great earthquakes, and whenever these earthquakes are going to come, they may cause a lot of devastation. And then, temporal, as I mentioned, there might be some locations which have not shown any sign of seismic activity, which have not ruptured for a considerable amount of time. Whenever I say considerable amount of time, I mean based on the information which is known to us. Again, when I say known to us, that means based on the past earthquake information collected from different literature, we have developed our earthquake catalogue. So, one is whether the earthquake has not happened at all, or second, is we do not have complete information about that particular earthquake.

So, that will also decide whether a particular location should be called a seismic gap or it should not be called a seismic gap. Rather, there is a need to study in detail about what has happened in the last 500 years, whether there was some event which at present we are considering has not happened, resulting in the declaration of that particular location as a seismic gap, or there was no earthquake at all. So, such investigations will help us in arriving at decisions on whether locations which are showing unruptured faults are actually the potential locations of seismic gaps which can experience major to great earthquakes in the future. In other words, the inter-seismic locking period of such segments on a fault is relatively longer. As I mentioned, maybe 100 years, 200 years, at least it should have shown some signature of seismic activity, but it has not shown. So, that means some kind of locking period is there. After that, once it reaches that locking period such that no accumulation of strain energy is further possible, we may experience some kind of seismic gap. Now, here we can see—so, this is one continuous segment of the fault line which is running all along maybe 500, 600 kilometers or maybe more than that.

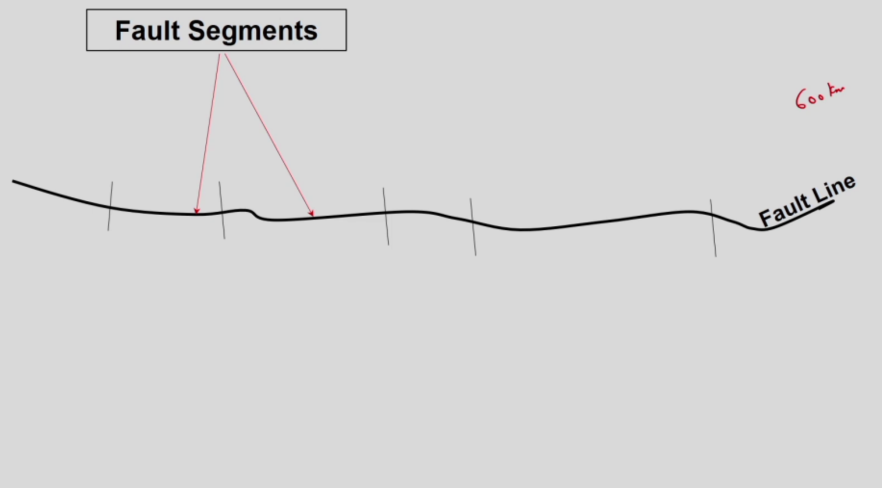


Fig: Simplified pictorial depiction of a Seismic Gap and the components involved

Then you see, not the entire length of the fault will undergo rupture during a particular earthquake. Why? Because considering the length of the fault might be 600 kilometers, suppose it is running. Now, it will be almost impossible that strain accumulation all along 600 kilometers happens at the same rate, triggering earthquakes at the same time because there are heterogeneities which are present in the medium; there are undulations which are present in the medium. Even the rate at which strain accumulation is happening will not be uniform all along the 600-kilometer length of the fault. So, in such a case, depending upon what is the strain accumulation happening here, here, here—different segments of the faults, which may be 100 kilometers, 80 kilometers—depending upon what is the governing tectonics, what is the fault plane solution dominating in different sections, one can identify what are the sections which are behaving independently. So, these are basically one fault line, and then within the fault line, depending upon the seismic activity, depending upon the dominating fault mechanism, one can again bifurcate or segregate different segments which are called as fault segments.

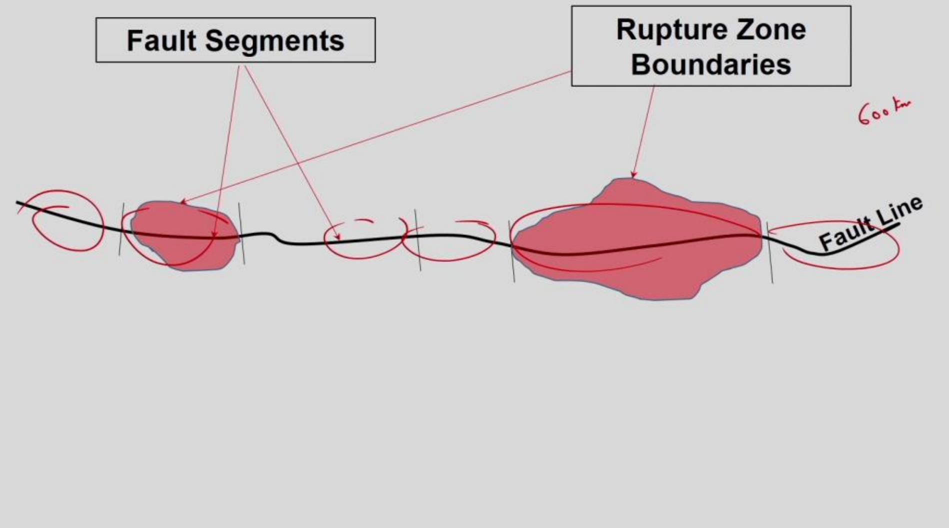


Fig: Simplified pictorial depiction of a Seismic Gap and the components involved

So, there are some locations which have shown rupture; so basically, these are the locations which have shown rupture. So, rupture, when I say, if you are looking at this fault line in plan, you will see some linear feature. Fault rupture will be happening perpendicular to this linear feature—means you are going below the ground surface and there is some length and some width which is actually undergoing rupture. So, you can see over here there was some length and width which was below the ground surface, and this entire area has undergone rupture. When it has undergone rupture, that means some energy which was otherwise getting accumulated before the rupture has actually triggered has been released in terms of seismic waves, and then maybe some portion of energy will remain there, and then further it will trigger in the next earthquake. Now, at the same time, you will see some segments which are showing here also—there is one segment which is showing some sign of seismic activity and rupture.

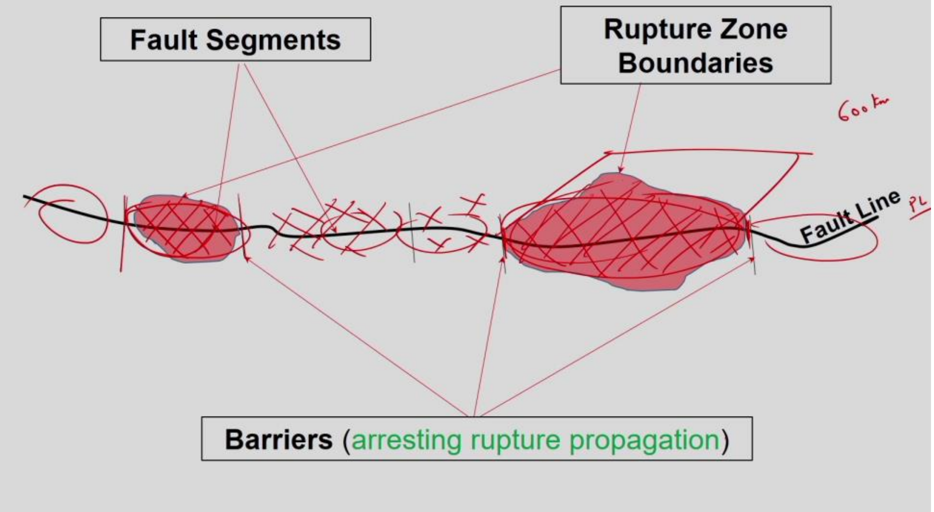


Fig: Simplified pictorial depiction of a Seismic Gap and the components involved

However, at the same time, there are some locations which are not showing any kind of rupture at all. At the same time, there are some barriers. So, you see, in this particular earthquake, this area has undergone rupture, and this is the barrier within which the rupture location is constrained. In this particular case also, the rupture location is constrained within this particular dimension. So, these are the barriers which are actually arresting further propagation of rupture. At the same time, you see, there are locations which have not shown any kind of rupture as far as the known information about historic earthquakes or recorded earthquakes is concerned or based on the limited information from the earthquake catalogue which has been developed so far. So, one can identify these as potential locations which are seismic gaps. As I mentioned, not just because some locations are there which are not showing any kind of rupture can one identify or nomenclature them as seismic gaps; rather, we have to have some supporting evidence suggesting that some kind of building up of strain energy is also happening over here. Building up of strain energy at a certain rate, based on in-situ measurements, based on satellite measurements suggesting something is happening—it is not completely inactive. So, inactive is different; not rupturing, not showing signs of rupture is altogether different. Maybe the accumulation is happening at such a pace that it may take maybe another 600 years for the accumulated strain energy to reach a level where it can actually trigger a major to great earthquake.

So, identification of seismic gaps: seismic gaps are generally identified to exist between the sources of two recent earthquakes. Prominent seismic gaps: some of the prominent seismic gaps are the center seismic gap or CIG, which exists in the Himalayas. Generally located, the center seismic gap is the location between 1934, there was an earthquake in Bihar-Nepal, so the rupture location of the Bihar-Nepal earthquake, and 1905, there was an earthquake in Himachal Pradesh, that is, Kangra earthquake. So, the rupture location of 1905 and the rupture location of 1934—between these two rupture locations there has not been any signature of major to great earthquakes, suggesting this is a potential location which is due for a major to great earthquake in the near future. Second one: you can see the Shumagin seismic gap in Alaska-Aleutian, where you can actually see there is a seismic gap between the rupture location of the 1938 earthquake and the 1948 earthquake along the Cascadian subduction zone. So, you can see another seismic gap. It is not located only in the Himalayas but across the globe. There are different locations where some segments are showing seismic activity, but some segments are not showing any sign of seismic activity, at least in terms of earthquake occurrence. Then the Guererro seismic gap, which is identified, is the zone located between the rupture zones of the 1957 earthquake as well as the 1979 earthquake. So, there was an earthquake in 1957 and 1979, and the location which is located between the rupture zone of the 1957 earthquake and the 1979 earthquake that has actually shown that has been identified as the Guererro seismic gap. So, once the designer or the agency which is involved in seismic hazard assessment should also take these into account because these are the potential locations which can produce significant ground shaking, though they are completely inactive in the last 700 years.

So, according to Mogi in 1979, there are two ways when two kinds of seismic gaps exist. So, one is the gaps in spatial distribution of the focal region. So, if you see in terms of earthquake occurrence, there are regions where there are earthquakes, but certain regions where there are no earthquakes. Similarly, in terms of lesser magnitude earthquakes, there is significant reduction in terms of seismic activity; even if you look into small magnitude earthquakes. So, those can also be identified as the regions which require actually further detailed investigation before you can call it a seismic gap. So, seismic gap of the first kind where you can see actually the the spatial distribution of rupture location is completely absent in certain locations. So, gradual accumulation of strain energy produces large earthquakes in the same region within a considerable time period. However, this large energy, many a time, will not be—firstly, there will not be an overlap of rupture locations, but at the same time, you will see narrow seismic zones which are existing because there is no possibility that two rupture zones of two different earthquakes can overlap with respect to each other. So, certainly, there will be narrow seismic zones which are not part of the rupture zone on one side or the other side—indication of seismic gaps. In the case of gaps in spatial distribution of rupture locations along a particular belt, there are postulates that a major to greater earthquake is due, which someday will happen and will fill this particular gap. So, whatever strain energy is getting built up in the last 100 years, 150 years, that portion—significant portion of that energy—will be released. Generally, it is released in terms of major to great earthquakes. Sometimes, small earthquakes can delay the occurrence of this major to great earthquake.

To identify such locations, one can explore the historical seismicity, even geodetic measurements, as well as tectonic data supporting whether there is some accumulation of strain energy, some activity is happening in and around those identified seismic gaps. The above space regularity was first pointed out by Fedotov in 1965 and later it was also confirmed by Sykes in 1971 for the Alaska-Aleutian seismic gap. So, if you look into this particular part: the Alaska Peninsula-Aleutian seismic belt, which is located to the northern part and eastern boundary of the Pacific Ring of Fire, which is a very prominent location for most of the earthquakes happening across the globe, you will see there is primarily the fault mechanism is right-lateral strike-slip faulting. Also, the direction of convergence becomes more oblique towards the arc and in the central and western Aleutians.

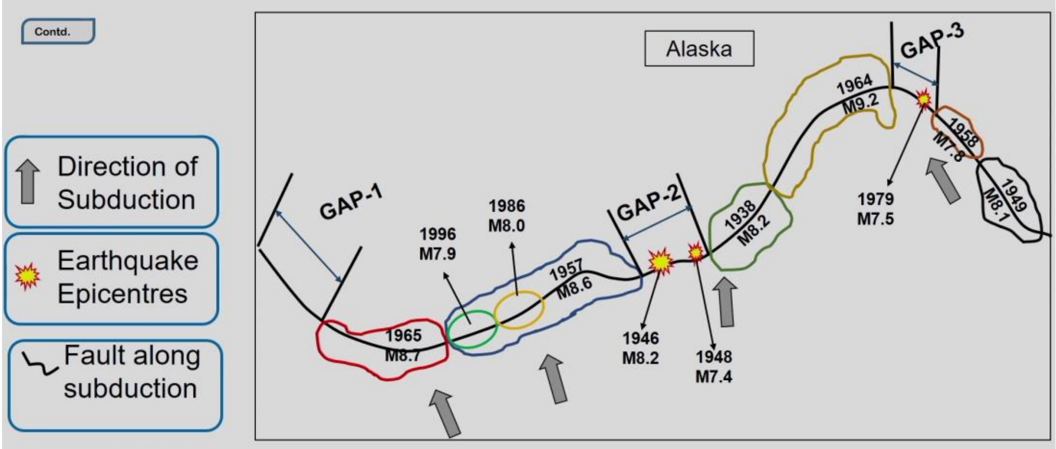


Fig: Pictorial representation of the Alaskan-Aleutian Seismic Belt consisting of the rupture zones (coloured polygons in the diagram above) of historic earthquakes and identified seismic gaps.

So, if you look at here, they are basically the Alaska-Aleutian seismic gap. So, you will see over here, before actually this particular location—you see this particular—the entire fault length is there, where you are having earthquakes in different years. Certainly, in this particular location, there was no earthquake other than 1946 and 1948. So, prior to that, the location gap 2 was identified as locations of potential seismic gap. In addition, you see this is the rupture location for the 1938 earthquake; this is the rupture location for the 1957 earthquake. As I mentioned in the prior slide, that overlapping of rupture zones will not be possible. So, there are some locations which have not shown any kind of rupture or potentially the reason for seismic gap. One again: you can see over here, which is basically later on there was some earthquake; the location is not shown over here because the rupture zone was not well defined. Similarly, over here, you can see 1958, 1964 there was an earthquake, but till 1979, for a longer period, there was no earthquake there. As a result, this particular segment was also identified as gap 3 for the Alaska-Aleutian seismic zone. So, three potentially identified seismic gaps along this particular belt were the seismic gap which is located along the western part where actually an earthquake in 1849 had occurred. Though, as I mentioned, the rupture location and magnitude were not clearly identified. Second one is the Shumagin seismic gap, which is located between the 1957 and 1964 earthquakes, and later in the year 1948, there was an earthquake, 1938 there was an earthquake, which actually ruptured almost half of the segment which was located between the rupture location of 1957 and 1964. So, again considering the current scenario, one can explore what are the chances of any rupture or further it can be explored. Similarly, towards the eastern part, 1958 and 1964 rupture zones were there, and in between the two, till the year 1979, when some rupture had happened, the zone between the rupture locations of 1958 and 1964 was identified as a potential eastern seismic gap at the Alaska-Aleutian seismic belt.

Now, the second kind of seismic gap, as I mentioned, at times, there will be absence in terms of rupture location. Secondly, there can be a gap primarily in terms of general seismic activity of smaller magnitude earthquakes in adjoining regions, and then there are some regions where there is significant reduction in terms of smaller magnitude earthquakes. So, those can also be, based on the gaps in terms of smaller magnitude activity, one can identify locations which are potential seismic gaps. So, these seismic gaps are distinguished by means of different reduced levels of seismic activity, primarily for lower magnitude earthquakes or smaller magnitude earthquakes. So, this is another way one can identify: one is like there are locations which have not shown any kind of rupture. Secondly, there is significant reduction even in terms of low magnitude earthquakes happening on a particular fault segment, indicating that can also be a potential seismic gap in the region.

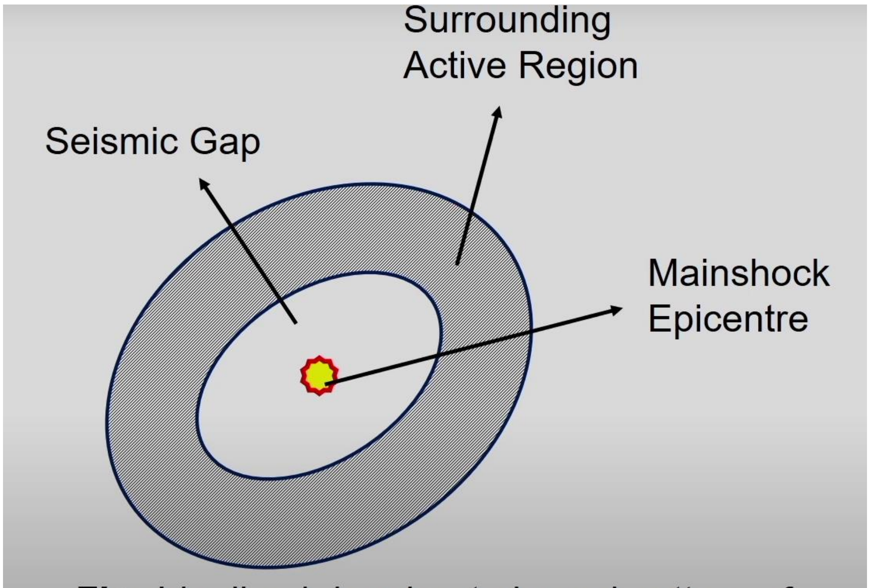


Fig: Idealised doughnut-shaped pattern of seismicity before a great earthquake

So, usually, you will see that in a round of that particular region, where there was some major earthquake, there is significant reduction in the seismic activity clearly suggesting that primarily in the doughnut shape, if you see as shown in the next slide, you see there is a surrounding region where there was some earthquake somewhere, and in the surrounding region, there is significant reduction in the seismic activity primarily for smaller magnitude earthquakes, suggesting that this particular region is also a potential seismic gap, primarily identified based on the reduction in the seismicity of smaller magnitude earthquakes.

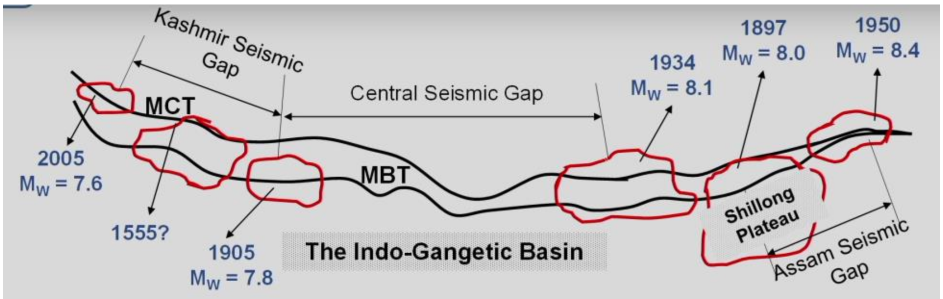


Fig: Pictorial Depiction of the Himalayan Seismic Gaps

MCT – Main Central Thrust

MBT – Main Boundary Thrust

Then there are seismic gaps—that is, the Himalayan seismic gap. So, you can see over here in 1987, based on the seismicity pattern, Khattri 1987 paper published identified three potential seismic gaps. So, from the west, we have the Kashmir seismic gap, which was almost 250 kilometers long segment located between the 1905 Kangra earthquake and the 2005 Kashmir earthquake, which was due for any earthquake occurrence since 1555. So, that seismic gap was termed as the Kashmir seismic gap. Then, the central seismic gap, as I mentioned, is the rupture location between the 1905 Kangra earthquake and the 1934 Bihar-Nepal earthquake. So, there were earthquakes in 1555 and 1833, but still, since then, almost close to 200 to 500 years, there has not been a significant earthquake of major to great magnitude earthquake which has happened in that particular region, suggesting this region is also a potential seismic gap.

Last one is Assam seismic gap there. So, 1950, there was an earthquake in Assam, and 1897, there was an earthquake in Sikkim. So, the rupture location between Assam and the Mishmi hill has not produced any significant earthquake, clearly indicating that there might be a gap existing known as the Assam seismic gap, which is due to cause a significant earthquake in the near future. So, again, these are postulates. So, there are some papers suggesting in support of the Assam seismic gap; there are some which are showing that actually it is not a seismic gap. So, these are the locations you can see here: 1897 earthquake Shillong; this is the rupture location. 1934, this is the rupture location. So, these are the locations which are actually suggesting potential seismic gaps. As I mentioned earlier, in addition to the Himalayas and the Alaska-Aleutian seismic gap, other seismic gaps also exist. So, the Guerrero seismic gap, which is basically a part of the Pacific coast of Mexico in Guerrero, located between the Cocos and North American plate interface, is one of the seismically active subduction zone in Mexico. So, several aseismic slip events have occurred, which have been confirmed by GPS measurements also. So, towards the west of this, there has been slip distribution in 1979 and 1985, and to the east, there are slip distributions because of the 1957 and 1964 earthquakes.

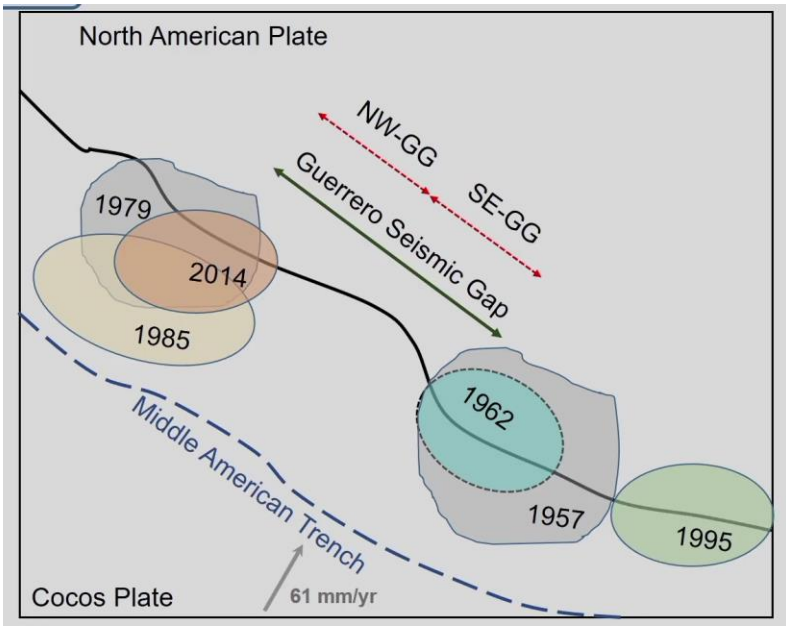


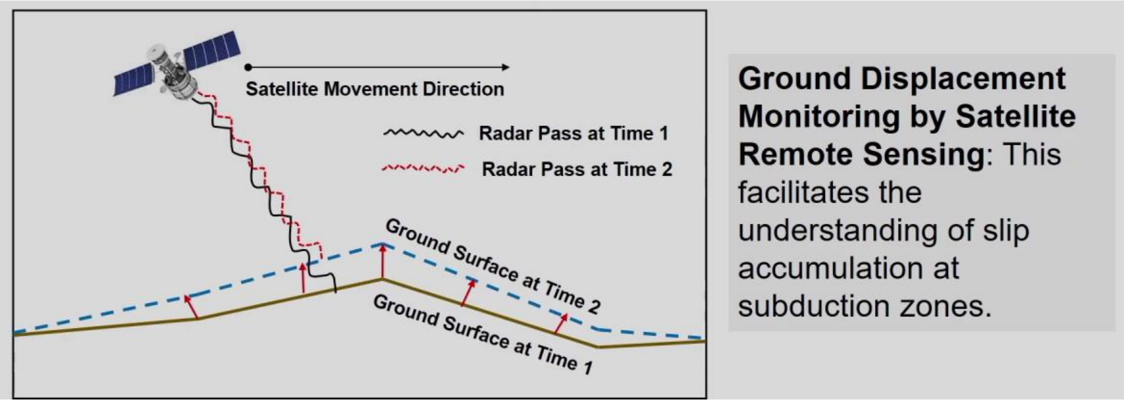
Fig: Representation of The Guerrero Seismic Gap at the South American Subduction zone [Drawn and Modified from Cruz-Atienza et. al (2018)]

So, there is another gap which exists in the Guerrero seismic gap; you can see over here. 1979, 1985, 2014, there were events on the other side: 1964, 1957, there were rupture locations, but since this rupture location, there is a gap. So, considering the first point, because of the absence of rupture locations between two already identified rupture locations, it is potentially a seismic gap. So, this is called the Guerrero seismic gap, located in the Mexican part. So, there are again further locations related to this particular gap.

Other identified seismic gaps across the globe include the Chilean seismic gap, identified as the Nazca and South American subduction zones. The Hellenic subduction trench, identified as the African and Aegean plate subduction zone, stretching from Greece to western Turkey—almost 250 kilometers in length—is identified as the Hellenic subduction trench due for an earthquake. The Dayi seismic gap, located in the Sichuan province of southwestern China and a part of the Longmenshan thrust belt. So, again, another seismic gap exists over there. The last one is the Cascadia seismic gap, located at the Cascadian subduction zone along the western coast of North America, where the Juan de Fuca subducts under the North American plate. There also, the Cascadian subduction zone exists. The Hellenic subduction trench is also there. The Dayi seismic gap also exists. The Chilean seismic gap exists. The New Madrid seismic gap also exists, identified as the location—almost 240 kilometers in length. The Key Channel seismic gap in the Philippines is also a potential seismic gap.

So, I have given here some information about well-identified seismic gaps across the globe. If one is interested, you can still go through a lot of literature which is available to give further information about these locations and can study why these are called seismic gaps and how these are relevant and important as far as regional seismic hazard studies, regional vulnerability studies are concerned. So, monitoring seismic gaps is important to keep a track of strain accumulation because strain accumulation is happening; though earthquakes are not there, strain accumulation will give you an idea about roughly how much on an average strain is getting accumulated and tentatively what are the potential locations where too much strain accumulation has happened, which is probably a location for future earthquake occurrence. So, a few methods based on which in-situ measurements can be done, like the global positioning system, will also give you an understanding about ground deformation and one can correlate with respect to strain accumulation. Then, based on the electrical conductivity of the Earth's crust, one can also identify the potential location offshore, ocean bottom pressure gauges, and GPS acoustic stations. So, there are some methods based on which one can go for a detailed investigation and narrow down some locations which are suggesting regions of strain accumulation.

And in addition, satellite data will also correlate with what is the rate at which ground deformation is happening in different locations. So, one is InSAR interferometry based synthetic aperture radar, based on which one can identify the rate at which ground deformations are happening in terms of fringes. Then, sea floor drill holes will also give you an indication about what is the rate, even though the accumulation is happening or deformation is happening at a very slow rate—what is actually that slow rate. And, of course, potential field measurements will also narrow down to some locations which can be identified as potential seismic gaps. Of course, one has to have more detailed in-situ investigations to support before claiming that a particular location is a seismic gap.



Ground Displacement Monitoring by Satellite Remote Sensing: This facilitates the understanding of slip accumulation at subduction zones.

So, thank you, everyone; this is all about the seismic gap. This is one pictorial view about how one can monitor ground displacement using remote sensing data and correlate with respect to strain accumulation. So, thank you, everyone.