Applied Seismology for Engineers

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Week – 03 Lecture - 02

Lecture – 06

Hello, everyone. Welcome to lecture 6 of the course Applied Seismology for Engineers. In today's lecture, we will be discussing about different analogies which can help the user in terms of identification of seismic sources. In earlier discussions, we have seen that whenever an earthquake happens, primarily along the fault plane, which is a representation of some plane of unconformity where possible movement in terms of the hanging wall and footwall must have happened during a particular earthquake. And whenever this movement happens, as a part of this particular movement, there will be some building up of strain energy, which gets released and causes earthquakes. So, when this energy release happens, there will be the development of seismic waves. These waves propagate to larger distances, causing damages, and even these waves interacting with near-surface material also leading to amplification and change in frequency content. So overall, whenever we are interested in finding out the potential ground motion in a particular region of interest, one has to be careful in identifying what the active sources are, which are available in a particular region.

In later lectures, we will also see how the faults, which are potential sources of earthquake occurrence, can be used to determine the seismic hazard values or to quantify the potential ground motion at a particular site of interest. So overall, in order to find out the potential ground motion, one is how big the earthquake was. In a later slide, we will also see that depending upon the magnitude of the earthquake, we can classify the earthquake as a minor earthquake, major earthquake, or great earthquakes. Similarly, depending upon the position of the epicenter of the earthquake with respect to plate boundaries, we can have maybe plate boundary earthquakes; we can have intraplate earthquakes also.

Again, depending upon the epicenter distance range, there are classifications that are given, which will be discussed in later classes. In today's lecture, we will primarily be focusing on how to identify a particular fault, primarily in terms of whether it should be called an active fault. An active fault means where one can say confidently that this is the fault or this is the seismic source that has the potential to again undergo an earthquake, primarily during the design life. Again, when we discuss seismic sources, one has to also take into account the importance of the structure, on which basically the earthquake loading has to be determined. When we are talking about routine buildings, we can go ahead with maybe the zonation maps based on which one can identify how much seismic loading is prone to or should be taken into account while designing a particular earthquake-resistant building.

However, whenever it comes to very important structures such as bridges, dams, nuclear power plants, one has to be more careful in terms of understanding the seismicity. Again, in terms of seismicity, it is not only about the seismicity which is known in terms of ground motion, which is known in terms of earthquake records, but also one can refer to isoseismal maps. In addition, one can also refer to what are the potential seismic sources, which are available in a particular region and the seismic activity corresponding to each of these seismic sources because there might be a possibility that there are seismic sources, but such sources have not been identified so far. Because again, during different sets of studies, there might be specific reasons, and again, depending upon the target of those studies, there might be a level of detail that might be explored in different regions to identify what active faults are, what seismic sources are, and what hidden faults are. Later on, when we discuss source characterization, we will also see that not every place will have well-identified information about faults. In such a case, what measures one has to take into account, what the guidelines and methodology are available, which can help even in times when earthquake information in terms of faults is not available. So how one can take past earthquake information without taking fault information into account will also be discussed in later lectures. In today's lecture, as I mentioned, it is mainly focusing on analogies that will help in identifying whether in a particular region there are faults. Secondly, if there are faults, again, if there are faults to take into account some direct or indirect features or representations on the ground, maybe subsurface features also suggesting that potentially a source is available in a particular region, which can also be identified using maybe remote sensing data based on GPS measurement, based on other types of in-situ measurements, and which will definitely give an indication that there might be a possibility an active fault might be there. So, how to decide whether a particular source is available in a particular region and how to decide this particular source to be called an active source or an inactive source.

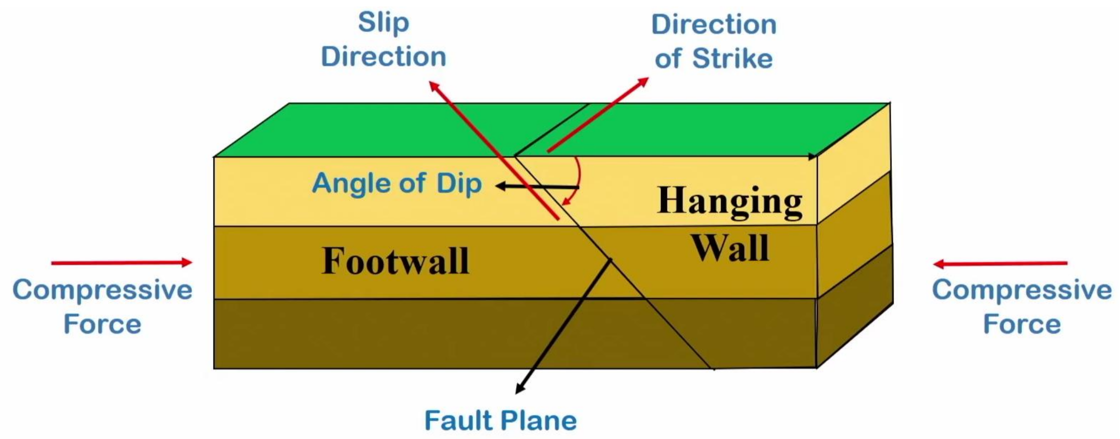
As far as the source is inactive, that means the source does not have significant potential to cause an earthquake, at least during the design life of the structure. If a fault is considered active, that means this particular fault, again depending upon the dimension of the fault, has the capability to cause an earthquake. As just mentioned, that depending upon the dimension of the structure, depending upon the dimension of the fault, a small fault may produce some magnitude earthquake; a larger earthquake can be produced by a significantly larger fault. And then again, if you are talking about a great earthquake, that means any earthquake having a magnitude greater than 8, you have to have significantly larger dimensions of the fault plane which are actually available for the release of seismic energy. So, if we are talking about active faults and inactive faults, in today's lecture we will be discussing about what faults are, in a nutshell, what faults are and how you define a particular fault. Now, when we are discussing the fault, it is basically a three-dimensional model or three-dimensional property of a particular plane. So how it can be represented, maybe in three dimensions, maybe on a two-dimensional plane, so that one can take this generalized information and use it depending upon the purpose, it can be used by different sets of people.

So, what are the important terminologies for how you define a particular seismic fault? As mentioned over here, seismic means a particular seismic source which is capable of producing an earthquake. Then, while doing this, we will also come across the criteria on which one should disclose that a particular fault should be called active. That means depending upon its activity or whether it is in its current state or during a particular user-defined period, again, that keeps on varying with respect to the region of interest to declare whether a particular fault has the capability to again show activity during the design life or it is not going to show. Then, mostly whenever we are discussing about active fault, identification of active faults, the neotectonics of the region will come into the picture to give you a possible hint, to give you an indirect indication that the region which you are talking about is potentially an active region. Potentially there might be a seismic fault which definitely requires more detailed investigation to verify. So, later on, we can bring geological evidence, we can bring maybe remote sensing observations, aerial photographs, and much more information to narrow down again that a potential fault has been identified in a particular region.

So, we will be starting with the objective to find out the loading because of the earthquake. Whenever we are going with hazard assessment, definitely we will take into account all possible seismic sources which are available in and around your particular region. Because whenever any particular seismic source is going to produce an earthquake, definitely there will be some ground motion which will be transferred to your site of interest. So, it may not be related that every time the seismic source and the site of interest should be in very close proximity, even an 8-magnitude earthquake can cause significant devastation, significant ground shaking, even at 500 kilometers, 550 kilometers radial distance from your epicenter or from your focus. So that means whenever we are interested in finding out the earthquake loading condition, we have to find out more confidently what are the active sources, which are available maybe in a 500–600 kilometer radial distance which, if taken into account, will give you more confidence about the seismic activity which is happening within your seismic province. So overall, the objective here is again to go ahead with the identification of active faults to gain more confidence in terms of what are the seismic sources available. In addition to the seismic sources, later on, we will also take into account what is the potential database which can be referred to in order to find out past earthquakes in a particular region that might be related to recorded ground motion, or it may be related to historic earthquakes.

So, again we will be discussing some of the characteristics based on which one can again narrow down to whether it is an active fault. Then in-situ measurements are there in terms of seismic tomography, which will help again in identifying maybe heterogeneity that is present in a medium or some thin linear features that are available along the ground surface, which can potentially narrow down like there are some anomalies that support the presence of active faults present in a particular region. Then development in case of seismic imaging, what are the recent advancements in terms of identification of enelastic properties in a particular region, whether in terms of using dense seismic arrays to find out properties on a larger platform in terms of frequency domain. So, all these we will also be touching upon here. Then we will also discuss what is active fault mapping, what information can be used, and where it can be utilized. Then, map representation—how we are going to represent this information, whether you are talking about faults, whether you are talking about the age of the fault, maybe you are talking about relative slips that are available or potential slips that are prone to happen during different faults. So, how these things are going to happen, again globally. So, we will be having datasets from different sources; how those can be combined in order to find out, again, the development of maps and what are the globally identified active faults based on such studies. Then, we will be referring to the earlier discussion which we will be having over here, primarily related to characterization of active faults. We will also be trying to solve one numerical which will directly give an indication that whenever we are talking about a particular seismic source, how roughly an idea about the size of earthquake it can produce can be obtained. Or otherwise, if we are having some measurement related to in-situ slip on a particular fault, how that can be utilized over here, or in-situ rupture which has happened along the fault but at different segments, so collectively how that information can be utilized here to find out what might have been the magnitude of that particular earthquake because rupture, surface manifestations, offsets—these are basically clearly visible features on the ground surface during different earthquakes. So, again, what are inactive faults, and at times it has been seen also, again, on a geological scale, there might be some faults that were active maybe on a geological time scale and have become inactive or vice versa. So, some faults were there which were inactive, but because of some processes that became dominant on a geological time scale, now these have become active faults.

So, overall, we will be touching upon the topics because, again, the objective of this particular course is to give you an idea about how the sources are producing earthquakes, how this earthquake, which is produced on a particular fault, or if the fault information is not there, how this information of past earthquakes can be utilized to quantify ground motion. Later on, this ground motion can be modified along the propagation path because of local site effects, how it can be utilized to quantify the liquefaction potential of a particular site, and in the end of this particular course, how collectively the information which we will be learning throughout the course can be utilized to develop microzonation maps for a particular study area.



So, going with the active fault, before that, we will be discussing seismic sources or faults. So, primarily when we discuss seismic sources, we are basically interested in finding out what features are available either on the surface or beneath the surface because many a times these features, which are showing potential movement on the ground surface, are also visible, but most of the time, these features or these movements will be happening at significant depth along the fault plane. So, in order to understand what is happening along the fault plane, according to the United States Geological Survey, a seismic fault is a fracture, so you can see here this is completely a fracture along which potential movement, or a zone of fracture along which the two blocks—one block, which is called as hanging block, which we discussed in an earlier class also, so the hanging wall, which is generally located above your fault plane or plane of rupture, and secondly, the foot wall, which is located below your plane of rupture or the plane along which the potential movement during a particular earthquake has happened—are available. Again, this hanging wall, this is the foot wall. Generally, the foot wall will be below the fault plane, and the hanging wall will be above the fault plane. Again, whenever the movement is happening, the movement must be happening along the dip direction. So, this direction in which the fault plane is oriented, the direction with respect to horizontal—so whatever angle it is making, that is called the dip angle. So, how much dip is there? If it is a 90-degree dip, that means the fault plane is almost vertical, and anything greater than 0 degrees and 90 degrees is also possible. If it goes more than 90 degrees, then we have the rule of V's, which is also discussed in the lecture.

Again, the direction of dip we have discussed is the inclination of the fault plane with respect to horizontal. If you see a particular fault plane on the ground surface, we will only be able to see a linear feature. So, how is the orientation of this linear feature existing on the ground surface? If you see this particular inclination with respect to north, how much the line which is representing the fault plane or the line which is the interaction of the fault plane with respect to the ground surface—what is the inclination of this particular line with respect to north? That is called the strike of the particular fault. So, the strike is going to give you what the orientation of the fault line or fault trace is, which is available on the ground surface. If you are talking about the fault plane, in addition to strike, we will be having another value that is called as dip of a particular fault. The dip is going to give you what the inclination is in which the fault trace or fault line has to be extended within the ground surface. Remember, on the map, we will have a clear indication about what the length of the fault is because accordingly, that particular length of fault trace is available on the ground surface. You can extend that particular length in the direction of the dip. It is approximately going to give you the fault plane. If we can also have an idea about the rupture width, then subsequently this particular dimension in which the fault plane is extending along the dip direction—that is going to give you a two-dimensional space along the fault plane, which is potentially the region in which either the significant portion or a small portion of that particular region will undergo rupture during a particular earthquake. So, we are talking about a plane along which two blocks are there: one is the hanging wall, the other one is the foot wall. Now, because of convection currents, which we have discussed in an earlier lecture also, what will happen is the two blocks will have some movement. This movement can be towards each other, classifying reverse faulting; it can be away from each other, normal faulting; or there can be slight pass movement, which is called a strike-slip fault. So, we can see over here the type of movement, the nature of movement. If the two blocks are moving away from each other or towards each other, in both cases, there will be, with respect to the foot wall, there will be movement of the hanging wall, whether it is moving away or whether it is moving towards. So, such movement, which is basically explaining the direction in which the hanging wall is moving with respect to the foot wall, is called slip direction, or it is also called as rake angle. So, this is called rake angle or slip angle, angle of slip. So, completely, if you have rake angle, you have dip angle, you have strike angle, and the fault trace. Using these four parameters, you will be able to actually locate a fault plane. Later on, we will also discuss fault plane solutions. So, actually, if you are going to represent this particular kind of movement—whether it is normal faulting, reverse faulting, or strike-slip faulting—that can also be represented in beachball solutions, which we will be discussing in other lectures.

So, this is the typical movement. Now, during a particular earthquake, what will happen? The two blocks will be moving away from each other towards each other, which can be shown over here in terms of this particular animation. So now, if we take into account this particular animation, there might be a particular plane that is common to both hanging wall and foot wall along which, because of this particular movement of hanging and foot wall, there is development of shear stresses, which is actually going to cause storage of strain energy, which will later on be released in terms of an earthquake. So, this is about the angle of dip, foot wall, hanging wall—this is more or less, in a nutshell, the definition of a particular fault, which will be required in order to locate a particular fault, at least on a global scale. So, using this particular fault trace coordinates, one can find out exactly where the fault trace is located. Then, take dip direction, you can locate the fault plane; taking strike into account, you can locate what is the orientation of the fault trace; and the slip angle—is going to give you what is the direction in which the movement along a particular fault is happening.

Now, if we talk about active faults, why is it required? Because not all the faults—firstly, if we take into account the linear features—not all linear features which are available, maybe on satellite data, maybe on aerial photographs, not all the features are capable of producing earthquakes. Like, if you are talking about linear features, many a time there will be continuous land where vegetation is growing that on an aerial photograph may give you some indication some linear feature is there, but certainly that feature is not related to fault or it is not capable of producing earthquakes. Similarly, shear zones can be there, which are again potential regions where shearing is happening, but whether it is causing an earthquake or not, again it has to be discussed. Folds are there, so it is not—it is called a very gentle process where the accumulation of strain will be happening, but certainly it will not lead to the occurrence of earthquakes.

So, active faults, as I mentioned in the beginning also, what are the faults, what are the seismic sources which have produced earthquakes in some geological time scale? But, in order to define whether these are again capable of producing some seismic event, that is called the identification of active faults. So, active faults can be defined as seismic sources that have moved—moved means any kind of potential movement between hanging wall and foot wall, any kind of movement which has happened along a particular source or a seismic fault in the recent past. How much is the recent past? That again depends upon the feature of the region, depending upon how much information is also available in terms of, maybe, geological evidences and so on. And in terms of recent past and may move—may move means these are the potential sources which can again cause earthquakes. Now, when it caused an earthquake in the past, that again depends on the region, tectonic settings, and geological evidences which are available to us. But we cannot ignore that these are the potential sources which can also cause an earthquake in the near future. That means if we are going to collect—if you are going to drop the probability that these can also produce earthquakes definitely—and if such sources are very close to your site of interest, if we are not taking this activity into account, what will happen? We will end up underestimating the seismic hazard of a particular source or seismic hazard of a particular region because, as the source is very close to your site of interest, definitely that particular source can cause more ground motion even during a small earthquake rather than a particular source which may be located at 400-500 kilometers distance away from your site of interest.

So, we cannot basically avoid the probability that even there is a source, what is the activity, whether this particular source has shown any significant movement in the past, or what are the chances it can show any significant movement again in the near future as far as the design life of the structure is concerned. And again, not every time the design life of the structure, but also one has to take into account the importance of the structure. Suppose a nuclear power plant is there; certainly, we will not only take into account the design life of the structure, we have to also take into account that, what if this particular infrastructure undergoes failure? Because it will not be simply the structural failure of a particular infrastructure, there will be radiation leaks, there will be a lot of devastation—like major scale devastation—which is going to be triggered in case a nuclear facility undergoes failure, primarily the reaction chamber if it undergoes failure, what kind of damage scenario is it going to trigger? So, taking that probability into account, which is one of its kind of havoc which nobody wants to have in a particular nuclear power plant, particularly in order to arrange the fission reaction before significant ground motion, which can actually cause any kind of leakage from the reaction chamber. So again, in such a case, what will we do? We will try to find out any particular seismic source which is available in your 600-700 km radial distance around your site of interest, depending upon whatever guidelines says, such that each and every seismic source around your site of interest should be able to identify. So that can be identified as—it can be further defined as a seismic source that has caused surface rupture. Many a time these will also cause some kind of rupture near the surface or even surface manifestation. Some direct hint of some movement has happened beneath the ground surface, maybe in terms of offset—a significant portion of ground before and after an earthquake, you can see it has been raised, primarily as surface manifestation. So, that again can be used in order to find out the magnitude of the earthquake. So, as per Trifonov and Mechette, 1993, potentially an active fault has been identified as faults which have shown any activity in less than 10 ka—ka is kilo annum, that means 1000 years—so anything which has shown activity in terms of possible movement, any kind of surface manifestation in less than 10,000 years, which is belonging to Holocene age in geological time scale, that can be called as active. And at the same time, any kind of activity, if not in 10,000 years, anything between 10,000 years to 1,30,000 years, which is called the Pleistocene period. So, whether the fault has shown or the seismic source has shown any kind of surface manifestation in the last 10,000 years or Holocene period or between 10,000 and 1,30,000 years, any kind of manifestation which the seismic source has created on the surface in terms of surface manifestation, that can again be called as an active fault. So, the study of active fault, as I mentioned, provides quite important information primarily about not only about the sources which have produced earthquakes in the past—but also at the same time, these are the sources, if found active, certainly can produce an earthquake in the near future. Again, as I mentioned, if you are able to locate those sources which are, again, maybe surface manifestation or maybe based on in-situ measurement, at least continue the points which are showing similar activity based on geological evidences or maybe based on tomographic observations, so it is going to give you a linear feature on the ground surface. Taking that linear feature into account, one can get an idea about what are the potential sizes which this particular earthquake can potentially produce in the near future. Right now, we are not talking about seismic activity; rather, we are only talking about taking the dimension of that particular fault—rupture length, rupture width—taking that dimension into account, what is the likely size of the magnitude which this particular seismic source can produce in the near future.

So, the study of active fault primarily is about the location of the potential sources which can produce earthquakes, which again will narrow down to what are the potential locations in which future earthquakes can happen, and if these earthquakes are going to happen, what will be the size of these earthquakes. Again, the concept, as I mentioned, is very important in nuclear power plants because whenever ground motion happens during a particular earthquake, and if it is going to be transferred to nuclear containment facilities, if the ground shaking is significant enough to cause any kind of radiation leak, there, it will not be only limited to the nuclear power plant but to a larger area, which is there may be in around a 500-600 kilometer radial distance or maybe more than that, which may be exposed to maybe significant radiation or maybe the lesser area also, but the devastation which will be caused in the nearby region will be significant. So, an earthquake which might be happening at some fault which is located 500 kilometers from your radial distance of nuclear containment facility, if it is causing any kind of leakage in the radiation surrounding that particular nuclear power plant, there will be a lot of devastation. So primarily, nuclear power facilities' identification of active faults is a continuous process, so unlike routine structures, whenever we are going for hazard analysis of a particular nuclear power plant, certainly, one has to take into account what are the active faults which are available in a particular region based on existing studies, and if possible, a separate detailed study related to the identification of active faults in a particular region can also be parallelly taken into account. Again, mentioned over here is Ka, is kilo annum, or 1 Ka means 1,000 years.

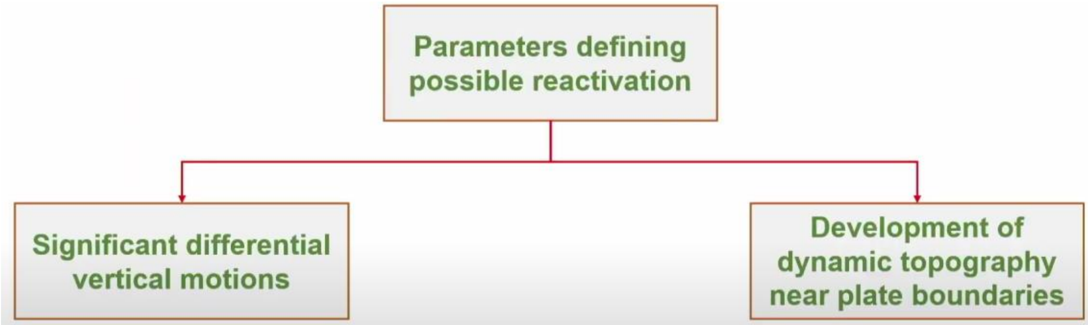
Identification of active faults will also help in identifying the locations because whenever there is an active fault, if it is causing any kind of ground subsidence or if it is causing any kind of surface manifestation offset, potentially, if it is going to get repeated in the near future, again these features will also get repeated. Similarly, with respect to ground fissures in terms of landslides, which is again the loading because of the occurrence of an earthquake on a particular fault which has been triggered on a particular slope triggering to landslide, so if you are finding close to a slide or close to a particular slope, we find an active fault that definitely increases the probability that this particular slope, which is very close to an active fault, can undergo failure in the near future. So, such kind of analogy can also be developed if we are able to find out the location of active faults and in addition to location, the size of the earthquake because you will be getting dimensions, maybe the length of the fault trace, or maybe two-dimensional information, or maybe the surface manifestation which also can give you an indication about the potential size of the earthquake. Similarly, with respect to liquefaction, so liquefaction is whenever ground shaking or the seismic waves generated during a particular earthquake are passing through a particular medium, these cause disturbance in the particle; particles undergo motion in particular in the case of liquefaction. There will be the development of excess pore pressure because of wave propagation; as a result of this excess pore pressure, it will push all the particles away from each other, so they will not be particles in close contact with respect to each other to offer resistance to shear loading; all the particles will be away from each other, such that if we see the consistency of the soil in liquefied state, it will be almost like a liquid; it is almost kind of flowing consistency. So if we are going to find out some cohesionless deposits or soil which is prone to undergo liquefaction based on the characteristics of the medium very close to your active fault, certainly one has to be extra careful that these are the locations which have undergone liquefaction, which have shown liquefaction in the past or are potentially liquefiable, but because these are also located very close to an active fault one has to be very careful while dealing with those sources because these can cause liquefaction.

Similarly, with respect to ground subsidence also, so a lot of ground subsidence again, the ground is very soft, there are more chances that because of overcoming load or even in addition to structure superstructure load, the ground can show any kind of subsidence settlement like that. So, one has to be more careful about these features to get repeated in case there is an active fault identified in the nearby region because these can cause again a lot of devastation, a lot of damages, and even at times, complete collapse of the building and corresponding casualties. So, characterization of active fault, as I mentioned, we are interested to find out active faults, and currently, maybe the rate of movement is not significant. If you take into account the average slip which is happening, maybe once in a year or maybe once in 10 years, that is not significant to decide whether the fault is active or not because the rate at which the slip is supposed to happen, at present, it is not that much significant since one has started taking in-situ measurement. So, characterization of active faults mostly depends upon the neotectonic period, what are the compressional stresses, what are the extensional stresses or tensile stresses, when these stresses came into existence first time on this particular fault which triggered some kind of movement along this particular fault, and because of this particular movement which continued for a certain period that had actually triggered earthquake occurrence. So again, it depends upon the neotectonic, of a particular region, and the active tectonics of a particular terrain, how active terrain, here we are not talking about a particular fault but terrain, so that means even if a particular fault is not showing significant movement, but there are seismic sources in and around your particular target active faults which are significantly active, definitely some component of those movements will trigger seismic activity on this particular fault as well. So active tectonics of the terrain is also important as far as the seismic activity of a particular active fault is concerned.

Now neotectonics, as I mentioned, we have to take into account the neotectonic features. So, this field of study, that is neotectonics, is primarily related to the horizontal as well as vertical crustal movement which is happening beneath the ground surface, primarily in the geologically recent past, and which may also be ongoing even today. So some kind of horizontal or vertical movement, manifestation, offsets which have happened in geological time scale, either it has happened in the past or in the past has happened but even also it is continuing in the present; collectively all these informations are going to give you information about neotectonics, that means some signature of activity in terms of crustal movement whether it is horizontal, whether it is vertical or whether it is a combination of horizontal and vertical both. However, there is a dispute about like how much time one should take into account with respect to the present in order to decide that any kind of horizontal or vertical crustal movement should be taken into account to decide that this should be considered as the duration of the neotectonic setting. This should be considered as the duration for which, based on neotectonic setting, one can define that a particular fault is active or not.

So, in order to resolve this controversy, neotectonism starts at different times for different regions, that is the general analogy. The onset of the neotectonic period or the current tectonic regime depends upon when contemporary stresses, if we remember the animation which was shown in an earlier slide, the two blocks are coming in contact with each other in terms of compression. So, when these compressional stresses or contemporary stresses firstly came into existence to cause any kind of potential movement along this particular fault, that will define what should be the region of neotectonism for a particular region of interest. For example, it is given over here, particularly for Apennines in central Italy, the duration for neotectonism can be as long as middle quaternary, which is ranging close to 7 lakh years with respect to the present. Similarly, we are talking about sub-Himalayan faults and thrust belt, the neotectonism can range between 2 to 3 million years from the present in order to take in-situ features to detect any kind of potential horizontal or vertical crystal movement or to locate potential surface manifestation belonging to these details or these periods to decide that this particular fault which is available as a linear feature in my study area is basically classified as active fault.

So, analysis of neo-tectonic movement, primarily related to how much is the movement which is happening, and which had happened, in maybe horizontal or vertical direction, gives you an idea about the time span for which the tectonic structure had been active, whether it is active at present or whether it was active in the past. So, all these features will cover when we go for neo-tectonic setting-based identification, and definitely, it will also quantify the deformation which has accumulated in order to get some information about what is likely to be the occurring magnitude for the future earthquake.



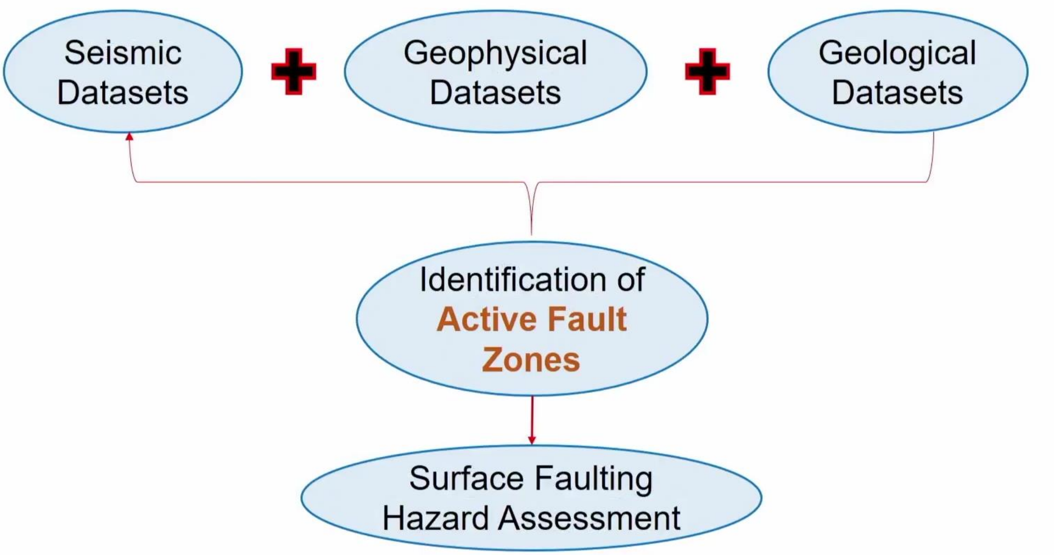
So potential parameters which can be taken into account to identify particular activation as well as deactivation, or in a nutshell, about active fault in a particular region. So, one can refer to significantly differential vertical motions. Secondly, one can take into account the development of dynamic topography near the plate boundaries. So, there, one can see about significant change in maybe sea level, maybe basin or fault inversion, also another feature which can be clubbed with respect to dynamic topography, which can again give you some hint or some parametric understanding about potential neo-tectonic of a particular region, and based on the neo-tectonic regime, one can identify whether a particular fault will be called as an active fault or an inactive fault. Similarly, with respect to lithospheric folding, one can club with respect to identification of parameters for neo-tectonic setting as well as with respect to identification of active faults.

So, sea level fluctuation, if we take into account, sea level fluctuation can be triggered by means of continental collision or because of subduction at the plate boundaries. Many a time, these can also be an indication of the building up of stresses along the two sides of the plate boundaries, which can also cause, in addition to collision, some kind of fluctuation in the sea level or mean sea level significant variation. So, if we are able to find out the features along the plate boundaries, which are giving an indication about fluctuation in the sea level in geological time scale, it is going to give you an indication about neo-tectonic activities, and subsequently, even in the raised region for inter-plate earthquakes, inter-plate system, also one can seek for these kinds of features.

Similarly, with respect to basin or fault inversion, that means before, if you talk about neo-tectonism, so considering the duration of neo-tectonism, the nature of the fault, whether it was belonging to normal faulting, now it has changed, it has gone to maybe normal faulting; if it was normal faulting, it has gone to reverse faulting. So, it is like before and after the neo-tectonic period, what is the change which has happened, which is an indication that completely change in or reversal in the terms of the dominating stresses on a particular fault mechanism. So that can also be taken into account as additional features in order to arrive at the parameters defining the activity of a particular fault. So sedimentary basins formed under extensional conditions are uplifted due to intra-plate crystal shortening; these are called basin inversion. Reactivation of the fault in the opposite direction to the original, that means initially it was normal faulting, later on it became reverse faulting, or it was reverse faulting and became maybe strike-slip faulting, or like completely changed in the nature of the movement along a particular fault plane.

Lithospheric folding, so intra-plate folding, so it is like a gradual process which had led to some kind of folding in the lithospheric regions, particularly related to strong oceanic lithosphere. So, these are an indication that stresses are concentrated primarily in a particular geometric and dynamic condition. So, this is basically, there are some concentrations of stresses which are happening along the oceanic lithosphere, which are indications of that in addition to the above two parameters, that there are some regions where some concentrations of stresses are going on, which can lead to narrowing down the study area for further detailed studies.

Now, characterization of active faults, as I mentioned in the beginning, that based on the type of movement which is shown, maybe in the Holocene period, or maybe in the Pleistocene period, in a general nutshell, it can be called an active fault. But again, what is the reason one has to be taken into, one should take into account to give a generalized understanding about active faults. So, United States Atomic Energy Commission in the year 1973 proposed a set of criteria to recognize potential faults to cause surface manifestation. Now we have moved from active faults to the faults which can at least give you surface manifestation. Again, those surface manifestations one can refer with respect to the neo-tectonic features or neo-tectonic setting, which will again help in identifying the active faults. So, one movement, at least based on the surface manifestation, any kind of feature which is giving an indication that at least one movement which has happened at or near the ground surface in the last 35,000 years. So, any kind of significant features available indicating that movement at the near ground surface in the last 35,000 years, you certainly call it an active fault identified based on surface manifestation. If not in 35,000 years, then more than one kind of movement which has happened in the last 5 lakh years, based again on surface manifestation details. So, it is again going to give you potentially, these are the faults which can be caused as active faults, primarily related to the US Atomic Energy Commission. Again, we can also take into account geomorphic features which are an indication of displacement at the surface. That means many a time because of occurrence, some land might be raised, an offset will be created. So, this is again evidence of displacement which is definitely visible on the ground surface, which are geomorphic features indicating some kind of building up of stresses or release of stresses at a certain time when the ground surface has happened, and at times faults curve is also there. So, you can directly see a portion of the fault available on the ground surface. So again, this is an indication that the particular fault is active or at least has been active in the geological past. Instrumentally, if you are having information about, like you can narrow down the epicenter of the earthquakes, you can take earthquake ground motion into account, definitely, it is also going to give you an indication about a particular fault which has been active even at present. And evidences, so you are many a time will be having the slip value, sometimes rupture characteristics of nearby regions, which will also indicate that the particular entire region has been active in terms of seismic activity. So, taking those evidences also into account and correlating surface features, maybe faults curve, displacement values, offset values, again can give you an idea that a particular linear feature which is available on the ground surface satisfies the condition for an active fault.

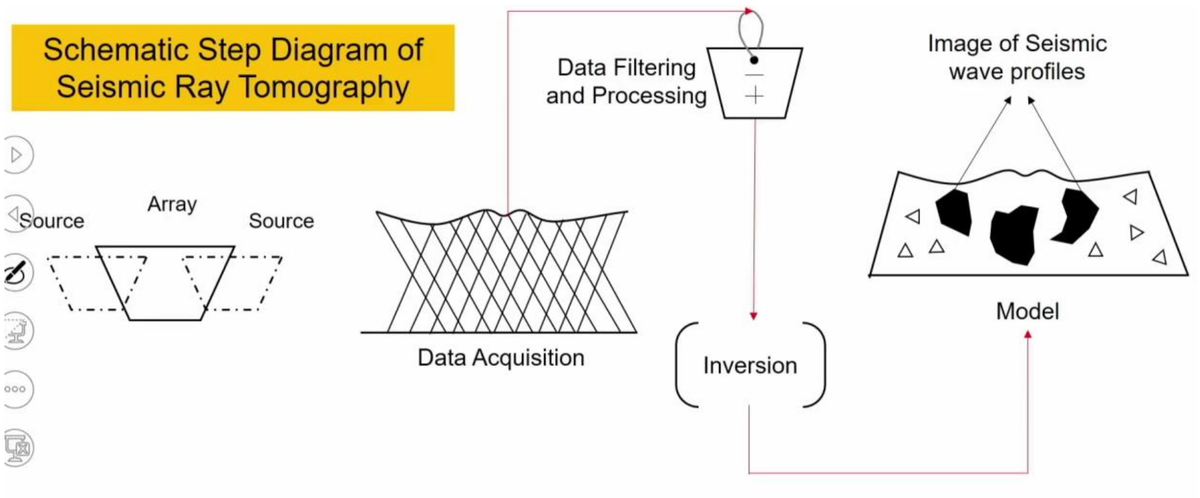


Now, as far as in situ measurements are concerned, we can go with seismic imaging, which helps in understanding the subsurface feature available within the ground surface, primarily in high resolution, and this can also be used in order to find out the surface ruptures of seismic faults or seismogenic faults or sources. So, one can take into account the seismic data, that means ground motion data, or if you are going with microtremor information, you can take those into account, club them with respect to geophysical geological data, which is again going to give you information about subsurface features. So, you are having some data in terms of how, for a particular signature, the ground has responded. Again, what are the characteristics of the medium, you can take maybe strength characteristics into account, maybe heterogeneity into account, club those again with geological database, what are the depositions available in a particular region, what are the crystal medium characteristics in a particular region, and what is the near-surface geology in a particular region. So, clubbing in situ data which is coming based on geophysical measurement, which are coming from sensor records, ground motion records, and the geological information, if these can be clubbed together, they definitely give an indication about the identification of an active fault in a particular region.

Again, I am repeating, the sole purpose of this particular lecture is to give an overview about what is an active fault and why an active fault identification in a particular region is important as far as primarily the hazard part is concerned. So, hazard is going to give you, potentially taking the faults in and around your particular site of interest, what is the expected level of ground shaking in a particular region or a particular site. So, one has to take, definitely, active faults into account in order to find out the locations which can show some significant features. Okay, so seismic tomography, as we mentioned, will help in identifying, maybe, the heterogeneity which is present in a particular region, so it's quite a useful tool as far as imaging the subsurface feature of Earth. It requires an involved iterative procedure where you can actually compare the signature which is coming from the initial Earth model and the actual ground motion signature, and every time, once you are going with the iterative procedure, you keep on modifying your initial Earth model such that the travel time between your, actual record, as well as the record which you are getting from your Earth model, can be minimized. That means now you are in the initial Earth model, which has undergone an iterative procedure, now has been revised significantly, and it is giving you a very close indication about what is the, characteristic of subsurface structure in a particular region or site of interest. So that is a significantly well-known and popular methodology as far as subsurface feature understanding is concerned.

So, as I mentioned, it requires minimizing the travel time difference between the actual record, as well as the record which you are generating based on a model subsurface characteristic, and it is generally compared in terms of the distribution of primary wave or shear wave velocities, how these are varying with respect to the distance, which is again an indication of medium physical properties, strength characteristics of the medium, which we will also discuss when we come to the lecture related to seismic waves in a particular medium. So, these variations will also help in understanding the change in the physical properties of the medium in terms of lithology, also in terms of the presence of porosity in a particular medium, and the fluid content which is available, maybe in unconformity, maybe in gaps, which can also cause significant effects in terms of triggering the events. Okay, so again, the seismic tomography, one can find out applications in terms of identifying variation in discontinuity, particularly Mohorovicic discontinuity, how there is change or dipping in Mohorovicic discontinuity because of seismic activity in different regions, one can look into. Then, how the in-situ tectonic settings are leading to indentation on the thickness of the crustal medium. Similarly, with respect to subduction of the lithosphere, one can also look into it when we are taking seismic tomography into account. Then there are other methods which can be used again to find out the subsurface features and to narrow down to understanding the tectonic setting of a particular region.

So, surface wave tomography is there, then controlled source seismology is there, then teleseismic tomography is there, local earthquake tomography is there, and ambient noise tomography is there. So, every time, whenever we are talking about tomography, basically, the attempt is to find out more accurately about subsurface features of the earth, which will also help in identifying whether it is related to rock, porosity, fluid characteristics, how these things in terms of primary and shear wave velocities are changing beneath the ground surface.



This is again the same thing which I mentioned, so we will take in-situ data, compare the in-situ data after particular processing because there will be noise also in that particular record. So, we have to filter out that noise and then compare this initial earth model, update it such that the signature is matching with your actual ground motion record. So, in the end, you will get seismic wave profiles which will help in identifying the variation in the medium characteristics in the subsurface medium.

Dense wide aperture acquisition, again, in this particular thing, we can use a large dense network of sensors, again, each sensor operating in a large range of frequency content, so that can give you very accurate information, even about thin layers which are available or small faults which are available in a particular region. So, accuracy can be enhanced if you are increasing, maybe, very closely spaced seismic sensors with a larger array aperture. That means you are now covering, at each sensor a larger array or a larger range of frequency content such that it can give you more accurate information, even about thin layers or small faults. Similarly, this can also give you a wide range of offset in order to go for deep penetrating refracted waves, so it is more accurate if you are going with the dense, wide-aperture acquisition. Identifying seismic anisotropy also is possible whenever we are going with a dense array, primarily related to the anisotropy available in a particular region. It is basically a representation of physical property variation along the subsurface medium, which is primarily related to change in the mineral alignment, it can be because of fracture orientation, or it can be because of fluid which is filled along these particular cracks, which sometime back we have also tried to target from seismic tomography. So, in the context of active faults, identification of seismic anisotropy reveals the orientation and intensity of folding and faulting which are available in a particular subsurface medium. So, active fault mapping, it is quite important as far as seismic hazard is concerned because it is going to give you potential regions in which potentially an earthquake can happen in the near future.

Wells and Coppersmith (1994) proposed

$$M = a + b \times \log(SRL)$$

M = Magnitude of Earthquake

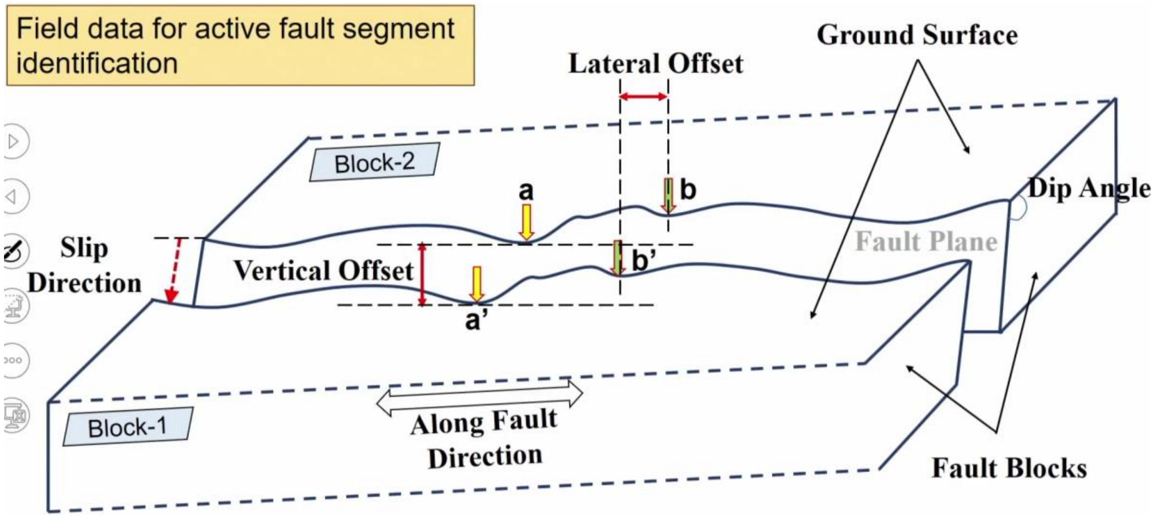
a, **b** = Coefficients depending on focal mechanism

SRL = Surface Rupture Length (in km)

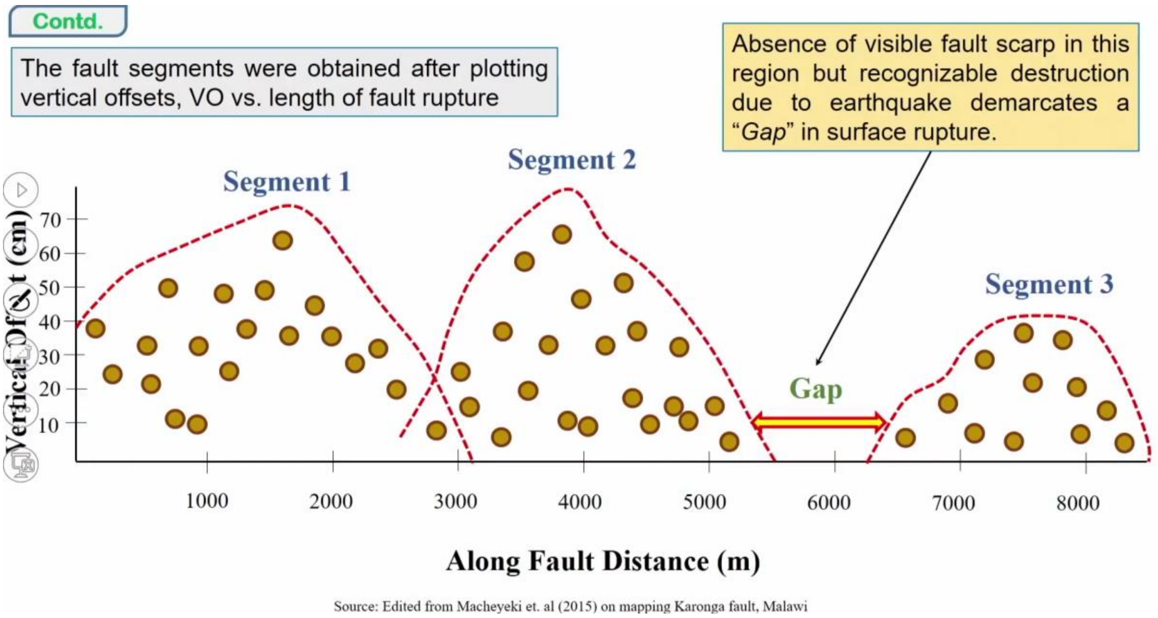
Fault Type	a	b	Range of Length (Km)
Strike Slip	5.16	1.12	1.3 – 432
Reverse	5.00	1.22	3.3 – 85
Normal	4.86	1.32	2.5 – 41
All	5.08	1.16	1.3 – 432

Now here, so based on in-situ investigation, what one can get is the potential surface trace of the fault, which is going to give you even the surface rupture length. So, Wells and Coppersmith, in 1994, proposed different correlations related to different fault mechanisms, where based on the surface rupture length which is available, one can identify what is the potential magnitude of the earthquake to be triggered. So, if you look at this particular equation, SRL is surface rupture length. If we know the value of SRL based on A and B, which are functions of what kind of fault mechanism one is dealing with, if we do not know the fault mechanism, again independent of that, we can have the value of A and B as shown over here. So, taking those values, taking surface rupture length which has been identified based on tomographic observations, can be brought over here, and then one can find out what is the potential magnitude of earthquake likely to occur, or what is the true potential in terms of the magnitude of the earthquake which can get repeated on a particular fault.

Again, so this continuing surface faulting and associated features, as far as seismic tomography is concerned, we can have many more informations. So, a mapping of surface features, mapping of vertical offset, again, it is going to give you an indication about pressure movements. Lateral offsets are also there, then measuring the strike and dip values, and then sand boils, sand liquefaction features. So, these are like geological techniques which will also give you an indication about potential activity in a particular region. Sources of error can be there if the GPS which is going to be used is of low precision. If there are too much of undulations, we cannot use it to accurately measure the distances, and as you are going very close to the surface, there will be a loss of confinement, as a result of which, whatever actual vertical and lateral offset had happened along the fault plane, that might be relatively bigger as far as the near-surface area is concerned. Generally, in terms of vertical and lateral offset which has actually happened in the subsurface medium, if you go very close to the surface medium or near the surface, because of low confining pressure, that particular offset will be significantly higher.



So, this can also lead to sources of error in field acquisition, as can be shown over here. So, there is some offset which is giving, like, vertical offset is there in the vertical direction, and as well as you can see over here, also some lateral offset on two parts of the fault blocks. You can compare before and after an earthquake; the two blocks which were in contact with each other have actually moved, but at the same time, these are surface manifestations. So, the offset amplitude at the surface, because of loss of confinement, because at the surface you do not have any overburden pressure. That will be significantly wider, it will be significantly deeper in comparison to the actual offset which is available beneath the ground surface.



Again, we can see that during a particular earthquake, there were a lot of manifestations or undulations which were there as part of surface manifestation, but it might happen that because of construction activity, because of maybe too much weathering also, some portion of the surface manifestation has gone. There can be a possibility of the existence of a gap in a particular region in terms of surface manifestations. So, you are having vertical offset, lateral offset; at the same time, you are also having gaps. So, one can take into account what are the surface manifestations which are running all along the length of this fault. So, you can see over here, primarily three segments are there which are showing some surface manifestation, some surface offset, in terms of segment 1, segment 2, and segment 3. The absence of a visible fault scarp in this region due to the earthquake demarcates a gap in surface rupture, which might be because of some recognizable or unrecognizable destruction because it is not well identified, even at times. So, one can go with mapping of the features which have been collected based on tomography, based on geological evidence, and also take into account the aerial photographs, having the photographs on a uniform scale and then correlating the details with respect to seismological, geophysical, and hydrogeological information.

Now, active fault mapping helps in estimating parameters for potential earthquakes, which have been mentioned in understanding the mechanical properties of the rocks in the subsurface medium, and even in terms of recent crustal movement, because every time when we go for active fault mapping, we will be taking into account the neotectonics of a particular region. This collectively will also be helpful in identifying the potential hazard in a particular region. So, categories in which the active fault movement can be utilized in terms of map representation is the rate of fault movement. So, in a particular region, you are having different rates of movement along different faults, so that can be mapped in the same fashion. Similarly, in terms of age, some faults show maybe movement in Holocene, some in Quaternary, some in Pleistocene, so accordingly, that can be resembled.

Based on the type of mechanism, fault plane mechanism, again on the map, we can represent different kinds of fault plane mechanisms. If there are some volcanic or hydrothermal activities, that can also be represented in the maps, which are also representing the location of active faults. And of course, if we are having fault plane solutions, there might be information about when the earthquake happened and what was the magnitude of the earthquakes, so that can also be clubbed over here in order to find out the location, in order to develop the map for active faults. So, some of the active faults across the globe—in Turkey, also, we are having some active faults identified. Similarly, in Guatemala, there are some earthquake faults which have been identified as active. In Africa, also, in South America, also, there are faults which have been identified based on in-situ measurements.

An earthquake event has been investigated to find an active fault produce a surface rupture in four segments. The surveyed lengths of the segments were found to be 880 m, 3860 m, 930 m, and 2710 m respectively along the direction of the rupture. The fault is supposed to have ruptured due to a build-up of compressive stress. Calculate the magnitude of the earthquake.

Now, this is one numerical—quickly, we can go through this particular numerical. So, there are faults, which are primarily indicative of compressive stresses; that means reverse faulting is there, and four segments are there which are going to give you, respectively, the length of the segment which has undergone rupture. So, these are the rupture dimensions along a fault plane; four places it has undergone rupture, and these are the values of those ruptures, and the fault plane mechanism indicates it is reverse faulting.

Solution

Since the fault ruptured due to compressive force between the two blocks, the fault is a **Reverse** / **Thrust** fault.

The total length of the Surface Rupture can be calculated by adding up the lengths of the individual segments.

So, the **Surface Rupture Length** (in km) = 0.88 + 3.86 + 0.93 + 2.71

= 8.38 km.

Now, According to Wells and Coppersmith (1994) , the magnitude of the earthquake will be given by the equation :

$$M = a + b*\log(SRL)$$

The fault being a reverse fault, **a** = 5.00; **b** = 1.22

Hence, the estimated magnitude of the earthquake = 5.00 + [1.22 * log(8.38)]

= **6.1** (Ans)

So, referring to the previous slide, where we were discussing Wells and Coppersmith's correlation, one can take into account the correlation related to reverse faulting. The total rupture length will be equal to SRL, which will be equal to the sum of all the rupture lengths which are given in the numerical. You will get a total rupture length of 8.38 kilometers corresponding to reverse faulting.

$$M = a + b*\log(SRL)$$

Whatever is the value of A and B, take into account, put the value in this particular equation, and one can get to know that this particular fault, which has shown four different segments of rupture, has actually produced an earthquake of 6.1 magnitude. That means during a particular earthquake, not the entire fault needs to undergo rupture; there can be small sections which can undergo rupture.

Inactive faults, as I mentioned, if it is not going to show any kind of movement along this particular fault, if it is not showing any kind of building up of stress regime on these particular faults, primarily these can be identified as inactive faults. But at the same time, there can be a phenomenon related to regaining of built-up strain energy scenarios, that means which can lead to reactivation of faults which were identified as inactive in earlier or in geological timescales, so reactivation is also primarily possible for active faults. So, there are some faults which are in an inactive state at present, which is given as here also Jinhe-Qinghe fault. Active and inactive faults can be distinguished based on the indication of displacement or surface manifestation, primarily in the neotectonic period of the terrain.

So, an active fault may be activated; an inactive fault can be reactivated because of so many factors, involving rupture in nearby faults, pressure depletion in hydrocarbon reservoirs that can also trigger some kind of seismic activity, and rifted continental margins that can also lead to continental collision, so that can also lead to fault reversal or, at times, reactivation of the fault. So, this is overall about what are the faults, what are the active faults, how one can identify active faults in a neotectonic region, what geological features, what in-situ measurements can be taken into account to identify potential surface manifestations. Thirdly, we also discussed if we have some information about what is the surface rupture length, how that can be taken into account to find out the magnitude of the earthquake. Even if we are discussing some historic earthquake, if we are able to find out surface manifestation or offset values, we can find out what might have been the magnitude of that particular earthquake.

So, thank you everyone, and this was all about active faults and what are the faults we should not call active as far as the neotectonics of a particular region are concerned. Thank you, everyone.